Natural Resources/Water Series No. 14

THE USE OF NON-CONVENTIONAL WATER RESOURCES IN DEVELOPING COUNTRIES

United Nations

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NOTE

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

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Foreword

On 16 July 1965 the Economic and Social Council adopted resolution 1069 (XXXIX) entitled "Water desalination in developing countries". That became the basis for the extensive work undertaken by the Department of Economic and Social Affairs in the 1960s and early 1970s on the subject of desalination and other non-conventional sources of water. The United Nations Water Conference further supported such research, in its Mar del Plata Action Plan where, under the heading "Research needs", it was recommended that research be promoted in the following areas, among others: weather modification; desalination, with particular reference to the treatment of brackish water; recycling of water; and water and waste treatment. International organizations were requested to take action to promote such research, including to "... investigate the possibilities of new technologies such as weather modification ... long-term weather forecasting, desalination and remote sensing to augment water availability". 1/

The Mar del Plata Action Plan also states that "Imported technologies for the management of water resources may require - as an intermediate phase in the transfer of technology - further study and experiment concerning the suitability of their adaptation to available resources and prevalent socio-cultural, economic and environmental conditions". Furthermore, "Water scarcity will often have a decisive influence on the development of appropriate technology. It may require in some cases a shift from traditional to relatively complex technologies ...".

Twenty years have passed since the United Nations issued a series of publications which paved the way for a serious consideration of water desalination prospects in developing countries. After the initial acclaimed volume, Water Desalination in Developing Countries, 2/ several other publications issued by the United Nations appeared in quick succession. However, the subsequent sharp increases in the price of oil during the 1970s, with the resulting high costs for desalted water, acted as a damper in the installation of new units in non-oil-producing developing countries. The United Nations thus sharply reduced the scope of its work in this field in the mid-1970s.

It was, therefore, felt that the time had come - some 20 years after the original work and mid-way through the implementation of the International Drinking Water Supply and Sanitation Decade - to review the sector once again, expanding consideration to broader range of sources of water supply, all of which currently carry the label "non-conventional". An attempt was therefore made to assess the pros and cons of various water desalination systems and of a series of alternative technologies under current economic conditions. In particular, the Department of Technical Co-operation for Development (which inherited the earlier work of the United Nations Secretariat) has tried to evaluate the extent to which progress in technological developments and related equipment, operation and maintenance costs (to the extent that these could be obtained) could create a favourable climate for a renewed interest in these "non-conventional" technologies by water-short developing countries or areas.

1/ Report of the United Nations Water Conference, Mar del Plata, 14-25 March 1977 (United Nations publication, Sales No. E.77.II.A.12), chap. I.

2/ United Nations publication, Sales No. 64.II.B.5.

The Department is indebted to O. K. Buros of CH2M Hill International Corporation for his continued and valuable technical assistance in the preparation of the present text and to Frank Rogalla, a Fulbright scholar at the New Jersey Institute of Technology, who worked as a United Nations interne on the preparation of chapter III.

EXPLANATORY NOTES

The following symbols have been used in the tables throughout the report:

Three dots (...) indicate that data are not available or are not separately reported.

A dash (--) indicates that the amount is nil or negligible.

A blank indicates that the item is not applicable.

Details and percentages in tables do not necessarily add to totals, because of roundings.

The following apply throughout the text and tables:

A full stop (.) is used to indicate decimals.

A comma (,) is used to distinguish thousands and millions.

Reference to "tons" indicates metric tons, and to "dollars" ($) United States dollars, unless otherwise stated.

Annual rates of growth or change, unless otherwise stated, refer to annual compound rates.

Surname and dates in parentheses () are keyed to the reference list.

The designations employed and the presentation of the material in the present publication do not imply the expression of any opinion whatsoever on the part of the Secretariat of the United Nations concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries.

Mention of firm names and commercial products does not imply the endorsement of the United Nations.

The examples given in the text are considered to be correct. However, the authors of the publication have not been able to visit the sites of all the 2acilities discussed. Therefore, some of the information regarding examples may no longer be accurate.

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CONTENTS (continued)

List of maps

CONVERSION FACTORS

To convert from:	To:	Multiply by:
mm	in.	0.039
cm	in.	0.394
m	ft	3.281
km	mi	0.621
km	NM	0.540
ha	acre	2.471
cm^2	sq in.	0.155
m^2	sq ft	10.764
km^2	sq mi	0.386
l	US gal	0.264
m^3	US gal	264.2
m^3	Imp gal	220.0
kg	lb	2.205
metric ton	lb	2,205.
metric ton	short ton	1.102
metric ton	long ton	0.984
$/$m^3$	$/1,000 gal	3.785
$/$m^3$/d	$/gpd	0.004
cm/s	ft/s	0.033
m/s	ft/s	3.28
m/s	mph	2.237
m^3/s	US gal/m (gpm)	15,850.
l/s	gpm	15.850
kW	1,000 cal/min	14.34
kW	hp	1.341
kW	shp	.734
kW	Btu/min	56.88

To convert from:	To:	Multiply by:
thousand joules	Btu	0.948
thousand joules	Wh	0.278
kWh	Btu	3,413.
kWh	MJ	3,600.
kWh	1,000 cal	860.
kg/MJ	lb/1,000 Btu	2.331
kg/cm^3	psi	14.223
kg/cm^2	atm	0.968
kg/m^3	lb/gal	0.008
atm	psi	14.7
kWh/m^3	kWh/1,000 gal	3,785.
m^3/d	gpm	0.183
m^3/d	1,000 gpd	0.264
N/m^2	1,000 psi	0.145
degrees celsius (°C)	Fahrenheit (°F)	$°F = 1.8°C + 32°$
ppm	g/m^3 at 15°C	0.999

ABBREVIATIONS

AgI	silver iodide
atm	atmosphere
BOD	biochemical oxygen demand
Btu	British Thermal Unit
°C	degrees (Celsius)
CEA	Commissariat à l'energie atomique
CFE	multi-stage controlled flash evaporator
cm	centimetre(s)
CSMCRI	Central Salt and Marine Chemicals Research Institute
CSIRO	Commonwealth Scientific and Industrial Research Organization
DIGAASES	Dirección General de Aprovechamiento de Aguas Salinas y Energía Solar
dwt	dead weight ton
ED	electrodialysis
EDR	electrodialysis reversal
°F	degree(s) Fahrenheit
G	giga (billion)
G and A	general and administrative (overhead)
gpd	gallons per day
gpm	gallons per minute
HFF	hollow fine fibre
HTME	horizontal-tube multiple-effect
IDEA	International Desalination and Environmental Association
IMO	International Maritime Organization
J	joule
k	kilo (one thousand)
KAE	Kompania di Awa i Elektrisidat di Korsou
kN	kilonewtons
kW	kilowatts
kWh	kilowatt hours
l	litre(s)

lb	pound(s)
LCD	limiting current density
M	mega (million)
m	metre
MED	multiple-effect distillation
MEMS	multiple-effect multi-stage
mgd	million gallons per day
mg/l	milligrams per litre
mm	millimetre(s)
MSF	multi-stage flash
MSF/FBE	multi-stage flash/fluidized bed evaporator
MW	megawatts
NW	nautical miles
NOAA	National Oceanic and Atmospheric Administration
O and M	operation and maintenance
ORC	organic Rankine cycle
OSW	Office of Saline Water
OTEC	ocean thermal energy conversion
OWRT	Office of Water Research and Technology
PEP	Precipitation Enhancement Project
ppm	parts per million
PR	performance ratio
psi	pounds per square inch
PVC	polyvinyl chloride
RO	reverse osmosis
shp	shaft horse power
SOLERAS	Saudi Arabia-United States Joint Desalination Project
ST	submerged tube
SWCC	Saline Water Conversion Corporation
SWRO	sea water reverse osmosis
TDS	total dissolved solids
TFC	thin film composite

ULCC	ultra-large crude carrier
USAID	United States Agency for International Development
USEPA	United States Environmental Protection Agency
VC	vapour compression
VLCC	very large crude carrier
W	watt
WHO	World Health Organization
WMO	World Meteorological Organization

INTRODUCTION

A. General

A meaningful differentiation must be made between the lack of water and the lack of water resource development in water-deficient areas. Water shortages may exist because capital or technical skills are not available to undertake major water development schemes such as ground-water development, dam construction and stream-flow regulation and installation of canals or pipelines. Sometimes, in the opinion of the authority handling water supply, the size of a community or of its industrial or other undertakings does not warrant an expenditure of the dimension required to make additional water available.

There are various ways of attempting to remedy water deficiency in areas where the present and potential supply of fresh water from conventional sources is inadequate for the level of demand. The existing quantity of fresh water may be better utilized by such means as decreasing waste or imposing rationing; and priorities can be determined for the particular purposes for which water may be utilized. Or, the available fresh-water supply may be augmented, when appropriate, by "importing" water via pipelines, canals, barges or other means, and by installing double pipeline systems to use salt or brackish water for suitable purposes. Water desalination is another useful way, when economically and technically feasible, of increasing the amount of fresh water available in a water-short area that is close to a body of brackish or sea water.

The United Nations recognizes the importance of water and its ready availability to the economic well-being of nations and peoples around the world, as evidenced by its declaration of the years 1981 to 1990 as the International Drinking Water Supply and Sanitation Decade (see General Assembly resolution 35/18 of 10 December 1980). The economic success of many developed countries is partially a result of the availability of large quantities of water for potable, agricultural and industrial purposes. Those water supplies have almost always been developed by conventional means such as using intakes, dams or reservoirs to provide surface water or wells to extract ground water. Treatment of those sources varies from none at all to the removal of suspended solids or hardness minerals, and overall costs are generally less than $0.25/m^3 ($0.95/1,000 gal).

The present publication discusses the development and use of selected non-conventional water resources. These are widely varied in scope and origin, ranging from the use of icebergs to the solar distillation of sea water. Their common characteristic is generally that they are more complex in development and operation than conventional sources, and the cost of the water produced exceeds, sometimes greatly, $0.25/m. Where it is possible to develop conventional water resources, that should almost always be the preferred solution. However, if this is not possible, then consideration should be given to the non-conventional water resource techniques discussed in the present publication.

There is no single non-conventional solution that is suitable for all areas. Each locality must carefully examine its own situation to determine which, if any, non-conventional method would be applicable. This should be part of a water resources development plan for the region, which might be placed within the context of the International Drinking Water Supply and Sanitation Decade (discussed below). The plan should examine present and potential needs and resources and chart a plan which arrives at courses of action that are feasible from the long-term financial, social and political points of view. An examination of this type may lead to the conclusion that the use of a non-conventional water resource is appropriate for all or part of a supply system or that it is not appropriate at all.

The present publication has been written to bring together some basic information on various non-conventional methods of developing water resources. Its purpose is to provide information so as to permit those methods to be adequately and fairly considered both for their positive benefits and negative aspects.

The selection and implementation of a non-conventional water project should be carried out with caution. None of the methods provide magical solutions, but will generally require large capital expenditures and continual long-term support with additional funding, technical labour, special parts, chemicals and continued attention to detail. Moreover, in most cases they involve considerably more risk than conventional solutions.

Conventional solutions, wherever possible, should be used but, if these are not appropriate and non-conventional development is feasible, the latter offers an opportunity to provide an area with water.

B. Progress made over the past 20 years in the use of non-conventional sources of water

From the mid-1960s to the early 1970s the Department of Economic and Social Affairs of the United Nations Secretariat, through its Resources and Transport Division, brought desalination to the attention of the international community through a series of technical and economic publications, as well as meetings and seminars. Those publications, which concentrated almost exclusively on desalination, are listed below in the references (United Nations, 1964, 1965, 1967, 1968, 1969, 1970 and 1973).

This early work contributed to an increased awareness of the role that desalination might play under appropriate conditions in developing countries. The publications traced the evolution of the desalination industry from its inception through the early 1970s. The current publication has been expanded considerably in scope, to include other non-conventional water resources: water transported either by tanker or iceberg; reclaimed waste water, for use in certain applications requiring lower quality water; and enhanced rainfall from weather modification techniques. Each chapter consists of sections on historical background, technical considerations, recent technological advances, applications in developing countries and economic considerations. The present volume was prepared by the Water Resources Branch, Natural Resources and Energy Division, Department of Technical Co-operation for Development, United Nations Secretariat.

The present section briefly traces the progress achieved over the past 20 years in non-conventional water resources. It compares some of the conclusions reached in the earlier United Nations desalination volumes with conclusions reached in the present study.

1. Desalination

Chapter I concentrates on the three major desalination processes in use today: distillation, electrodialysis and reverse osmosis. In the United Nations studies, the technologies available for desalting sea water were primarily in the distillation field. Since the first commercial multi-stage flash (MSF) sea-water evaporator was built in 1960 and up to the present, significant developments in distillation have been few and none have enjoyed comparable impact (Wood, 1982). On the other hand, since 1978 sea-water reverse osmosis (SWRO) technology has advanced considerably, through development of membranes which can be operated at higher pressures. The development of SWRO has been the major technological advance in sea-water desalination since the early publications of the United Nations on this subject. The major development in sea-water desalination which had been expected in the mid-1960s but which did not occur was in freezing technology. The freezing technology has still not become commercially viable and has not lived up to the promise of earlier years.

In brackish water desalting, aside from the important advances in reverse osmosis, the main technological advance since about 1972 has been the development of the electrodialysis reversal process. That improvement reduced some of the problems experienced in the standard electrodialysis process, and has contributed to making the electrodialysis process a reliable and well-accepted technology.

The considerable experience that has been gained over the past 20 years and improvements in technology in desalination using the distillation, electrodialysis and reverse osmosis processes have made desalting a widely accepted technology, supplying high-quality water to arid areas which had formerly been restricted from long-term social and industrial development. In the mid-1960s desalination was still a novelty, much of the work in the field was experimental and many of the early plants failed to meet expectations. At present, it is a largely reliable technology on which many countries depend for their daily water supplies. However, the costs are still relatively high; such high prices for water can only be justified under very site-specific conditions.

The major prediction made in the 1960s which has not come true was that the tremendous research and development effort in desalination technology would lead to a continuing decrease in costs per unit of product water. The probability of a continued downward trend in the cost of desalted water in developing countries was foreseen. This has not been the case, although costs in the early 1980s have stabilized to some extent. The 10-fold rise in oil prices since 1970, combined with high interest rates and inflation of materials prices, have made this trend impossible to accomplish. There was also the prospect that increased incomes of people in developing countries would put the costs of desalted water within their reach.

It has become sadly apparent that incomes in poor countries have not risen as expected, and desalination has become a viable technology only in middle-income and oil-exporting countries. Desalting projects in less developed countries might be supported by Governments or international agencies, under the International Drinking Water Supply and Sanitation Decade programmes, but costs of such water are still beyond the means of most rural communities in poorer countries.

2. Transport of water

Chapter II discusses methods of providing water to an area which involve the transportation of water on a large scale. Those methods involve the use of tankers and icebergs to transport water across a sea or ocean to the place where it will be used.

The possibility of transporting large quantities of water by tanker has recently become much more attractive for several reasons. With economies of scale resulting from the construction of very large crude carriers (VLCCs) and ultra-large crude carriers (ULCCs) from the late 1960s to the early 1970s, the unit costs of transport by tanker have declined since the late 1950s. Moreover, with the current glut in the oil market, more than half of the tanker fleet was laid up and transport costs were barely enough to cover costs of operation in 1984. Shippers were willing to consider transporting water as long as they were compensated for any additional costs involved. With the new regulations of the International Maritime Organization (IMO), introduced in October 1983, tankers will be required to reserve certain clean ballast tanks (up to 30 per cent of total carrying capacity) for fresh water, in order to reduce pollution. Those tanks could be used for transporting water to arid areas on return voyages.

In the late 1950s and early 1960s the transport of water by tanker was generally not feasible because of the low cost of the commodity compared to the high cost of transport. At present, several such transport schemes are operating, and many tanker operators are promoting water shuttle services, in order to utilize the excess capacity of the tanker fleet. The cost of used tankers is very low at present and some owners are buying up old tankers for the purpose of transporting water. In certain circumstances, developing countries along the tanker routes could benefit from selling water, and arid oil-exporters or island countries would be markets for the transported water.

On the other hand, the possibility of transporting icebergs for their high-quality water still remains in the realm of speculation. Considerable research on icebergs has been carried out, especially by the International Ice Patrol and universities. By the mid-1970s, the idea of harnessing icebergs for vast amounts of water had captured the imagination of many scientists and laymen, particularly after Saudi Arabia initiated a programme to look into the feasibility of delivering icebergs to that country. A wealth of information on icebergs was brought together at a conference on iceberg utilization held at Ames, Iowa, in 1977 (Husseiny, 1978). Following that conference, interest in such a scheme seems to have waned, probably because the economic and technical feasibility of such a scheme looked questionable. The need for fresh water may not yet be great enough to justify the risk and expense of towing an iceberg to fill that need.

3. Water reuse

Chapter III discusses the reclamation of waste water as a method to reduce demand for higher-quality water. Over the past 20 years, countries have paid much greater attention to reusing and recycling treated waste water in order to reduce pollution and conserve water. Reuse of waste water has mainly been advocated for non-potable purposes such as agricultural irrigation, ground-water recharge and industrial in-plant recycling. Reuse has generally been practised in the industrialized countries, where considerations of pollution control often entered into the decision to reuse water. The reuse of waste water for potable purposes has not yet been proved safe, and any current direct reuse for drinking is small and experimental in nature. Increased concern over trace organics and other low-level contaminants in recent years has added a new element of caution to waste-water reuse, even in agricultural and industrial applications.

In developing countries there is limited scope for waste-water reuse, since many of the nations do not have sewerage systems that collect the used water. In small villages dependent on standposts for water supply, there is generally no system for collecting used water. However, there is certainly scope for constructing new industries with recycling systems for water. Moreover, domestic waste water that is collected can be used, after treatment, for agricultural purposes. As water becomes more scarce and developing countries become more concerned about conservation of water, the reuse of treated waste water in agriculture and industry is likely to become considerably more important.

4. Enhancement of existing supplies or sources

Chapter IV is devoted to a discussion of the possibility of enhancing existing water supplies by increasing rain or reducing evaporation. Research into cloud seeding techniques has been very active over the past 20 years. In the early and mid-1960s there was considerable optimism in countries such as the United States of America, Australia and Israel that weather modification could provide the additional water supply required to meet the growing demand in agriculture, industry and municipalities. While results have been very positive in one country (Israel), the earlier optimism in other countries has been tempered by experience. Rain-making is a very risky business and its success is extremely difficult to document statistically. Because of the high risks involved, many communities depending on rain would not want to invest in such a venture. Moreover, during a dry or drought period, there are generally not enough clouds suitable for seeding. The technology works better during wetter periods and is most useful for filling reservoirs or recharging aquifers. Thus, the infrastructure has to be available to catch the water. While most countries have reduced their programmes in this field, the World Meteorological Organization (WMO) has in recent years launched its Precipitation Enhancement Programme. It is hoped that research carried out under that programme may lead to a better understanding of the processes of weather modification.

C. Objectives of the International Drinking Water Supply and Sanitation Decade

The International Drinking Water Supply and Sanitation Decade, launched by the United Nations in November 1980 (see General Assembly resolution 35/18) has as its main objective the extension of water supply and sanitation services to all people, particularly in rural areas of developing countries, by 1990. The United Nations agencies involved in promoting the objectives of the Decade throughout the developing world are assisting Governments to implement national plans for the drinking water and sanitation sector. In many water-short areas, national plans and programmes involve considerable development of non-conventional water resources.

The non-conventional water resources discussed in the present volume do not create new water, but only expand the potential for treating and utilizing water sources that were previously considered unusable or unavailable. This means that sea and brackish water, waste water and water located in distant places can now be considered as potential sources of fresh water.

For the developing countries that have shortages of fresh water, use of non-conventional sources expands their supply of fresh water, provided that the locality can afford this type of water. The capital and operating costs associated with desalination and tanker transport, for example, are high, and the high operating costs continue as long as water is produced.

On the other hand, the use of a non-conventional water resource may offer the possibility of improving standards of living. A small desalination plant, for example, could provide a reliable source of fresh water for areas that in the past have relied on the uncertainties of nature for water. It can also reduce the distance over which water is transported from the source to the user, as desalination can make closer, previously unpalatable, sources usable. Since this transportation is often by truck, barge, animal cart and/or carried by women, desalination can often produce savings in fuel, money or time.

1. Comprehensive service for all

The global target adopted by the Decade is to provide all people with access to drinking water of a quality and quantity that will yield improvements in public health. This implies a strategy that gives precedence to under-served people who are not covered by existing programmes. In very arid areas, remote rural or coastal communities, desalination of brackish or sea water may provide a source of clean drinking water otherwise unavailable. Current experiments using desalination units coupled with solar or wind energy systems may eventually provide a viable technology for remote communities. Barging of water or reuse of waste water might provide lower-quality water for industrial or agricultural uses, making limited supplies of higher-quality water available for domestic use. The use of such sources would reduce the necessity of constructing long-distance pipelines to remote areas. Small-scale desalination plants would upgrade existing supplies of brackish water and could contribute to an overall improvement in public health.

Non-conventional sources may be a viable supplement in areas where the supply is insufficient because of population growth, pollution or a failure of supply. People have already had to supplement their water supplies by either walking long distances or paying vendors high prices for minimal amounts of water. A desalination plant, reuse of waste water for selected purposes or transportation of water by tanker may provide the necessary supplements to under-served rural areas, in many cases for less than what the people currently spend on water.

2. Human resources development

Where complex technology is needed to develop a non-conventional water resource, a trained, motivated and properly supported staff can be the best investment made in the facility. For example, many developing countries have a serious shortage of the type of skilled or trained labour necessary to operate a desalination or waste-water treatment plant. Without a nucleus of trained people, operation can be difficult and possibly disastrous, depending on the type of plant. However, as has been demonstrated in several developing countries, people with little formal education can become effective plant operators if they are properly selected, trained, motivated and technically assisted in their jobs.

3. Appropriate technology

The ability of the community to take responsibility for operation and maintenance of the facilities will be an important factor in the choice of technology. Generally speaking, it is desirable to choose a few simple models of water supply and sanitation facilities which can be standardized and thus replicated throughout the country, and for which spare parts could be locally manufactured. This is not only true for conventional types of dams, wells and pumps, but also for relatively simple village-scale non-conventional facilities.

It is very difficult to generalize on the appropriateness of non-conventional water resources in developing countries. Desalination has been used to produce municipal water supply in Curaçao (Netherlands Antilles) since 1928 and in Egypt since the early 1930s. Both those places currently have a wide variety of desalination units operating successfully. Waste water has been reused in agriculture for more than a century in India and barging of water has been used periodically in Europe and the Caribbean over the past 100 years. According to location, one or more non-conventional sources may be considered appropriate.

4. Economic viability

In determining the economic viability of a village project, its benefits may be intangible and difficult to quantify, such as improved public health and the freeing of women from carrying water over long distances. In many cases, the village water supply projects may be viewed by the Government as social investments, rather than investments that will yield economic returns. However, in the case of a non-conventional water resource project, it will be necessary for the villagers to pay for operation and maintenance of facilities or barging fees in the long term. Therefore, the economic viability of the project must be determined jointly by the government agency and the community.

It should be remembered that households in water-short areas already rely on very expensive sources of water. Villagers may pay a lot each day for water to live on, and therefore they cannot build up the capital necessary to construct a better water supply system. The Government may be able to provide the assistance needed to invest in a non-conventional water resource, if the community pledges to cover all operation and maintenance expenditures.

I. DEVELOPMENT OF BRACKISH AND SEA-WATER SOURCES

A. Introduction

In the past, brackish and sea water were not considered resources that could be developed for potable or agricultural use. The high levels of salts in those waters made them unpalatable for human consumption and impossible to use for normal agriculture. However, the use of desalination processes has now made those saline water resources available for man's use.

Desalination (also known as "desalting" or "desalinization") refers to the process of removing salts from water. The concept is not new, having been experimented with and discussed for at least 2,000 years. What is new (and therefore makes desalinated water a "non-conventional" source) is the development of commercially viable processes.

The desalination industry as it exists today began approximately 30 years ago in the early 1950s. Previously, small stills had been used to produce fresh water on ships for several centuries and distillation technology was well known in certain industries.

The use of marine-type distillation plants for land-based municipal applications was discussed by various localities in the Caribbean and elsewhere in the early 1900s. Installations were constructed in locations such as the Netherlands Antilles and Egypt. While the technology (distillation) was available, the major problem was economics. The cost of distilling sea water or brackish water to produce fresh water was quite high when compared to conventional water sources. Only a few special applications and/or local communities could afford the cost. These were mostly confined to military and special industrial applications.

In 1950, there were only a few scattered land-based desalination plants for water production, with the world-wide capacity being about 10,000 m^3/d (2.6 million gallons per day (mgd)). By 1984, both the technology and economies of scale had improved so that the world-wide desalination capacity had grown to about 7,500,000 m^3/d (2,000 mgd). The period between 1950 and the mid-1980s can be divided into three phases: discovery, development and commercialization (Buros and others, 1984). During that period the major effort has been concentrated on four desalination processes: distillation, freezing, electrodialysis and reverse osmosis. The growth of each of those processes during that period is shown in figure I.

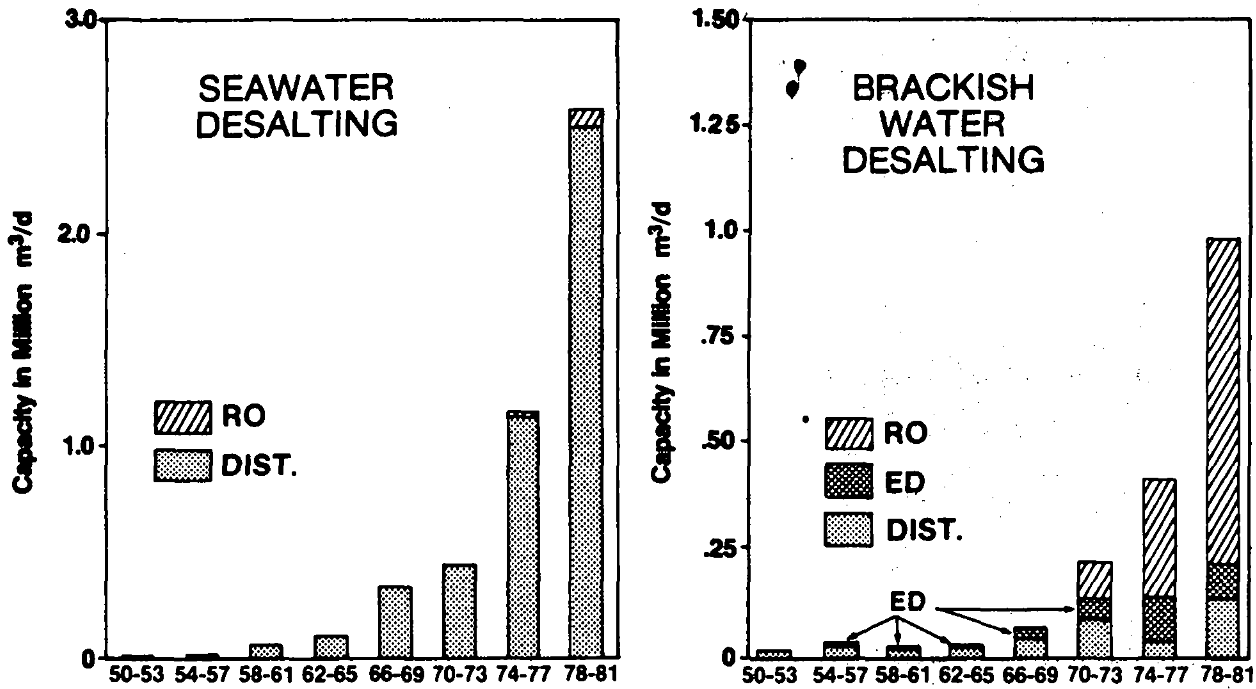

Figure I. Growth in desalination capacity, 1950-1981

1. Development of technology

(a) Discovery: the 1950s

In the 1950s distillation was the only viable means of desalinating either brackish or sea water. Most of the early plants were small, isolated multiple-effect distillation plants with capacities of 20 to 60 m^3/d (5,300 to 16,000 gpd) and the product was used mainly for boiler feed water.

In 1952, the United States Government formed and funded the Office of Saline Water (OSW). That agency and the work it sponsored established much of the technical basis for the development of the present desalination industry. OSW, and its successor, the Office of Water Research and Technology (OWRT), budgeted over $US 300 million for studies, research and demonstration plants over a period of 30 years until it was disbanded in 1982.

All of the desalting processes were in their infancy in the 1950s. In the mid-1950s the multi-stage flash process, developed and patented in Scotland, soon replaced the use of submerged-tube multiple-effect plants for fresh water production by distillation. The use of the MSF process has grown steadily and currently represents about two thirds of all the desalination capacity in the world.

The other process for desalting sea water, which seemed to have good potential in the early years was freezing. Although patents acknowledging the principle of desalting saline water by freezing had been filed as early as the 1920s, no significant work occurred until the 1950s, when various companies in the United States and Israel began work on producing freezing-based desalting units.

The desalination of brackish water by electrodialysis was a major technological breakthrough in the 1950s. One of the factors that brought about the creation of OSW was the development and demonstration in 1951-1952 of an electrodialysis unit that could desalinate brackish water. The unit demonstrated that the desalting of brackish water could offer potential costs significantly below those for distillation, which was the only other process being used for that purpose. Units were built and a number were sold and operated in the Middle East and the United States of America.

In 1953, the basic principles of the reverse osmosis (RO) process for desalting saline water by pressurizing saline solutions against a semi-permeable membrane were demonstrated. Further work in the late 1950s improved membrane flux, stability and salt rejection so that it could be viable for commercial use.

Two important documents summarize much of the thinking and technical knowledge of this discovery phase of desalting. These are the Office of Saline Water's Proceedings of the First International Symposium on Water Desalination (United States Department of the Interior, 1965) and the United Nations publication, Water Desalination in Developing Countries (United Nations, 1964). A summary discussion of desalination processes in the latter publication concentrated mainly on the various distillation processes such as multiple-effect, multi-stage flash and vapour compression (VC) and discussed freezing and electrodialysis along with liquid extraction and ion exchange, but did not mention reverse osmosis, which was still in the laboratory stage. The publication for the first time reviewed prospects for the application of desalination technology in 53 water-short developing countries.

It is estimated that the desalination plant capacity sold or installed between 1951 and 1960 was about 117,000 m^3/d (31 mgd). Its distribution by process is shown in table 1.

(b) Development: the 1960s

In the 1960s work proceeded on various methods of desalination, such as distillation and freezing processes, electrodialysis, reverse osmosis, and ion exchange and liquid extraction. During that time, researchers and manufacturers capitalized on the basic knowledge gained in the 1950s to develop commercial products for the potential market. Efforts were made to reduce the cost of water by the use of innovative designs and materials. Researchers thought that the overall costs for producing fresh water by desalting sea water could be reduced to about $0.35/$m^3$ ($1.30/1,000 gal) by the end of the decade.

Although various types of distillation plants were built during this decade, the predominant design was based on the MSF process. To reduce water production and capital costs, designers worked to increase efficiency by attempting to increase the upper temperature limit at which the units would operate and to use a variety of low-cost construction materials. A number of plants in the 4,000 to 8,000 m^3/d (1.1 to 2.2 mgd) range were installed in the Caribbean, North America and the Middle East.

Meanwhile, a number of companies in the United States and Israel were working on a variety of freezing desalting processes. In terms of thermodynamics, corrosion and materials, the freezing process was potentially more economical than the distillation process, which was its only real competitor for desalting sea water. Unfortunately, the mechanics of manipulating ice and vapour formation inside the units proved to be difficult. By 1969-1970, the only commercial installation was at a hotel in the United States Virgin Islands, while demonstration plants existed in Israel and the United States.

Electrodialysis units continued to be developed and sold for brackish water applications in various parts of the world and a small number of manufacturers began to enter the market. Materials and operations were improved based on this experience. Operational problems were occasionally experienced in the formation and deposition of precipitates and other solids in the stacks.

In the reverse osmosis field, researchers concentrated their efforts on developing a device and membrane geometry that could efficiently incorporate the membranes previously developed. The four configurations that received the greatest attention were spiral-wound, plate and frame, tubular, and hollow fine fibre. By the late 1960s, a few RO units were in operation in the United States for treating brackish water, mostly for industrial applications.

The United Nations published two studies which presented actual data on desalination plant operations during the late 1960s (United Nations, 1969 and 1973). These were in the form of detailed inventories of plants, including size, costs and materials of construction. The first inventory covered operational data on 57 plants in 21 countries for the year 1965. The second covered operational data during 1968 for 94 plants in 22 countries. In the United States, OSW began an inventory effort in 1968 which collected less extensive data but covered more plants. That inventory has been repeated every few years, with the seventh inventory being produced in 1981. An eighth inventory is expected in 1984 or 1985.

Table 1. Desalination plants installed or sold during the period 1951-1980

Type of process	Capacity Installed or sold in the period (m^3/d) 1951-1960 a/	1961-1970 a/	1971-1980 b/
Distillation			
Multi-stage flash	26 720	506 080	2 702 000
Vertical tube	22 020	134 550	207 200
Submerged tube	63 180	11 450	8 570
Other	4 890	24 900	163 000
Freezing	--	380	110
Electrodialysis			
Standard	300	37 290	101 840
Reversal (EDR)	--	--	139 320
Reverse osmosis	--	8 570	1 041 800
Total c/	117 110	723 220	4 364 140

Type of process	Capacity Installed or sold in the period (million gallons per day) 1951-1960 a/	1961-1970 a/	1971-1980 b/
Distillation			
Multi-stage flash	7.05	133.53	713.01
Vertical tube	5.81	35.50	54.67
Submerged tube	16.67	3.02	2.26
Other	1.29	6.57	43.01
Freezing	--	0.10	0.03
Electrodialysis			
Standard	0.08	9.84	26.87
Reversal (EDR)	--	--	36.76
Reverse osmosis	--	2.26	274.88
Total c/	30.90	190.82	1 151.49

a/ Based on data from N. A. El-Ramly and C. F. Congdon, Desalting plants inventory report No. 6 (Washington, D.C., United States Department of Interior, 1977).

b/ Based on data from N. A. El-Ramly and C. F. Congdon, Desalting plants inventory report No. 7 (Honolulu, Techno-Economic Services, and Ipswich, Massachusetts, National Water Supply Improvement Association, 1981). Included in the El-Ramly and Congdon report but not in the present table are desalting plants to be built after 1980. These amount to about 2.19 million m^3/d (580 mgd) in added capacity.

c/ The present table does not include plants with capacities of less than 95 m^3/d (25,000 gallons per day) capacity.

It is estimated that the desalination plant capacity sold or added between 1961 and 1970 was about 723,000 m^3/d (191 mgd). Its distribution by process is shown in table 1 above.

(c) Commercialization: the 1970s and beyond

The escalation of energy costs significantly affected the desalination industry during the 1970s. On the one hand, the increased energy costs reduced the potential desalting market in many of the oil-importing nations and dashed the hope of desalting sea water for $0.35/$m^3$ ($1.30/1,000 gal) or less. On the other hand, it created a tremendous market for desalination equipment in the oil-rich, water-short areas of the Middle East and North Africa.

During this period, the MSF design continued to be the leading distillation process used throughout the industry. Sales in the Middle East were very heavy and were dominated by Japanese and European manufacturers. One of the important lessons learned in the 1970s was that the use of inferior materials in constructing plants, and/or improper operation, especially with acid-fed MSF plants, resulted in severe problems. A major effort was undertaken to develop effective means of scale control and to reduce corrosion in distillation plants.

From 1980 to 1983 Saudi Arabia expanded the gigantic complexes at Al Khobar and Al Jubail to final capacities of about 250,000 m^3/d (66 mgd) and 1,100,000 m^3/d (290 mgd), respectively, using dual purpose MSF plants.

Today, designing and constructing a reliable MSF plant with reasonably predictable operation and maintenance costs is possible, if the desired materials can be specified and operations controlled. Most large distillation plants are now installed in conjunction with power plants and utilize waste heat from the latter, which has lowered energy costs and improved economies of scale.

Work on the freeze-desalting process essentially came to a halt during the 1970s. The extensive problems and lack of commercial success caused most of the manufacturers who were developing freeze-desalting processes to drop out of the market.

By the early 1970s electrodialysis installations with capacities of 5,000 to 10 000 m^3/d (1.3 to 2.6 mgd) were being routinely sold. In 1973 the electrodialysis reversal process was made available commercially. This new process reversed the polarity and flow in the stacks at regular intervals, thus reducing the scaling problems and allowing operation with the use of a minimum of pre-treatment chemicals.

One company continued to dominate the market with its patented electrodialysis-reversal process. It made almost all of the electrodialysis sales in the past five years. Improvements have come in the production of larger-sized modules and better membranes which have decreased energy usage, fouling and capital cost.

The biggest competitor to electrodialysis is RO. When overall costs are accounted for, electrodialysis can compete quite well with RO in the treatment of water with a low level of total dissolved solids (TDS) and some difficult waters, despite the low costs generally associated with reverse osmosis.

Reverse osmosis has become an accepted and reliable desalination process in 14 years of commercial experience. Brackish water units as large as 5,000 m^3/d (1.3 mgd) were being installed by 1975 and 40,000 m^3/d (10.6 mgd) installations were being sold by the end of the 1970s. The use of RO as a method to desalinate brackish water has become widely accepted. Of the four membrane configurations developed in the 1960s, only the hollow fine fibre and the spiral-wound modules achieved signficant commercial success.

During the mid-1970s, several manufacturers began to produce small quantities of RO membranes that were capable of desalinating sea water efficiently. After a series of trial installations, a large 12,000 m^3/d (3.2 mgd) plant was sold to and operated in Saudi Arabia. By the end of 1980, over 54,000 m^3/d (14.3 mgd) in sea-water RO capacity had been sold or installed (El-Ramly and Congdon, 1981). By 1984, RO had become a serious competitor to distillation as a process for the desalination of sea water.

2. Development of markets

During the early years, the largest number of desalination plants were installed in the oil-exporting countries in the Middle East and in connection with the exploration and exploitation of natural resources. The other major buyers of desalination plants were tourist resorts and the bottling and food processing industries. Supply of desalinated water for municipal or domestic use was of relatively minor importance. Beginning in 1971 the capacity of plants sold to municipal and domestic water supply agencies began to outstrip those purchased by industrial and power plants. In 1979-1980, of the total desalination plant capacity sold, some 2.4 million m^3/d, about 80 per cent was for municipal water supply.

An estimate of the desalination plant capacity sold or added between 1971 and 1980 is about 4.3 million m^3/d (1,150 mgd). Its distribution by process is shown in table 1. The current estimate of installed desalination capacity world-wide is 7.5 million m^3/d (2,000 mgd). The distribution of desalination capacity in 1980 by region is illustrated in figure II.

The growth of desalination capacity since 1970 has been considerable in the oil-producing areas of the Middle East and North Africa; about 2.8 million m^3/d (740 mgd) of desalting capacity was purchased or installed in those areas during the 1970s. An additional 1.7 million m^3/d (450 mgd) was added or ordered in those regions from 1981 to 1983. Much of this increase can be attributed to energy cost increases which provided additional funds for investment in oil-exporting countries. The Middle East and North Africa accounted for about 65 per cent of the world's desalting capacity in 1981. The second largest market was the United States of America and its territories, with 14.2 per cent of the total world capacity, followed by Europe with 7.3 per cent of the total (El-Ramly and Congdon, 1981).

It is expected that the market for large plants in the arid, oil-exporting countries will continue to be the largest market for desalination plants and desalted water. In those markets, it is unlikely that desalting concepts with much lower specific energy demands than current MSF processes would be developed, especially since many of those plants are already linked with power production in thermal power stations. Until other developments are proven commercially, it is expected that traditional operators will adhere to the well-tried MSF plants.

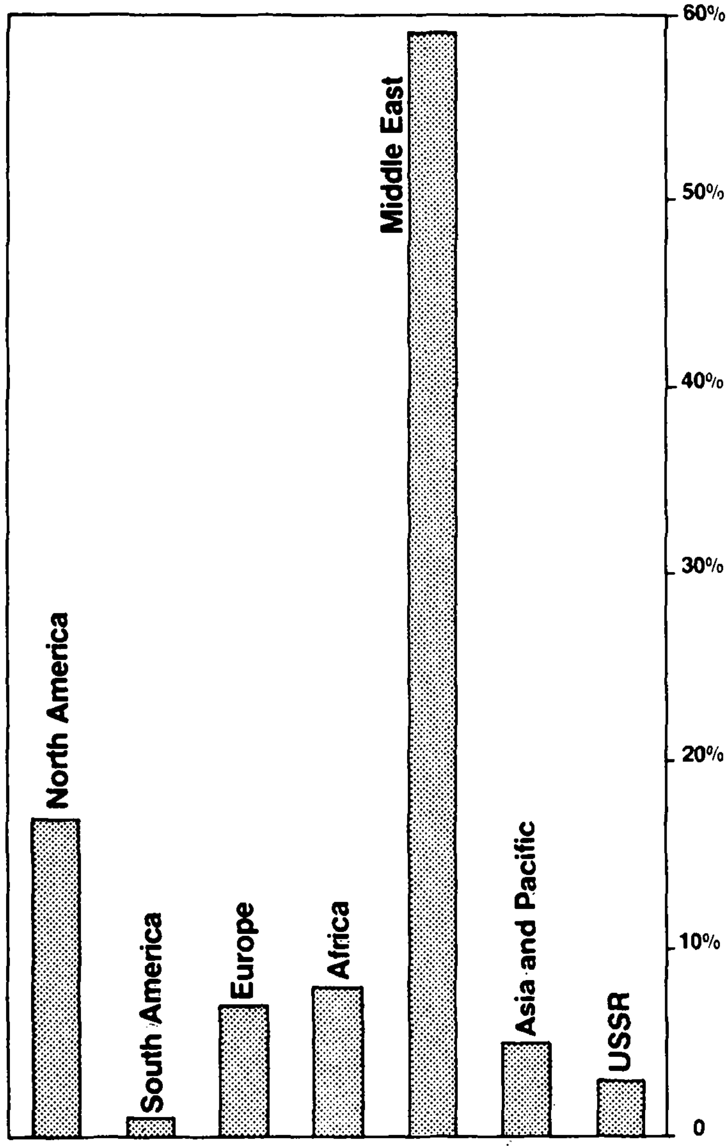

Figure II. Distribution of desalination capacity by region, 1980

Until relatively recently, the demand for desalted water in energy-importing industrialized countries had been restricted to meeting localized or specialized needs such as boiler feed water make-up. Through increasing industrialization, coupled with the imposition of environmental constraints, the demand for desalting is likely to increase dramatically in some countries, such as the United States, Japan and those of Western Europe (Wood, 1982).

The third market, which is expected to grow considerably in the future for relatively small desalination plants (say below, 1,000 m^3/d), is in developing arid countries, to meet the needs of tourist hotels, construction sites and isolated small communities lacking in almost every type of natural resource as well as finance. Although their economic conditions vary widely, they share a need for simple plants, capable of operation with minimal maintenance and attendance, yet having overall reliability. Among the technologies that might fit those needs are: mechanical vapour compression evaporators, where an electrical supply is available or diesel generation is feasible; solar distillation plants; and small-scale reverse osmosis treating brackish well water (Wood, 1982).

Government agencies are still the largest producers of desalted water. Most of the largest installations, used mainly to supply domestic requirements, are in the hands of central or local government undertakings. Often a municipality derives its water from many different sources, including desalination. Thus, costs may be averaged out to determine tariff levels. Moreover, industries may be charged more than domestic consumers, especially if they require high-quality water.

3. Process selection

Of the four major processes: distillation, freezing, reverse osmosis and electrodialysis, only freezing has still not become commercially viable. Therefore, it will not be discussed further in the present volume. The remainder of the chapter discusses distillation, reverse osmosis and electrodialysis technologies in greater detail. Much of this discussion has been taken from more detailed work on this subject contained in The USAID Desalination Manual (Buros and others, 1980). That volume contains extremely useful technical descriptions and diagrams, and is recommended for any agency in a developing country contemplating the purchase of a desalination plant.

Of the three commercially proven processes discussed in the next three sections, there is no one "best" method of desalination. Generally, distillation and reverse osmosis are used for sea-water desalination, while reverse osmosis and electrodialysis are used for brackish water desalination. However, the selection and use of those processes can be very site-specific; they must be selected very carefully, especially in developing countries. Before any commitment is made regarding desalination in a particular location, competent professional assistance should be secured to evaluate the application.

Cautious optimism had been expressed in the 1960s concerning the role of water desalination in assisting water-short areas of developing countries to meet their water needs. The optimism was based on the rapid growth in water demand in water-short areas and on the increased pace in development in some water-short areas of developing countries. Those factors would stimulate the development of infrastructure and level of technical training, thereby providing the necessary ingredients of energy, power and trained personnel for a desalination plant. This has certainly happened to some extent in the Middle East and in the islands in the Caribbean and the Mediterranean. New areas have been opened up for development and numbers of personnel have been trained. However, development has been very expensive and often the training of local technicians has been insufficient. In many plants, foreigners continue to operate the facilities, even after many years.

One of the major considerations in the selection of a desalination process is its cost. In comparison to the costs of most water sources developed and treated in industrialized countries by more conventional means, desalinated water may be from 2 to 50 times more expensive. Although there have been considerable efforts to reduce costs, desalinated water is still expensive. The process is inherently energy-intensive and improvements in equipment and efficiency have been offset by rapid increases in energy costs. However, despite the substantial costs involved, the availability of desalted water can be an economic boon to an area. Where water is scarce, it is often transported over long distances by truck or animal. When the water is sold, its unit price often exceeds that of desalted water. Therefore, the economic conditions to support desalination already exist in many water-short areas.

B. Distillation

1. Historical background

Distillation, the most widely used and best known process for desalting water, has long been in operation in forms of varying efficiency. Distillation of water for potable purposes has been practised on-board sea-going vessels for nearly 400 years. Patents were issued in the seventeenth century in England for commercial distillation units (Baker, 1948).

Early processes for controlled evaporation of liquids with a high content of total dissolved solids involved the production of salt and sugar. Solar evaporation was and still is used for the production of salt. Technologies using multiple-effect evaporators (to be discussed in annex I) have been used since the beginning of this century in the production of sugar. The evaporation process was used to separate the dissolved sugar from the juice squeezed from the sugar cane. The process was economical since sugar was a high-value product - the byproduct, distilled water, although useful, could not justify the cost.

The early applications of distillation of sea water for potable purposes came in ocean-going sailing ships. Sea water was distilled in small quantities on the ship's cook stove using a very basic still consisting of a pot, a condenser and a collector. This process was inefficient and inconvenient, but it augmented water carried in casks or collected from rain. Some marine stills of the single- and multiple-effect variety were introduced in the late 1800s and appeared for the next few decades. In certain water-short areas these were adapted for use on shore.

A land-based submerged-tube desalination unit for potable water production was installed at Curaçao, in the Netherlands Antilles, in 1928. Others were built scattered around the world where high water costs were acceptable. However, as a result of high costs, the concept was not widespread, and the potable water desalination capacity installed by the 1940s was insignificant.

During the Second World War considerable work was done in the United States on vapour compression units which could be used on-board ship as well as in isolated bases around the world. Those units were designed to operate at relatively high temperatures (100 to 105° C (212 to 220° F), in order to reduce the size of the compressor, but they experienced more problems with scaling than the lower-temperature submerged-tube units (Watson, 1976).

The concept of multiple-effect evaporation was known from the early part of this century, and units with one to four effects were used for desalination of brackish or sea water from the 1940s to the 1970s in many parts of the world. In 1958 a plant having five 6-effect submerged-tube units (total capacity of 9,500 m^3/d (2.5 mgd) was constructed. This was the largest of the submerged-tube plants built, as the process was largely displaced by the multi-stage flash process in later years.

In 1957 the multi-stage flash concept was patented by Robert Silver of Scotland. The first significant plants of this type were built in Kuwait and on the island of Guernsey. The first Kuwait plant built in 1957 had a capacity of 2,400 m^3/d (0.6 mgd) with four stages. This was followed closely by units with 19 and 22 stages. The Guernsey installation of 2,804 m^3/d (0.75 mgd) built in 1960 had 40 stages. From this beginning the multi-stage flash concept dominated the field of sea-water distillation, and in 1981 multi-stage flash plants accounted for about 90 per cent of the world's installed distillation capacity (El-Ramley and Congdon, 1981). The various distillation technologies and major engineering considerations are described in detail in annex I below.

2. Technical considerations

The distillation process has evolved into a mature technology, used widely around the world. Over 55 countries have distillation plants, with a total capacity of about 5.5 million m^3/d (1,450 mgd). The water is used primarily for municipal purposes plus some industrial applications.

Three major processes are generally used. These are multi-stage flash, multiple-effect and vapour compression.

(a) Multi-stage flash

The world's distillation capacity is dominated by multi-stage flash plants which continue to be widely used as part of dual-purpose (electricity and water) systems using waste steam as the prime source of energy. Individual units as large as 19,000 to 38,000 m^3/d (5 to 10 mgd) are being built. A massive installation with a total capacity of about 1,100,000 m^3/d (290 mgd) was completed in Saudi Arabia in the early 1980s.

Properly designed and operated, an MSF plant has proved to be a reliable and economical unit for the desalination of sea water. They do, however, require construction with high-quality materials and careful operation.

(b) Multiple-effect

About 8 per cent of the world's distillation capacity is accounted for by multiple-effect plants. Those plants have been built in a variety of configurations and designs. Units have been built as large as 20,000 m^3/d (5.3 mgd) but most are less than 2,000 m^3/d (0.53 mgd). They are usually installed as dual-purpose plants and have the potential to be highly efficient. However, the wide success and preference of certain large users for the MSF design and problems with some prototype multiple-effect plants have limited its use, especially during the past five years.

Recently a number of low-temperature multiple-effect plants in the 2,000 to 5,000 m^3/d (0.53 to 1.3 mgd) size range have been built and are being operated in the Caribbean region with good results; that experience should aid in increasing the popularity of the process.

(c) Vapour compression

Vapour compression units account for about 2 per cent of the world's distillation capacity. They are small units, generally under 400 m^3/d (0.11 mgd) in capacity, their capacity being limited by the size of compressor available. These units operate alone and require some type of rotating energy (or a steam jet) to operate the compressor. This is usually an electric motor or diesel engine. They are widely used on offshore oil platforms, at construction sites or for resort hotels.

(d) Hybrid units

Hybrid units which combine MSF, multiple-effect and/or vapour compression in a variety of ways to desalinate sea water have often been suggested, but there are very few operating examples. The main advantage to this type of arrangement would be a more efficient and economical plant.

(e) Major problems

The major problems in distillation plants have generally resulted from materials failure, improper operations and inadequately proven prototype designs (Watson, 1976). Control of scale formation is the major operating and design constraint. Details of technology and problems are presented in annex I below.

3. Recent technological advances

(a) Reliability

The increased reliability of distillation plants, especially MSF and vapour compression designs, is a significant advance in technology. The experience gained in design, material selection, fabrication and operation has enabled distillation facilities to be operated reliably with reasonably predictable life-cycle costs.

This reliability has enabled distillation plants to form the basic water supply in many areas such as Kuwait, the Netherlands Antilles, Saudi Arabia, the United Arab Emirates and the United States Virgin Islands.

(b) High-temperature additives

Multi-stage flash plants operating at temperatures above 88° C (190° F) require some type of special treatment to control the formation of scale in the units. Traditionally, this has been sulphuric acid. The acid is effective and generally available but there are problems with handling, and, if used improperly, excessive corrosion or scaling can result.

The use of high-temperature polymer-based scale control chemicals as a substitute for acid offers a great potential for operating multi-stage flash plants at high temperatures without the inherent (and often disastrous) disadvantages of acid. The additives appear to be effective in inhibiting scale formation, safer to handle than acid and generally non-corrosive. Compared to acid, only small amounts of the polymer are needed. A body of experience is beginning to be developed in the use of these additives. Plants such as the 8,500 m^3/d (2.25 mgd) acid-fed plant in Curaçao have successfully substituted an additive during trial runs and more acceptance of additives can be expected in the future. Not all the trials have been as successful, but if the polymer-based additives continue to show positive results in long-term operations, the change from acid to additives where appropriate could bring some definite benefits to distillation. A detailed discussion of scaling and the differences between acid and additives can be found in annex I.

The additives may be priced comparably to the acid that they replace, so that a savings in chemical cost is not always possible. However, competition might reduce additive costs in the future. In addition, many plants that are designed to operate at both medium and high temperatures might choose to operate at the high temperature when a safe reliable scale control method can be utilized. This would allow greater thermal efficiency as well as savings through reduced maintenance costs and shutdowns.

(c) Large-scale units

In the early 1970s the largest units built were approximately 9,500 m^3/d (2.5 mgd), but the design of the MSF process has now matured to the point that MSF units are routinely manufactured in sizes up to 38,000 m^3/d (10 mgd) by fabricators around the world. This scale-up ability is vital to a reduction in costs for large distillation projects. Materials, operating temperature and method of scale control selected still vary, depending on the economics and the operating application desired by the owner.

It is expected that larger units of the horizontal-tube multiple-effect design will be built and operated successfully. This design, as well as very large multiple-effect units, can be expected to be marketed in direct competition with multi-stage flash plants.

(d) Materials developments

Titanium. Titanium has high resistance to the corrosive and erosive environment found in the brine heater and the other high-temperature portions of a plant. Titanium is more expensive than some of the copper-nickel (Cu-Ni) alloys, which has restricted its use in plants almost exclusively to the heat transfer surfaces (tubes). Although its thermal conductivity is lower than most commonly used tube materials, its other attributes, such as smooth surface, thinner wall potential and high corrosion resistance, compensate to some degree for this (McCue, 1975).

The first titanium-tubed MSF plant (3,800 m^3/d (1 mgd) was built in 1965 for the Martin Marretta bauxite refinery on the island of St. Croix in the United States Virgin Islands. Continued operation for almost 20 years has required only minimal repairs. Other titanium-tubed plants have been built since that time and have proved to be very reliable.

Plastic. Usage of reinforced thermosetting resin materials for water boxes, external low-pressure brine piping and pump cans has increased in recent years. This material, generally epoxy or polyester, is made from a variety of resins which are strengthened by reinforcement with glass fibres. These non-metallic materials are not affected by corrosion, but may become brittle from high temperatures.

Some thermoplastic materials such as polyvinyl chloride (PVC) or polypropylene are used for low-temperature brine piping without being reinforced. Some engineers believe that the technology exists to utilize plastics more extensively in distillation fabrication. Indeed, the fabrication of almost an entire MSF plant (except the tubes) was proposed by engineers in 1979 (Morin and Johnson, 1980).

Aluminium. Aluminium was used during the 1970s to construct several distillation plants in the 2,000 to 5,000 m^3/d (0.53 to 1.3 mgd) range. Aluminium is relatively inexpensive, easy to fabricate and has a high thermal conductivity. However, it must be operated at low temperatures (less than 75° C (167° F) and brine velocities within the plants must be kept below about 0.9 m/s to avoid deterioration of the aluminium (Veenman, 1978).

A 3,800 m^3/d (1 mgd) aluminium multiple-effect distillation plant built in 1974 has been operating at Eilat, Israel, and six more plants of the same general design have been constructed in the Virgin Islands.

In late 1979 the second of two 3,800 m^3/d all-aluminium MSF plants was constructed on the island of Aruba in the Netherlands Antilles. A very large 38,000 m^3/d (10 mgd) aluminium plant using a multiple-effect design was designed for construction in Israel in the mid-1980s.

Concrete. Work has been carried out in several countries on the use of concrete as a shell material. This material has corrosion resistance, thermal strength and cost characteristics which indicate potential for future use. It can be built with less skilled labour from many materials which are procurable near the site (Water Re-use Promotion Centre, 1983). Test plants have been built in Japan and France (Nojiri and Fujii, 1976). Problems with concrete include attack by both hot brine and hot condensate, and the attachment and sealing against both pressure and vacuum of metal penetrations through the shell.

(e) Foam ball cleaning systems

Use of foam ball cleaning systems (referred to as the Taprogge system) for use in distillation plants has increased in the past decade. In this system, foam rubber balls are introduced into the tubes of the various sections of an MSF plant along with the recycle flow. These balls help to scour out soft sludge and silt deposits. Some plants using the system have reported good results, including increased thermal efficiency and reduced number of shutdowns (Romeijn and Eimer, 1978). Foam ball cleaning is not effective on all distillation plants nor on all scales. The systems can be costly and their application must be carefully selected.

(f) Membrane distillation

In 1981-1982, companies in the United States of America and Sweden introduced a sea-water desalting process which operates on the basis of the selective passage of water vapour (versus liquid) through a membrane barrier. A small test centre has been operating in Florida since 1982. Several small (20 to 40 m^3/d) units have been sold and are now functioning. This new process has not been validated by any extensive commercial operating experience. Its greatest potential may be with waste heat or solar collectors as a primary energy source.

(g) Low-temperature multiple-effect plants

During the early 1980s six low-temperature multiple-effect plants were constructed in the United States Virgin Islands. These were dual-purpose installations with capacities of 2,000 and 4,000 m^3/d (0.53 and 1.3 mgd).

The units' performance has been good. The plants are easy to start up, operate and shut down. They run at a top temperature of about 70° C (160° F). The tubes are made from aluminium, the shell from coated carbon steel, and some of the piping from plastics. A polyphosphate chemical is used for scale control.

(h) Hybrid plants

A number of hybrid plants combining various processes have been conceptually designed and discussed within the desalination industry, but few have been constructed. In the mid-1970s two 9,500 m^3/d (2.5 mgd) combination VTE-MSF (vertical tube evaporator-multi-stage flash) plants were built in the Virgin Islands. Although they had a high theoretical thermal efficiency, in reality they have not performed well, requiring extensive overhauls and repairs.

The use of multiple-effect units as a topping unit for existing MSF plants has been proposed (Cox, 1982). The horizontal-tube multiple-effect unit would be used to increase the production of the existing MSF plant without using additional fuel, while lowering the operating temperature of the MSF portion of the plant. The topping unit would be installed ahead of the existing brine heater. The alterations would raise the thermal efficiency of the plant considerably.

Another proposal has been for a combined vapour compression unit with vertical tube foam evaporation (VCVTFE) (Senatore, 1982). The vertical tube foam evaporation uses a surfactant that has been added to the sea-water feed to enhance evaporation (Sephton, 1980). This hybrid would use a 4-effect evaporator with a diesel driven compressor. Supposedly, the process is highly efficient and less costly than either RO or MSF.

A barge-mounted hybrid combining vapour compression, vertical tube foam evaporation, and multi-stage flash (VC-VTFE-MSF), with a capacity of 5,000 m^3/d (1.3 mgd), was built and tested in the Federal Republic of Germany (Ohlemann and Emmermann, 1983). The unit used 24 vertical effects, 2 vapour compression effects and a three-stage MSF cooler. Under test operation in the North Sea, the unit exhibited a high thermal efficiency.

(i) Other recent developments

A number of other recent innovations that are either just being introduced or are being developed are briefly described below.

Computer control. Several companies have developed computer software that monitors and controls the operation of the large MSF plants through the use of such devices as sensors and micro-processors. This could permit greater control over the operation of the plant. It also introduces a new type of technology to the plants for which both benefits and new potential problems must be examined.

Barge mounted desalination plants. The use of barge mounted distillation plants for use in the Middle East and other water-short areas has been studied and proposed by a variety of companies and agencies. The advantage to this type of facility would be that the unit could be built and test-operated at the manufacturer's instead of the user's site, which would supposedly allow for savings in labour and freight, and permit better quality control. The completed unit would be towed to the site and operated while moored. The unit could then be moved from place to place if required. The unit could also be used temporarily while on-shore facilities are built. A large 2,500 m^3/d (0.66 mgd) ship-mounted unit was built in the Federal Republic of Germany in 1982 for Abu Dhabi (Wangnick, 1982).

Multi-stage controlled flash evaporator (CFE). This type of unit has been commercially developed by Aquanova, B.V., of Rotterdam, the Netherlands. Two of these units were placed in operation in Aruba in 1979-1980. They are vertically stacked multi-stage flash plants made of aluminium and some plastic. The design lends itself to modular construction with compact flash chambers which reduce energy losses and have the potential for lowering capital and operating costs.

Conversion to vapour compression. It has been proposed that some existing low-temperature horizontal-tube multiple-effect units could be modified to be run as vapour compression units with the addition of a large compressor and some modifications. This would allow those units to operate independently of existing steam supplies (Hoffman and Ophir, 1982).

Multi-stage flash/fluidized bed evaporator (MSF/FBE). This process was developed by Delft University of Technology and Esmil, the Netherlands. It utilizes a vertically stacked multi-stage flash configuration with straight vertical heat recovery tubes. In order to obtain the high heat transfer necessary in the heat recovery (and condensation) tubes so as to limit their length (and the height of each stage), solid particles (usually glass beads) are introduced into the feed water. These fluidized particles disrupt the laminar flow along the inside of the tube walls to enhance heat transfer while inhibiting scale formation (Veenman, 1976).

(j) Future technology

It can be expected that future distillation technology will concentrate on improving reliability and economy through better material life, higher thermal efficiencies, improved scale control and more controlled operations. These developments will be important in maintaining the competitiveness of distillation with sea-water reverse osmosis.

4. Application in developing countries

The use of the distillation processes in developing countries offers its greatest potential in the desalination of sea water. This potential is best realized when the process is used in conjunction with low-cost energy obtained from low-pressure steam as part of a dual-purpose electricity-desalination facility or from another source of low-cost waste heat.

As far as the multi-stage flash and multiple-effect plants are concerned, the greatest problems in developing countries relate to the complexity of operation and maintenance. This is especially true of plants with high thermal efficiencies (performance factors) operating at temperatures ranging from 95° to 120° C (200-250° F). Associated with those plants are pumps, vacuum systems, de-aerators, chemical feed systems and brine heaters, many of which operate at high temperatures in a highly saline environment.

This requires that meticulous attention be paid to operation and that the facility have the capability to supply maintenance services involving skilled personnel, appropriate tools and an adequate supply of parts and materials.

If facilities are to be built in areas where trained, skilled operators and maintenance personnel are not readily available, it is prudent to ensure that such facilities are designed and constructed conservatively. This means that care must be taken to select the proper materials of construction and a design which can withstand abuse. Immediate capital costs may, therefore, increase, but the long-term operating costs will probably be much lower. Many of the operating problems of the MSF plants may be alleviated by the introduction of the new polymer-based additives.

The vapour compression plants appear to have a higher thermal efficiency than MSF plants, but these plants generally require high-cost energy, which increases their overall operating costs. The units employing compressors have high efficiencies but require the maintenance of a high-speed compressor. Conversely, the steam jet ejector is not exceptionally efficient, but requires minimal maintenance.

Since the 1970s, the Middle East has dominated the market for distillation units. Saudi Arabia accounted for over 31 per cent of the world's desalination capacity, while other countries in the Middle East, including the Islamic Republic of Iran, accounted for another 28 per cent (El-Ramly and Congdon, 1981).

(a) Saudi Arabia

In Saudi Arabia, sustained economic growth in many areas had been almost impossible because of inadequate supplies of fresh water. The major conventional supplies to Jeddah and Riyadh are from well water supplies. However, the quality of those sources has been deteriorating rapidly and has become increasingly saline. Most of the well waters in the country are either brackish or are turning brackish. Because of the limited conventional supplies available, Saudi Arabia has come to rely heavily upon desalinated water. It is by far the largest market for desalination facilities, with a total capacity of 2.5 million m^3/d (660 mgd) in 1983. Of that total, approximately 2 million m^3/d (530 mgd) is accounted for by MSF plants. Additional capacity of 380,000 m^3d (100 mgd) was being built or considered for construction by the Saudi Arabian Saline Water Conversion Corporation (SWCC). SWCC has commissioned the largest MSF facility in the world, which, when completed at Al Jubail on the Persian Gulf, will have a capacity of about 1.1 million m^3/d (290 mgd). It will include 40 19,000 m^3/d (5 mgd) MSF units located side by side. The water produced will be pumped over 485 km (300 mi) inland to the capital city of Riyadh. This is a huge undertaking and could probably only be contemplated in a country such as Saudi Arabia, which has ample capital resources, considerable experience with MSF plants, relatively cheap energy costs and relatively expensive water costs.

The operating history of MSF plants in Saudi Arabia indicates that long-term operational reliability and production capacity are dependent on:

(a) Selection of proper materials of construction compatible with maximum operating temperature and given feed water pre-treatment method;

(b) The extent and type of feed water treatment method employed;

(c) The experience and skill of operating personnel.

The experience has shown that MSF plants, when properly designed and constructed with appropriate corrosion-resistant materials, have performed satisfactorily with on-stream factors of as high as 95 per cent with minimum maintenance problems.

Plants with low on-stream factors are generally constructed with less corrosion-resistant materials and have been operated and maintained by insufficiently trained personnel. In general, plants designed for high-temperature operation (above 90° C) on acid treated sea water have experienced more operational problems (scaling of heat transfer surfaces and corrosion of carbon steel) than low-temperature non-acid plants. Moreover, because of the need to use high-cost corrosion-resistant materials in construction, the capital costs of MSF plants have increased considerably over the past 10 years (Jamjoon and others, 1979).

An analysis of the operational history of the Jeddah I project, constructed in 1972, was carried out for SWCC (Kutbi and others, 1982b). The Jeddah I plant, located on the eastern shore of the Red Sea, is a dual-purpose plant consisting of identical twin-steam generating units, electric-power generating units and sea-water desalination units, with the necessary auxiliary system to operate the units. At full capacity, Jeddah I can produce 50 megawatts (MW) of electric power and 19,000 m^3/d (5 mgd) of distilled water. Monthly operation reports over an eight-year period were kept and analysed to identify causes of failure or shutdowns.

The major cause of shutdowns of the plant was extensive corrosion of the venting systems, evaporator stages and pipe work. Corrosion resulted from intermittent operation owing to initial start-up and shut-down problems, acid leaks at the point of injection and a very unstable venting system. Those problems were caused by materials that were not sufficiently corrosion-resistant (such as carbon steel), imperfect repairs and an inadequate maintenance and replacement programme. Major components of the system had been constructed of carbon steel and, after a few years of operation, considerable leaks appeared in the high-temperature module in the flashing brine area of the flashing stage due to corrosion. Some modifications and design changes were implemented to mitigate the extent of the operational and design problems and many parts were replaced by or lined with stainless steel (Kutbi and others, 1982b).

Another analysis of the operating history of the Jeddah plants by the same authors concluded the following:

(a) Poor operating conditions are the main cause of trouble to all systems;

(b) Most of the operator's time is spent in attempting to keep the plants producing water and little time is spent reviewing operating data and analysing problems which decrease the plant's reliability and operating life;

(c) Poor maintenance of the plant's equipment was due to insufficiently experienced and capable operation and maintenance personnel;

(d) Operation was also hindered by lack of spare parts;

(e) Most instrumentation and controls of the MSF plants were inadequate;

(f) Failure of the automatic controls was increasing, due mainly to lack of simple maintenance and daily testing.

In fact, recent operating experience reports of the Jeddah desalting plants reveal that they operate under conditions substantially different from what they were designed for. The reports also show that the plants are plagued with a greater number of shutdowns and plant maintenance needs. In summary, the plants have not been able to produce either the amount of pure water at the expected cost or operate satisfactorily over the full expected life of the system (Kutbi and others, 1982a). However, as pointed out in a survey by the University of Petroleum and Minerals, Jeddah I was the first major MSF plant put in operation in Saudi Arabia. Hence, lack of experience in operating it is quite understandable. In addition, the heavy demand for water made shutdowns, necessary for preventive maintenance, very difficult (Maadhah and Wojcik, 1981).

By 1980, there were four plants operating at Jeddah, comprising 320,000 m^3d (85 mgd) capacity. SWCC has been able to carry out extensive experiments with these and other units to compare the relative merits of acid and additives in controlling scale formation and corrosion (Nada, 1982). Of the MSF plants in Saudi Arabia, 28 per cent use acid for scale control and 60 per cent use additives.

With the Jeddah III and IV plants (75,800 and 265,000 m^3/d, respectively), extensive experiments were carried out using both acid and additives for scale control in identical units. The tests with high-temperature additives were not as encouraging as expected: corrosion rates were higher than for acid; there was heavy demister fouling, heavy scale deposition and high anti-foam consumption. The conclusion reached by Nada (1982) was that external de-aeration to reduce the dissolved oxygen level of the make-up effluent was essential for both types of plant to minimize corrosion. This was consistent with earlier experiments at Jeddah I. Operating experience at Jeddah III indicated that the acid-treated units were more reliable and flexible. Furthermore, the operating costs for chemicals were lower for the acid plant than for the additive plant.

One conclusion to draw from this is that high-temperature additives in themselves are not a total solution. Each application should be carefully studied and trial runs conducted to ensure that the equipment and conditions are suitable for additives.

(b) Other Middle Eastern countries

Kuwait, the United Arab Emirates, Qatar and Bahrain have much in common with Saudi Arabia. They are all very arid, located on the Persian Gulf and are almost completely dependent on desalted water. Also, they are all committed to a policy of industrialization and development. Thus, their per capita requirements for fresh water are relatively high. Those four nations accounted for approximately 1.5 million m^3/d (395 mgd) capacity in 1981, and are expected to retain a large share of the world's desalting capacity.

Problems with the MSF plants in those countries have also been similar to those in Saudi Arabia: primarily corrosion of carbon steel flash chambers and flaking which leads to contamination of the water. It has been found that, in Bahrain for example, the greatest problem facing the desalting industry has been a lack of trained operators. Training facilities were provided, but it was not possible to attract the necessary staff, in competition with private industry where salaries are higher and working conditions better. Therefore, it has generally been necessary to contract out operation and maintenance to the plant manufacturer while trying to build up a group of staff and to give them the necessary skills. While there was a very high loss rate of trainees, eventually the necessary numbers were built up in Bahrain, helped by an improved salary structure which was more competitive with outside companies.

After 20 months commercial operation of the MSF plants in Bahrain under operation and maintenance contracts with the manufacturers, a full Bahraini team under the Electricity Directorate was able to take responsibility for the plants. Operational experience of the plants has given the Directorate staff valuable experience in assessing the requirements for trained staff for future desalination plants. Moreover, plant performance and operational problems have given the justification for alterations in future plant specifications and materials selected (Khalaf and others, 1981).

In early 1982, a firm located in the Federal Republic of Germany delivered a 2,500 m^3/d ship-mounted multi-stage flash evaporation plant to Abu Dhabi. The company noted that the investment for this type of plant was much lower than for a land-based one; water production costs were lower; the period for delivery was much shorter; the plant could be easily moved in case of emergency; and repairs could be carried out in harbours with ship-repair facilities (Wangnick, 1982). Operation of such a plant, however, seems heavily dependent on the foreign supplier and the existence of a suitable mooring place.

Other arid areas in the Middle East and North Africa which are dependent to some extent on desalination for fresh water are the Islamic Republic of Iran, the Libyan Arab Jamahiriya, Oman and Algeria.

In the Libyan Arab Jamahiriya, the total capacity of large MSF units put into operation from 1976 to 1980 amounted to 165,000 m^3/d (43 mgd) at 10 sites. Again, there were problems of design that were exacerbated by poor maintenance. The main problems with maintenance were: the impossibility of finding local technicians for serious training; lack of standardized equipment; lack of manuals in Arabic; corrosion of materials; and marine growth in the salt water intakes.

It has been found that reliability rather than efficiency is of paramount importance in developing countries. Good reliability, besides saving costs of repair, is essential in a country suffering from an acute shortage of locally trained operators and skilled personnel. Furthermore, poor reliability may lead to actual water shortages at crucial times (El Hares and Aswed, 1979).

Despite the problems encountered in the Libyan Arab Jamahiriya, the MSF process is still considered a very reliable process since scaling or a decrease in heat transfer efficiency has little effect on a plant's fresh water output capacity. The experience in the Libyan Arab Jamahiriya has led to a reluctance to experiment with new techniques. Experimentation becomes too expensive in developing countries with acute shortages of skilled labour. The authorities feel that new techniques should only be considered after extensive running experience has demonstrated reliability in developed countries.

As for additives versus acid dosing of plants, the Libyans prefer additives, which offer ease and simplicity of operation at the expense of higher capital and operating costs. Since ease and simplicity of operation are very important in developing countries, additives may offer a better alternative in many cases, especially combined with appropriate materials of construction. Although direct capital costs will be higher, in the long run there should be fewer problems with corrosion and scaling and, therefore, fewer shutdowns and repair and overall less costly water (El Hares and Aswed, 1979).

In Oman, the Ministry of Electricity and Water commissioned a 27,000 m^3/d (7.2 mgd) MSF plant which supplies water to the area around the capital city of Muscat. The plant has supplied water to the capital area since start-up and utilizes an annual one-month shutdown for maintenance. The unit was designed for flexibility in operation temperature, scale control and production capacity. It can produce about 19,000 m^3/d (5 mgd) at lower temperatures (90° C), using polyphosphates as scale control agents or about 27,000 m^3/d (7.2 mgd) at higher temperatures (113° C), using acid or other suitable high-temperature scale control agents. The operation of the plant can be varied using higher or lower temperatures so that the output will reflect the demand for water (Chalchal, 1979).

(c) Other water-short countries or areas

Other developing countries or areas that have gained considerable experience in MSF desalting are Mexico, countries of the Caribbean, Malta, Israel and Hong Kong.

In 1968, the Mexican Government's Federal Electric Commission (CFE) started up the first of two units which comprise their 28,400 m^3/d (7.5 mgd) MSF distillation installation at Rosarito in Baja California. The water produced at the plant supplies a portion of the needs of the area around the city of Tijuana, as the available natural resources of potable water are insufficient. This plant was one of the largest facilities in the world at the time of construction.

The plant is an MSF design with two 14,200 m^3/d (3.75 mgd) units. Each unit has 44 stages (40 heat recovery and four heat rejection stages) and uses recirculating brine. The top temperature of the feed water in the brine heater is 113° C (235° F), and acid is used to control scale formation in the units (Gomez, 1979).

The units were designed to use steam from the adjacent electricity-generating plant. Steam is extracted between the high and low pressure turbines which were modified to permit this extraction.

Generally, the desalination facility has been able to operate at about 63 per cent of its design capacity. The product water contains approximately three times the level of TDS expected from the design.

Some of the major operation problems during the past 10 years involved the heat recovery and reject tubes, flash chamber corrosion and the brine heater. Corrosion products, flakes and copper and iron oxide sludge accumulated in the tubes in the heat recovery stages, reducing heat transfer and therefore plant production. Various methods of tube cleaning both during operation and shutdown periods were tried. The addition of the Taprogge sponge ball cleaning system (with locally produced soft balls) proved to be one solution to the problem.

Erosion and corrosion of the heat rejection tubes were caused by sand, mud and marine organisms in the sea water. The interior areas and divisions between the flash chambers suffered severe corrosion of the carbon steel material. This corrosion caused air leakage into the chambers, thereby accelerating corrosion and reducing heat transfer efficiency. Many areas in the plant required protection of the carbon steel by lining with stainless steel (Gomez, 1979).

Frequent start-ups and shutdowns have been very hard on the plant and have resulted in considerable corrosion. The plant is still operating, but requires continued maintenance and repairs because of corrosion.

The oldest land-based distillation plant in the western hemisphere was built at Van Slobbeweg in Curaçao (Netherlands Antilles) in 1928. Another plant was constructed at Penstraat in 1929 and the earlier plant was expanded, so that total capacity reached 400 m^3/d by 1932. In 1948 the Government of Curaçao approved construction of six more distillation units at Mundo Nobo and expansion of Penstraat, for a total production of 2,700 m^3/d. The Mundo Nobo plant was further expanded in 1956 by two 1,000 m^3/d (264,000 gpd) evaporators connected to an electricity-generating plant. By 1963 the Penstraat plant had been closed and the Mundo Nobo plant further expanded to a capacity of 6,000 m^3/d (1.6 mgd) for fresh water. In 1976 the Water and Power Corporation of Curaçao (Kompania di Awa i Elektrisidat di Korsou (KAE) was formed to take over the power and water production at Mundo Nobo. Further expansions of both electricity-generating capacity and water production were carried out from 1976 to 1982. In December 1982 the civil works related to the installation of a new evaporator with a production capacity of 10,000 m^3/d (2.6 mgd) was initiated. It is expected that this evaporator will be in operation at the beginning of 1984. The islands of the Netherlands Antilles have the longest working experience with distillation units and can provide useful information to other developing areas (Water and Power Corporation of Curaçao, 1983).

5. Generalized costs for distillation plants

The major capital costs associated with large distillation plants are for heat transfer surfaces (usually tubes), the containing shell, pumps and piping, generally in that order. Since the heat transfer surface is one of the most significant factors in plant capital cost, considerable effort has been directed towards reducing such costs. Significant cost items outside the plant are the raw water intake, brine disposal and product storage.

The major costs in operation are for the thermal energy to produce steam (or another primary energy source), labour, chemicals, and other power (for pumping, motors etc.). Thermal energy makes up at least 60 to 80 per cent of the projected operating costs of moderate-sized multi-stage flash and multiple-effect plants (Fluor Engineers, Inc., 1978).

The major capital cost is for heat transfer surface and the major operating cost is for thermal energy. Generally, if one is decreased, the other must be increased. Each plant is usually a compromise, therefore, between the type and amount of heat transfer surface installed in the plant and the amount of thermal energy necessary to produce a unit quantity of water.

The cost estimates used below (see table 2) are for plants to be located in the United States of America. A much more extensive analysis and discussion of those costs can be found in the report, "Desalting seawater and brackish waters; 1981 cost update" (Reed, 1982), which was the basis for costs in the pesent section.

A cost breakdown for a range of distillation plants from 3,800 to 38,000 m^3/d (1 to 10 mgd) in capacity is shown in table 2. The following three types of distillation units are shown: acid-fed multi-stage flash, non-acid-fed (polyphosphate) MSF and non-acid-fed multiple-effect distillation (MED) units. The acid-fed unit operates at a maximum brine heater temperature of 120°C (250°F); the MED unit operates at 75°C (167°F); and the polyphosphate MSF operates at 90°C (194°F).

The total unit capital costs range from $1,214 to $2,770/$m^3$/d ($4.60 to $10.49/gpd) depending on size and scale control method used. Within the range, the 3,800 m^3/d (1 mgd) polyphosphate MSF plant has the highest unit cost and the 38,000 m^3/d (10 mgd) MED plant has the lowest unit cost.

Operating costs (exclusive of capital recovery) range from a high of $1.05/$m^3$ ($3.97/1,000 gal) for the 3,800 m^3/d (1 mgd) MSF non-acid-fed plant to a low of $0.59/$m^3$ ($2.23/1,000 gal) for the 38,000 m^3/d (10 mgd) MED plant. The total water cost (which includes capital recovery) ranges from a high of $2.68/$m^3$ ($10.05/1,000 gal) to a low of $1.31/$m^3$ ($4.90/1,000 gal) for the same plants.

In general, the estimated costs for the MED units were lower in both the capital and operating categories. There is considerable experience with the type of MSF plants discussed in the study, but only limited experience with the aluminum-tubed MED plants. Six of those plants have been installed and began operating in the United States Virgin Islands in the 1980s.

Table 3 lists the general assumptions used in the cost study by Reed (1982), which is the main basis for cost assumptions for desalination in the present volume.

Table 2. <u>Distillation: sea-water desalting cost estimates</u>

(In thousands of US dollars)

Plant capacity m³/d (mgd)	3,800 (1)	3,800 (1)	3,800 (1)	19,000 (5)	19,000 (5)	38,000 (10)	38,000 (10)
Type / Scale control	MSF a/ Acid-fed	MSF b/ Non-acid	MED c/ Non-acid	MSF Acid	MED Non-acid	MSF Acid	MED Non-acid
Direct capital costs	6 024	6 440	5 110	19 726	15 385	36 370	28 105
Indirect capital costs							
Int. during construction	497	532	164	1 808	1 265	4 331	2 577
Working capital	439	127	89	1 926	303	2 738	564
Contingencies plus A and E	904	967	741	2 959	2 310	5 455	4 235
Proj. mgmt, overhead and profit	2 259	2 419	1 916	7 397	5 773	13 639	10 539
Total capital costs	10 123	10 485	8 020	33 816	25 046	62 533	46 020
Annual O and M costs							
Labour d/	238	238	217	305	252	571	252
Energy - steam e/	495	594	446	2 475	2 230	4 950	4 460
Energy - electricity e/	113	294	140	565	700	1 130	1 400
Chemicals	57	67	28	286	140	572	280
Other	36	36	84	86	270	158	500
Total O and M costs	939	1 229	915	3 717	3 592	7 381	6 892
Fixed charges f/	1 822	1 889	1 444	5 907	4 508	11 256	8 284
Total annual costs	2 761	3 118	2 359	9 624	8 100	18 637	15 176
Cost of water							
$/m³	2.37	2.68	2.03	1.65	1.39	1.61	1.31
$/1,000 gal	8.90	10.05	7.60	6.20	5.22	5.95	4.90
Unit capital cost							
$/m³	2 672	2 770	2 118	1 785	1 322	1 650	1 214
$/gpd	10.12	10.49	8.02	6.76	5.01	6.25	4.60

(Source and footnotes on following page)

(Source and footnotes to table 2)

Source: Adapted from S. A. Reed, Desalting Seawater and Brackish Waters: 1981 Cost Update (prepared for the United States Department of Interior, Office of Water Research and Technology, by Oak Ridge National Laboratory, Oak Ridge, Tennessee, 1982).

The general assumptions used in establishing these cost data are listed below in table 3.

All cost estimates are in 1981 United States dollars.

A and E = architect and engineering.

O and M = operation and maintenance.

a/ MSF plant: multi-stage flash unit using acid for scale control; performance factor = 12; maximum brine heater temperaturs of 121°C (250°F); recirculation with a concentration factor of 2 and an 85 per cent plant factor.

b/ MSF plant: multi-stage flash unit using polyphosphate for scale control; performance factor = 10, maximum brine heater temperature of 90°C (194°F); and an 85 per cent plant factor.

c/ MED: multiple-effect horizontal-tube unit using aluminium tubes; performance factor = 12; maximum brine heater temperature of 75°C (167°F); and an 85 per cent plant factor.

d/ Labour cost includes an additional 40 per cent for general and administrative overhead.

e/ Energy cost based on using oil as a fuel at a cost of $32/bbl ($5.8 \times 10^6$ Btu/bbl) producing prime steam at 538°C (1,000°F) at $8.98/10^6kJ ($8.50/10^6 Btu). Steam cost for the distillation plant is based on $2.30/million Btu, with electricity being generated on site for a cost of 7.5¢/kWh.

f/ Based on a 30-year capital recovery at 18 per cent interest.

Table 3. General assumptions used in the Oak Ridge National Laboratory study on desalination costs (Reed, 1982)

1. Direct capital costs include: site development but not land; infrastructure (common facilities, roads, intake and outfall systems, electrical utilities etc.); and plant.

2. Sites in continental United States. No major problems with brine disposal or the construction of intakes or outfalls.

3. Indirect costs include interest during construction, project management, overhead and profits. Interest rate of 11 per cent on capital during construction period.

4. Contingency plus architect/engineering fee was 16 per cent of direct and indirect capital costs.

5. Plant load factor: 85 per cent for sea-water systems; 95 per cent for brackish water systems.

6. Chemical costs in $/kg: antifoam $2.31; sulphuric acid (100 per cent) $0.53; polyphosphate $3.98; sodium hexametaphosphate $0.70; potassium permanganate $1.43; sodium hydroxide $0.46; sodium sulphite $0.13; chlorine $0.30.

7. Membrane replacement costs based on manufacturers' price and a membrane life of: 7.5 years for electrodialysis; 3 years for brackish water RO; and 5 years for sea-water RO.

8. Operation and maintenance labour cost based on inputs from manufacturers and users.

Figure III shows recent estimates for capital equipment costs versus capacity for distillation plants installed in a continental United States location. The costs are for plant equipment, including civil works, and all indirect costs such as interest and project management. Generally speaking, costs for plants built and installed outside the United States are considerably more expensive, as they are likely to include costs for such non-plant components as pipelines, reservoirs, housing complexes, auxiliary power plants, transportation and tariffs on imported equipment.

Figure III was developed by Reed (1982) in lieu of merely adding inflation to the cost figures in his earlier reports because, over the past several years, there has been an increase in the true cost of distillation plants. As a result of improved specifications and higher performance ratios, the increase in costs seems to have been higher than that for capital goods generally (Wood, 1982). The improved specifications generally call for more extensive use of non-ferrous materials such as titanium, copper-nickel alloys and stainless steel, as dictated by field experience. The increased reliability of such plants, however, is considered an important factor in developing countries, as it reduces maintenance and repair costs considerably in the long term.

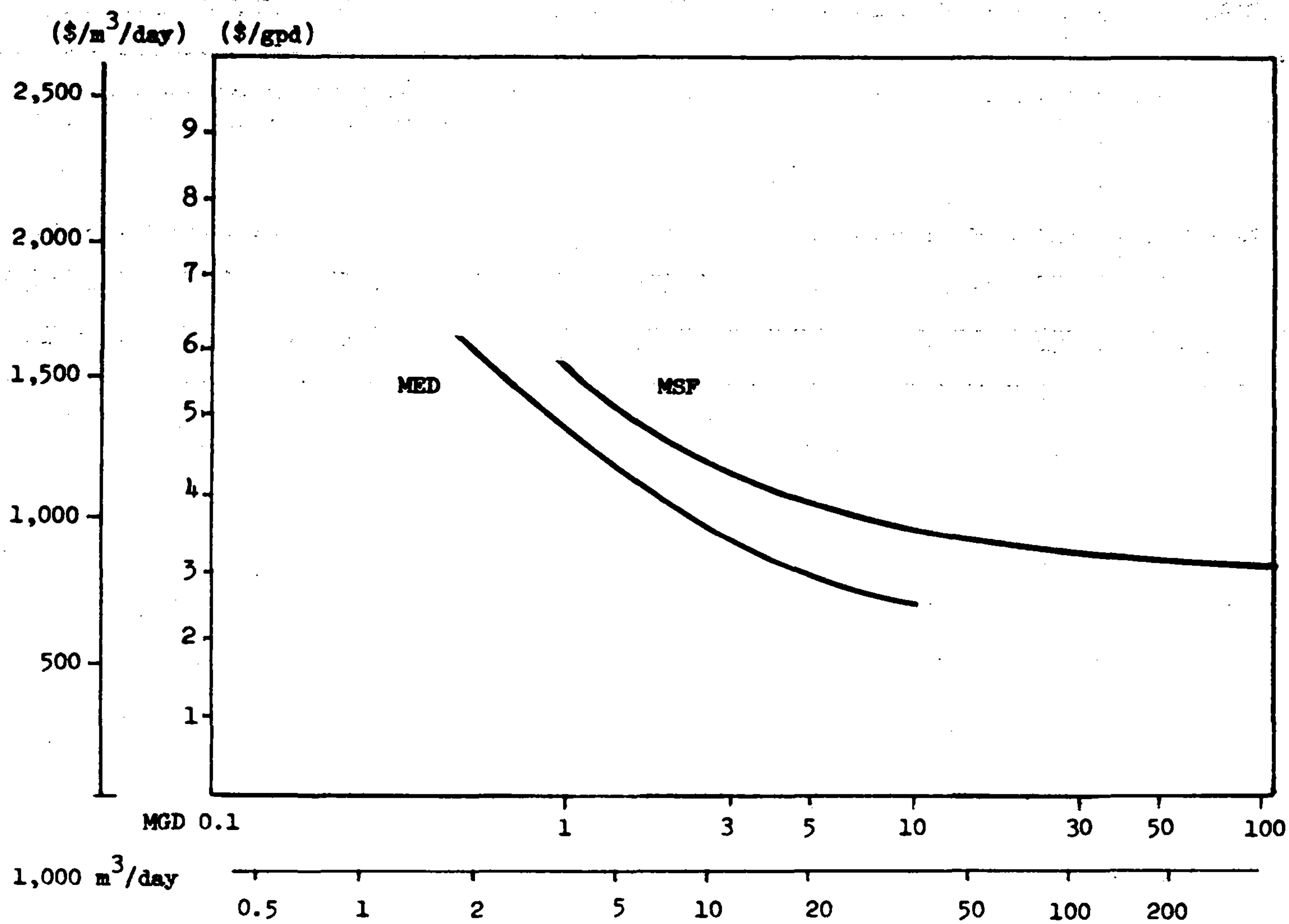

Figure III. Capital equipment cost: sea water desalting by distillation

<u>Source</u>: Adapted from S.A. Reed, <u>Desalting sea water and brackish waters; 1891 cost update</u> (prepared for the United States Department of Interior of Interior, Office of Water Research and Technology by the Oak Ridge National Laboratory, Oak Ridge, TN, 1982), Report ONRL/TM-8191.

C. Electrodialysis

1. Historical background

The phenomenon of membranes having selective ionic permeability was investigated at least as far back as the 1890s (Curran and others, 1976). Much of the early work was done relative to the properties of living cells. Separation processes utilizing the principle of the attraction of charged particles to electrodes in an electrolyte have been developed, as electrophoresis, by the various life sciences.

By fabricating ion-selective membranes from various materials, several units were built to purify water during the period 1910 to 1930 in Europe (Friedlander and Rickles, 1966). The development of membranes with both good ion selectivity and good mechanical characteristics was a major problem. In 1935 ion exchange resins were synthesized and in 1940 a multi-cell unit was developed having alternate product and brine cells similar to the present-day configuration (Curran and others, 1976).

The modern electrodialysis industry came into being in the 1950s in the United States when sheet membranes made from ion-exchange resins were perfected and patented (Juda and McRae, 1953). In February 1952, Ionics Incorporated demonstrated electrodialysis on a pilot scale as a new method which used electricity to desalt a saline solution by removing the dissolved salts. The electricity attracted the ions through special plastic membranes which retained the ions and created a low-salt solution. That demonstration has had far-reaching effects on the technology and development of water desalting. It showed that a practical desalting method could be based on a physical principle other than the boiling of water and condensing of steam. Moreover, the use of synthetic polymeric membranes in electrodialysis led to major developments in the use of membranes for other applications, including reverse osmosis and ion exchange. This demonstration helped to convince the United States Government to fund the Office of Saline Water, which played an important role in the development of desalination over the next 30 years.

Another significant aspect was that electrodialysis had relatively low costs for desalting brackish water. The availability of a process to treat brackish waters stimulated a whole new market, and led in the following two decades to a careful cataloguing of the inland brackish water resources of a large portion of the world (Katz, 1977a).

The first commercial sale of a brackish water unit was made to Arabian American Oil (ARAMCO) in 1954 to supply water to an exploration crew. The first municipal use of electrodialysis was for the community of Awali in Bahrain, the unit having been purchased by the Bahrain Petroleum Company in 1955. A number of other units went into service in the 1950s and early 1960s in several Middle Eastern countries to supply fresh water for oil production camps, military installations and industry. In 1958, electrodialysis was first used in the United States for a municipal application at Coalinga, California. Other municipalities followed suit, and electrodialysis units were soon treating a variety of brackish waters around the world.

Although much of the original development was carried out in the United States by Ionics Incorporated, other manufacturers developed ion exchange membranes, and/or began producing electrodialysis units in the late 1950s. The market has been dominated by Ionics, however, which has produced about half of the world's standard electrodialysis units and all of the electrodialysis reversal units.

The total installed electrodialysis desalting capacity amounted to approximately 31,000 m^3/d (8 mgd) at the beginning of 1970. The capacity increased rapidly in the 1970s, mainly as a result of commercial improvements such as the development of polarity-reversing electrodialysis equipment (Katz, 1977b). Technical and engineering aspects of electrodialysis are discussed in detail in annex II.

2. Technical considerations

Electrodialysis is a widely used method of desalinating brackish waters. Currently there are installations in over 26 countries, with an estimated total capacity of 273,000 m^3/d (72 mgd), both for industrial and municipal applications.

Two major processes are used, the first being standard electrodialysis, which has been used commercially since the 1950s. The second is a polarity-reversing process known as electrodialysis reversal, which has been commercially available since the early 1970s. When properly designed and operated, both processes have proved effective in desalting brackish water and certain highly saline solutions.

The number of manufacturers active in the electrodialysis field is few. The industry is dominated by the original developer, Ionics, in the United States, with most other units being produced by Japanese manufacturers. Ionics has sold electrodialysis reversal units almost exclusively since 1973. This process currently represents just over half of the installed capacity in the world.

Electrodialysis is a direct competitor with the reverse osmosis process for desalting brackish water. Since energy requirements for electrodialysis are closely related to the salt content of the water, the electrodialysis process is usually the most economical when treating brackish waters with a low level of dissolved salts.

The major parts of an electrodialysis unit are the rectifier (to produce direct current), a membrane stack, and a low-pressure pump to circulate water through the system. Electrodialysis units are generally built to standard sizes ranging from 55 to 950 m^3/d (15,000 to 250,000 gpd), with one or more of the units combined to produce larger sizes. The membranes and stacks can be tailored to suit the water being treated.

A typical plant is in the range of 200 to 750 m^3/d (53,000 to 200,000 gpd), with the largest installation being a 15,000 m^3/d (4 mgd) plant at Corfu, Greece.

3. Recent technological advances

In recent years, the major technological advances in the electrodialysis process have occurred in two areas: the commercial introduction of the electrodialysis reversal process, and the increased reliability stemming from minor design changes based on process experience.

(a) Electrodialysis reversal process

After development in the late 1960s and early 1970s, the reversal process was introduced commercially by Ionics, Incorporated. By 1974 that company had shifted almost all its production to this process. By 1981 they had installed 228 plants, with capacities greater than 95 m^3/d (25,000 gpd) throughout the world, for a total of 139,000 m^3/d (36.7 mgd) capacity (El-Ramly and Congdon, 1981). Thus, for the first time the electrodialysis reversal process had surpassed the electrodialysis process in total installed capacity (the latter with 135,000 m^3/d for plants larger than 95 m^3/d).

(b) Reliability

The domination of the electrodialysis market during the past 30 years by one firm (Ionics) has produced some advantages in that Ionics has concentrated almost exclusively on building one standard model. This has developed into the company's current product line using many interchangeable parts between models. Ionics has thus been able to concentrate on improving the basic components and their reliability. Those improvements have come about through research and development as well as extensive field experience.

With the high reliability that electrodialysis has attained in much of its equipment, the major constraint to its application is the high power usage required relative to the reverse osmosis process at the higher total dissolved solids levels. Power requirements are expected to be reduced in the future, however, through the development and improvement of various components within the stack.

Among the new technologies developed to increase reliability and efficiency are improved membranes, spacers, other materials and hardware. For example, a new anion membrane based on aliphatic rather than aromatic chemistry became available in 1980. This membrane is interchangeable with existing membranes and is supposed to have increased capacity and improved anti-fouling properties compared to other membranes.

(c) Design improvements

In an effort to reduce capital costs, especially on large installations, certain design changes have been examined, many by Ionics under contract to the now-disbanded Office of Water Research and Technology of the United States Department of Interior. These include the use of larger membranes with a higher effective utilization of membrane area. Overall resistance of the stack has been substantially lowered by increasing the area of the hydraulic spacers and membranes approximately threefold over the size of the commercial standard available in the United States. The effective membrane area per cell pair has been increased by the same proportion and the membrane area utilization was increased by roughly 40 per cent through the use of a new design of hydraulic spacer. At the same time this new spacer was made thinner than current commercial spacers to effect a considerable reduction in solution resistance per cell pair (Mattson and Lew, 1982). Those improvements lower energy consumption and increase product water recovery.

The research carried out for OWRT also involved a study of methods to utilize the stack so that stages within a stack could be independently removed for maintenance without disassembly of the cell pairs in the stages above them. This could save considerable time during maintenance.

Moreover, some efforts are being carried out in the United States using electrodialysis in combination with photovoltaic cells to desalinate brackish water. The most cost-effective application of this solar desalination process would be in isolated areas where fuel is costly and difficult to obtain.

(d) High-TDS applications

Work has been carried out in Japan, China and the United States on the use of electrodialysis for the desalination of sea water. Research sponsored by the United States OWRT had as its aim the economic desalination of sea water using high-temperature electrodialysis. A 200 m^3/d (53,000 gpd) sea-water electrodialysis unit was built at the United States Government's desalination test facility at Wrightsville Beach, North Carolina. The unit was designed to desalt sea water at temperatures in the 66°C (150°F) range. The design took advantage of the reduced resistance of the membranes and the increased conductivity of water at elevated temperatures in order to reduce power consumption significantly (McRae and others, 1977; Goldstein 1979). The overall objective of the United States experiments was to reduce electrical power consumption to a target goal of 7.9 kWh/m^3 (30 kWh/1,000 gal). Beginning in January 1981 a prototype stack, employing full-sized membranes and gasket separators, was subjected to a series of shop tests at 60°C (140°F). When extrapolating from the prototype to a full-sized plant operating at 66°C (150°F), the corresponding total power consumption would have been reduced to 9.9 kWh/m^3 (37.5 kWh/1,000 gal). In actual practice, there should be a further drop in electrical power required by the large plant. Overall, the results of the shop test were thought to demonstrate the capability of the electrodialysis process to demineralize sea water with an electrical power requirement that closely approached original target goals (Mattson and Lew, 1982).

Another possible use for this type of high-temperature high-TDS application would be in desalting geothermal waters. A pilot unit of this type has been tested at the United States Department of Interior's geothermal test site at Holtsville, California (Boegli and others, 1977).

There has been some research carried out on concentrating brine (and producing potable water) using electrodialysis in combination with ion exchange. Part of the concentrated brine is used to regenerate the ion exchange resins. This is considered a significant development since there is a strong, continuing interest in minimizing the volume of waste brine to be discharged from inland brackish water plants.

(e) Other developments

Japanese firms have also been involved in an extensive development programme in the electrodialysis field. The Japanese industry has been using electrodialysis for the production of salt since the process was introduced in the 1950s (Yambe, 1977). Along with the development of salt manufacturing, the companies have applied electrodialysis to the production of potable water from brackish and sea water, some industrial uses and the treatment of municipal waste water.

The Japanese have worked on developing vertically oriented membranes and spacers in contrast to the horizontally oriented membranes generally used in the

United States and have developed sheet flow configurations instead of the tortuous path used by Ionics.

From 1972 to 1981 Japanese manufacturers had installed four municipal water plants using electrodialysis, with a total capacity of 2,300 m^3/d (0.6 mgd), and 11 other plants for industrial purposes, with a capacity of 32,700 m^3/d (8.6 mgd) (El-Ramly and Congdon, 1981). The electrodialysis industry in Japan has undertaken some experimental and/or commercial developments in automatic chemical cleaning, heterogeneous membranes, sea-water membranes and large membranes, among others (Kishi and others, 1977); Kawahara and others, 1977; Seto and others, 1977).

4. Application in developing countries

The principles of operation of an electrodialysis unit are fairly straightforward. Its major application in developing countries in the foreseeable future is with the desalination of brackish water. As with any desalination process, it is very important to select and develop the raw water source properly and to choose the appropriate pre-treatment for that water. Because electrodialysis is the desalination process most energy-sensitive to the level of dissolved solids in the water, a key to its overall success is being able to predict (preferably by proper testing) the long-term TDS level of the water source and hence the unit's future performance.

The operation of electrodialysis plants requires personnel able to operate and maintain pumps, motors, rectifiers, valves and automatic activating equipment. Necessary skills would include the ability to disassemble and reassemble membrane stacks and the capability to read meters and/or graphs and make relatively simple process decisions based on those readings. Although the combination of associated pumps, piping and automatic valves is a bit more complex than that of a comparable reverse osmosis unit, the electrodialysis process offers several advantages for developing countries. The first is that it is a low-pressure (3.4 to 4.8 atm (50-70 psi)) system which employs standard pumps (rather than high-pressure pumps as in reverse osmosis) and the associated piping and valves can be made of material such as polyvinyl chloride, which is more readily purchased and repaired than materials such as stainless steel.

The second advantage is that, in case of severe scaling or clogging problems that cannot be relieved by in-place cleaning, the stacks can be disassembled, hand-cleaned and then reassembled. This can be a time-consuming, labour-intensive task, but in many areas labour is readily available. Furthermore, this disassembly and hand-cleaning procedure is often far more satisfactory than the purchase of new units, which may be required with reverse osmosis units when they become heavily fouled with precipitates or sediment.

Moreover, the use of the electrodialysis reversal method can almost eliminate the use of chemicals during operation, reducing the necessity of buying, transporting, mixing and adding chemicals on a continuing basis. This reduces the procurement and transportation problems that exist in many developing areas, although it does add some additional complexities associated with motor-operated valves etc. The only significant consumables necessary on a day-to-day basis, therefore, are electricity and cartridge filters.

A properly designed and installed electrodialysis unit can run for hours at a time with little attention. The system can handle power losses fairly satisfactorily, but it does need trained technical supervision.

As mentioned above, one of the main advantages of the electrodialysis process is its proven reliability, which makes it particularly attractive for desalting brackish water in developing countries. The 2,500 m^3/d (0.66 mgd) plant built in 1962 for municipal supply to Buckeye, Arizona, is still operating satisfactorily and was expanded in 1980 to handle peak loads. Other electrodialysis plants which have been operating for many years are competitive in both cost and reliability at low salinity levels with similar sized plants using other processes. An example is the standard electrodialysis plant originally installed at Sanibel Island, Florida, in 1973, which has since been expanded to an 8,000 m^3/d (2.1 mgd) facility. This plant has been intensively operated by the Island Water Association under difficult conditions but it has proved to be competitive in desalting low TDS waters with a reverse osmosis facility commissioned in 1980 on the same island (Derowitsch, 1982). Operating problems at the electrodialysis plant have centred around fouling of the stacks owing to insufficient pre-treatment, corrosion of components and a deteriorating ground-water supply. The latter has necessitated the construction of new wells using improved techniques.

The first large electrodialysis reversal plant was constructed for the municipality of Corfu, Greece, by a joint venture between Ionics, Incorporated and Technom, an Athens firm, in co-operation with the municipality. Design for the 15,000 m^3/d (4 mgd) plant was begun in 1974; the plant was to be 15 times larger than existing polarity reversal units which had recently entered commercial service. The plant performance tests were conducted in October 1977, a complete maintenance overhaul was carried out in the winter of 1977/78, and full operation began in the summer of 1978. The Corfu plant is a "zero chemical feed" plant - the reversal process does not require the addition of chemicals in the desalination process, although some muriatic acid is used in the in-place cleaning system (Andreadis and Arnold, 1978). Following polarity reversal, which occurs every 18 minutes at staggered intervals according to module, there is a purge of both brine and product compartments. This braks up polarization film and flushes away loose scale (Arnold, 1979).

The influent feed water to the plant is a blend from several ground-water sources. The blended water is filtered through 10-micron cartridge filters, processed through the stacks and then stored in a reservoir before use. The dilute blend of waters has a TDS of approximately 1,400 ppm and the product water TDS level is about 500 ppm. The concentrate brine is recirculated and the make-up water comes from the Chrysiis spring, the most saline of the water sources (Andreadis and Arnold, 1978).

The modular design of the Corfu facility - six parallel modules, each containing 10 membrane stacks arranged in four parallel banks - provides the flexibility to meet seasonal changes in municipal demand and the capability to take care of maintenance requirements during peak periods of operation. The plant operates about nine months per year to satisfy the higher demands of the tourist season, but is shut down during the winter, thus providing an opportunity for complete plant maintenance.

Some operating problems were encountered during the start-up and initial period of operation, primarily with the stacks, hardware and external factors

(Arnold, 1979). In the membrane stacks there were some initial problems with minor variations in the spacers between the membranes, causing a poor hydraulic flow distribution and hence some blockage of cells. This was alleviated by the installation of spacers of proper and more uniform thickness.

Some hardware problems were encountered with pneumatically operated valves for the reversal system. These were corrected by resizing some of the pneumatic operators and installing additional equipment for drying the air supply in the pneumatic system.

Outside the system, reduced production and disruptions had been caused by a lack of sufficient water and frequent breakages of old lines in the collector system for the feed water. The latter resulted in an increase in suspended solids and iron slimes in the feed water after the repairs had been performed and the pipelines flowed again, which caused plant upsets and premature clogging of the cartridge filters.

Other countries that have carried out extensive experiments with the electrodialysis process are the Union of Soviet Socialist Republics, China and India. All three countries have developed their own ion exchange membranes and have fabricated the electrodialysis apparatus.

In the Soviet Union, thousands of electrodialysis units have been installed in populated areas, agricultural complexes and mines. However, existing methods of electrodialysis are only used under certain circumstances because of its high power consumption. Experiments are being carried out to determine the relationships between temperature, the values of critical current densities and the parameters of flow hydrodynamics at low concentrations in the influent water. The results of the experiments have been taken as the bases for an optimization model of operating parameters for high-temperature electrodialysis units. The model has identified conditions under which elevated temperatures of treated water could be used to lower power consumption and optimize production. Feed water can be heated either from external power sources or from the heat released in the process of desalination (Smagin and others, 1983).

Similar experiments have been carried out in China, where the technique of electrodialysis has advanced greatly in the past 20 years. Recent experiments have shown that when water with the same TDS, but with different temperature and quality, is desalted in the same electrodialysis apparatus, the limiting current density (LCD) varies drastically. The value of LCD in turn directly affects the desalting capacity of the electrodialysis unit, the amount of fresh water produced and the costs of production. Therefore, the Chinese are formulating methods of calculating the effects of different water qualities and temperatures on LCD (Song Xutung and Chen Guang, 1983). Those experiments should help them predict the long-term performance of the electrodialysis units, as well as the appropriate pre-treatment needed.

The Chinese have also developed salt water electrodialysis reversal units for islands along the coast. The first plant was a 200 m^3/d plant installed on Meishan Island in 1978. Its performance during an initial 1,500-hour period was stable, using power consumption of 20 kWh/m^3, and desalting water of 35,000 ppm to produce water of 500 ppm. When the plant was disassembled, no scale was found in either the concentration compartments or the electrode compartments. In order to reduce costs and simplify operation, the plant was modified in 1979 from a

12-stage three-group configuration to a 10-stage two-group configuration. The modified plant consumed power at 18.1 kWh/m^3 of water at 31°C. Of that power, 15.2 kWh was used in electrodialysis and 2.9 kWh was used in pumping. The polarity of the electrodes is reversed once every 24 hours. The results of the field operations showed:

(a) The design of this plant is successful. Its performance is stable and the problem of water shortage on such islands can be solved with this type of plant;

(b) By using wire titanium coated with ruthenium as anode and cathode, and by rinsing the electrode compartments with high-velocity flows and periodically reversing polarity, the plant does not need acid during operation;

(c) Product water must be treated if used for drinking (Song Shi and Pei-qi Chen, 1983).

Finally, the Central Salt and Marine Chemicals Research Institute of Bhavnagar, India, has developed and manufactured components of an electrodialysis unit which is to cater to the needs of the rural population in India. A 14 m^3/d (3,700 gpd) electrodialysis unit was installed and used in the village of Motagokharwala in Gujarat State for about one year. The operator was a villager trained in its operation, and supervision was provided by the Institute. The source of water for this installation was the village well, which had a TDS level of 4,000 ppm. The electrodialysis unit reduced this level to about 1,000 ppm and the water was well received by the villagers for drinking and cooking (Rao, 1980).

The Institute found that electrodialysis had an edge over reverse osmosis, being the lowest energy-consuming technique for waters of salinity between 1,500 and 4,000 ppm. The technical feasibility of electrodialysis using the ion-exchange membranes prepared at the Institute has already been established and supported by field trials over a long period. The optimum conditions for obtaining product water of 1,000 ppm have been tested in terms of energy, current density and voltage. It has been found that brackish water with TDS of 1,800 to 4,000 ppm can be desalted to yield potable water with a very low energy requirement ranging from 0.5 to 2.1 kWh/m^3 (1.9 to 7.9 kWh/1,000 gal) (Harkare and others, 1982).

5. Generalized costs for electrodialysis plants

Electrodialysis reversal is now the dominant configuration for the electrodialysis process, having accounted for almost all electrodialysis installations in the past five years. The figures discussed below are therefore for electrodialysis reversal equipment. The cost of converting brackish water to fresh water by electrodialysis reversal is a function of total dissolved solids, water composition, temperature and other factors. The ability of the electrodialysis reversal process to operate at high recoveries treating feed water with high concentrations of silica or calcium sulphate brackish waters can give the process some important cost advantages relative to reverse osmosis. The costs of product water from representative electrodialysis reversal desalination plants are presented in table 4 and are based on two different feed water compositions. Those typical waters have TDS contents of 2,076 ppm and 3,475 ppm, respectively. The cost figures are estimates for plants to be located in the United States of America. A much more extensive analysis and discussion of those costs can be found in Reed (1982), which was the basis for costs used in the present section.

Table 4. Electrodialysis reversal: a/ brackish water desalting cost estimates

(In thousands of US dollars)

Plant capacity	3,800 m^3/d (1 mgd)		19,000 m^3/d (5 mgd)		38,000 m^3/d (10 mgd)		94,600 m^3/d (25 mgd)	
Feed water type	1	2	1	2	1	2	1	2
Direct capital costs	1 262	1 436	5 348	6 113	9 719	11 133	21 466	24 632
Indirect capital costs:								
Interest during construction	26	29	177	201	450	510	1 277	1 447
Working capital	53	72	267	306	486	556	1 073	1 232
Contingencies plus A and E fee	214	245	927	1 059	1 704	1 952	3 811	4 370
Total capital costs	1 555	1 782	6 719	7 679	12 359	14 151	27 627	31 681
O and M costs								
Labour b/	59	59	119	119	147	147	189	189
Electricity (5¢/kWh) c/	96	179	479	893	958	1 786	2 395	4 464
Membrane replacement	19	28	92	139	185	278	463	695
Chemicals and filters	22	22	97	97	163	163	407	407
Other	4	5	17	21	32	39	70	88
Total annual O and M costs	200	293	804	1 269	1 485	2 413	3 524	5 843
Fixed charge d/	280	321	1 210	1 382	2 224	2 547	4 973	5 703
Total annual costs	480	614	2 014	2 651	3 709	4 960	8 497	11 546
Cost of water:								
$/m³	0.36	0.47	0.31	0.40	0.28	0.38	0.26	0.35
$/1,000 gal	(1.38)	(1.77)	(1.16)	(1.53)	(1.07)	(1.43)	(0.98)	(1.33)

Source: Adapted from S. A. Reed, Desalting Seawater and Brackish Waters: 1981 Cost Update, op. cit.

(Footnotes on following page)

(Footnotes to table 4)

Notes:

For the general assumptions used in establishing these cost data, see table 3.

All cost estimates are in 1981 United States dollars.

A and E: architect and engineering.

O and M: operation and maintenance.

Feed water No. 1: TDS 2,076 ppm - uses a two-stage electrodialysis reversal system (referred to as water No. 3 in Reed, 1982).

Feed water No. 2: TDS 3,475 ppm - uses a three-stage electrodialysis reversal system (referred to as water No. 4 in Reed, 1982).

a/ Electrodialysis reversal, 95 per cent plant factor, feed water temperature 21° C (70° F).

b/ Labour cost includes an additional 40 per cent for general and administrative overhead.

c/ Electrical consumption for the 3,800 m^3/d plant assumed to be 1.5 kWh/m^3 (5.5 kWh/1,000 gal) for water No. 1 and 2.7 kWh/m^3 (10.3 kWh/1,000 gal) for water No. 2.

d/ Thirty-year capital recovery at 18 per cent interest.

A two-stage electrodialysis reversal system was selected for treating water No. 1 and a three-stage system for water No. 2. For analysis purposes, both systems are assumed to operate at a recovery of 80 to 87 per cent, and each is designed to yield a product water of 500 ppm TDS.

The total capital costs for electrodialysis reversal increase with the number of stages. Based on the data from table 4, total capital costs are estimated to vary from $\$470/m^3/d$ ($1.78/gpd) for a 3,800 m^3/d (1 mgd) three-stage system desalting a difficult-to-treat water (water No. 2) to a low of $\$335/m^3/d$ ($1.27/gpd) for a large 94,600 m^3/d (25 mgd) two-stage system desalting a relatively easy water (water No. 1). Estimated operating costs (without capital recovery) for those same units ranged from $\$0.22/m^3$ ($0.84/1,000 gal) for the three-stage system processing water No. 2 to a minimum of $\$0.11/m^3$ ($0.41/1,000 gal) for the large system treating water No. 1.

Total water costs were estimated for brackish water desalting by electrodialysis reversal in 1981, including operating costs and a capital charge based on all other inputs. The estimated costs range from a low of $\$0.26/m^3$ ($0.98/1,000 gal) for the large plant treating water No. 1 to a high of $\$0.47/m^3$ ($1.77/1,000 gal) for the 3,800 m^3/d (1 mgd) plant treating water No. 2.

D. Reverse osmosis

1. Historical background

The desalination of water by reverse osmosis is a membrane process in which the water from a pressurized saline solution is separated from the solutes and flows through an appropriate membrane. Although osmotic pressures are directly associated with the overall process, reverse osmosis is not, as the name might imply, the reverse of osmosis (Sourirajan, 1980). Membrane phenomena have been explored for many years, an example being the experiments of Abbé Nollet on diffusion through animal membranes, published in 1748. However, until recently, membranes were hardly even considered for water treatment.

In the early 1950s experiments were conducted under the auspices of the United States Department of Interior, which showed that artificially prepared cellulose acetate membranes possessed characteristics of salt rejection and water permeability, which made them potentially attractive as semi-permeable membranes for desalination (Membrane Systems, Inc., 1982). Working at the University of Florida in the early 1950s, Reid and Breton demonstrated that a cellulose acetate membrane could be used to desalinate water. They produced a dense film type membrane that had good rejection characteristics but a low water flux* (Breton, 1957). This was about the same time that electrodialysis was first being commercially introduced in the United States by Ionics Incorporated at Boston, Massachusetts.

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* Membrane flux: the quantity of water that can pass through a given area of membrane in a specific unit of time. Usually expressed in $cm^3/cm^2/sec$ ($gal/ft^2/day$).

Later in the 1950s, Sidney Loeb and S. Sourirajan conducted research work at the University of California treating millipore membranes so that one of their surfaces was altered, producing a membrane that combined salt rejection and a high water flux. Further work by Sourirajan and others culminated in the production of an asymmetric cellulose acetate membrane, which formed the basis for commercial development of reverse osmosis as a desalination process (Loeb and Sourirajan, 1961). By the late 1960s a tremendous variety of membranes was already available or just emerging from the laboratory into commercial markets. The major problems for early membrane makers were the configuration and quality control. They had to find a practical method to support and configure the membrane so as to allow it to withstand the high pressures involved (27 to 68 atm (400 to 1,000 psi)) while permitting water to pass through it. There was also the problem of how to maintain the quality of a membrane as they moved it from laboratory to commercial production, a difficulty which remains today (Parrett, 1982).

The first reverse osmosis membranes were small sheets the size of writing paper. They evolved into the plate-and-frame module: a stack of double membranes, each pair separated by woven plastic spacers (Parrett 1982). Between 1966 and 1968, desalination systems using the plate and frame, tubular, and spiral membrane configurations were commercially available. Of the three, the spiral proved to be the most commercially viable and was largely developed by the General Atomic Corporation (now Universal Oil Products) at San Diego, California, under a contract with the United States Office of Saline Water.

Major chemical companies worked on hollow fine fibre membrane development. In the early 1970s, E. I. Du Pont de Nemours and Company introduced and began to produce commercially viable membranes using asymmetric polyamide material. Dow Chemical's efforts during that period were directed towards the commercial production of membranes based on cellulose triacetate.

Currently, spiral and hollow fine fibre membranes are generally the most frequently used commercially, and they are widely available for the desalination of water for potable purposes. By packing a large amount of membrane area in a small container while supporting the fragile membrane so that high speed pressures (up to 68 atm or 1,000 psi) could be used, manufacturers of hollow fibre and spiral-wound modules could pursue applications that processed thousands of gallons of water per day. The modules thus marked a quantum advance over the original plate-and-frame systems, which could process only a few gallons per day (Parrett, 1982). An improved plate-and-frame configuration has been developed in Europe, but its use is relatively minor at this time. Tubular membranes are still produced in small quantities for special applications, usually involving waste-water treatment, but they are not produced widely.

Early in their development, membranes were commercially produced only for brackish water desalination. Sea-water membranes require much higher pressures and salt rejection capabilities, and took longer to develop. They were developed experimentally in the 1970s and several small demonstration units were built. During the period 1977-1978, several companies began to produce sea-water membranes in commercial quantities, using either a polyamide hollow fine fibre membrane of a polyamide thin film composite membrane with a spiral configuration. Technical and engineering aspects of reverse osmosis are described in annex III below.

The largest installations to date are a 20,000 m^3/d (5.3 mgd) plant commissioned by the Government of Malta, which uses hollow fine fibre membranes; a

12,100 m^3/d (3.2 mgd) plant at Jeddah, Saudi Arabia, which uses spiral modules; and a 3,000 m^3/d (0.8 mgd) plant at Punta Moron, Venezuela, which employs the hollow fine fibre design. The plants began operation in 1982, 1978 and 1980, respectively.

2. Technical considerations

The reverse osmosis process has evolved into a viable, practical means of desalinating both brackish water and sea water. By 1981 it was used in over 63 countries and had a total installed capacity of over 1,475,000 m^3/d (390 mgd) both for industrial and municipal applications.

Both spiral-wound and hollow fine fibre membrane configurations are widely used for desalination of brackish water and sea water. There are approximately 14 years of commercial experience with brackish water applications and about six years with sea water.

The reliability of properly designed, constructed and operated brackish water plants has been adequately demonstrated. Data are still being accumulated on sea-water installations. The typical reverse osmosis facility is in the range of 760 to 2,300 m^3/d (0.2 to 0.6 mgd). The units can be built almost any size owing to the wide variety of membrane sizes (and capacities) available. A standard membrane module which is generally used in large plants has a capacity of 760 m^3/d (20,000 gpd) and units with multiples of this are easily assembled.

The major components of a reverse osmosis plant are easily fabricated at a factory and then shipped to the plant site where they are assembled. The plants generally operate at pressures between 17 to 30 atm (250 to 450 psi) for brackish water and 54 to 68 atm (800 to 1,000 psi) for sea water. The pump necessary to produce this high pressure is the major energy requirement for the plant.

The membranes have a finite life which, under good conditions, can be about five years for brackish water plants and three or more years for sea water. Under unfavourable conditions, this membrane life could be reduced to several months.

Major problems encountered are in fouling and other damage to the membrane, which shorten its life or adversely change its salt rejection or flux characteristics. Generally, problems of this sort are associated with the feed water, pre-treatment and/or materials of construction.

3. Recent technological advances

The commercial application of reverse osmosis has grown rapidly since the early 1970s. The spiral and hollow fine fibre membranes have emerged as the most commercially viable configurations for large-scale production of potable water. There is now a body of experience with brackish water membranes; some plants have been operating up to 10 years, demonstrating that the membranes can have a sustained working life. The use of RO for sea-water desalination has proved commercially viable in recent years with the construction of some large plants and the development of new membranes. The major advances made in recent years are briefly described below.

(a) Salt water reverse osmosis

The major technological development in reverse osmosis in the past decade has been its commercial application for desalination of waters with a TDS between 10,000 and 50,000 ppm. Hollow fine fibre and spiral membranes for use with sea water were introduced in the mid-1970s and have been used in a variety of desalting applications. There are insufficient operational data to confirm the projected life of sea-water membranes, but most manufacturers offer at least a three-year guarantee on sea-water membranes installed in properly designed and operated plants, and there are installations where that life has been exceeded. Details of SWRO applications are discussed in annex III below.

With the installation of a number of plants in the early 1980s in the 4,000 to 12,000 m^3/d (1.1 to 3.2 mgd) range, manufacturers are now gaining experience in the operation of commercial sea-water reverse osmosis plants. Since much of the construction is the same as for brackish water plants, the major questions entail materials of construction, pumps and the long-term operation of the high-pressure pumps.

(b) Large-scale plants

Reverse osmosis plants in the 8,000 to 20,000 m^3/d (2 to 5.3 mgd) are now being routinely designed and built for both brackish water and sea-water desalting. Large-scale sea-water reverse osmosis facilities in this range have been constructed in Malta, Saudi Arabia, the United States of America and Venezuela. Brackish water reverse osmosis plants treating up to 60,000 m^3/d (16 mgd) have been constructed and operated and plants of up to 370,000 m^3/d (98 mgd) are being designed and constructed.

(c) Membrane developments

Significant developments have been made in commercial membrane technology. There are now a large variety of membranes available for both sea-water and brackish water applications in both the popular hollow fine fibre and spiral configurations as well as in the lesser used plate and frame and tubular designs.

The widespread production of thin film composite (TFC) membranes since about 1978 has provided a new family of membranes, for which salt rejection, chemical resistance and flux characteristics can be varied to meet specific applications. Those types of membranes, which are currently produced in the spiral configuration, have been used successfully to process sea water, brackish water and reclaimed waste water. Those membranes have exhibited improved tolerances to high-temperature feeds, high and low pH, and organic fouling (Mattson and Lundstrom, 1979).

Membranes which process brackish water using significantly lower pressures of about 13.6 to 17 atm (200 to 250 psi) have been commercially on the market since about 1982. A 3,800 m^3/d (1 mgd) installation has apparently been operating successfully since early 1983 at Venice, Florida.

Among some of the significant applications using thin film composite membranes are: a 12,000 m^3/d (3.2 mgd) sea-water plant at Jeddah, Saudi Arabia; a 1,150 m^3/d (0.3 mgd) industrial waste treatment facility at a textile dyeing plant in Pennsylvania; and a 9,500 m^3/d (2.5 mgd) waste-water reclamation plant for a power station in New Mexico, the United States.

Other membrane developments have been wet/dry membranes which can be shipped dry (but untested) to the plant site, thus reducing weight and the possibility of biological degradation. Some work has been undertaken in producing membranes in larger size modules, such as 30 cm (12-inch) diameter spirals, in an effort to reduce overall costs.

(d) Energy recovery

The high pressures (54-68 atm or 800-1,000 psi) involved in sea-water reverse osmosis have prompted the investigation of the use of various energy recovery systems to utilize a major portion of the energy in the brine reject stream. The pressure loss between the feed water and the brine discharge in a sea-water membrane module is usually only on the order of 1.5 to 3 atm (22 to 44 psi) and the brine stream is often discharged at about 54 atm (800 psi). The fact that almost 70 per cent of the brine is discharged at this high pressure has long been recognized as a major energy waste. However, the problem was not addressed commercially until sea-water reverse osmosis became feasible on a large scale.

The potential for energy recovery is high and recoveries of up to 2.6 kWh/m^3 (10 kWh/1,000 gallons) of prodct water may be possible. A variety of energy recovery devices such as impulse (Pelton) turbines, reverse running pumps and flow-work devices have been tried for this type of application. These can use the high-pressure brine stream to produce energy (rotating and otherwise) which can be used to deliver shaft power to the main pump, to operate a generator to provide electric power, or otherwise reduce the amount of additional energy required to create the initial feed water pressure. A new type of turbine, known as a biphase turbine, has also been suggested for energy recovery in reverse osmosis systems.

At least two pump companies currently offer vertical turbine pumps in pairs for RO; the second pump serves as an energy recovery device. The additional cost is mainly for the second pump. The systems offer recovery efficiencies of between 70 and 90 per cent, depending on their size. At 1981 energy prices, those devices could lower the cost of desalted water by 10 to 20 per cent for a 1,900 m^3/d (500,000 gpd) plant (Andeen, 1981).

4. Application in developing countries

The principle of operation of a reverse osmosis plant is relatively straightforward. However, its ultimate success depends on proper development of the raw water source, selection of suitable equipment and pre-treatment, and careful operation. If any one of these is lacking, severe problems can occur.

The operation of the plant requires personnel who are able to operate and maintain motors and pumps, mix chemicals, read meters and graphs, and make relatively simple process decisions based on those readings.

Reverse osmosis equipment can be adversely affected by neglect associated with inadequate pre-treatment of the raw water source, addition of chemicals, adjustment of flows etc. The membranes can rapidly foul and fail, and a serious error may require the replacement of all or a portion of the membranes.

Although replacement of the membranes can be expensive, it involves a portion of the plant which is anticipated to have a life of only three to five years under good conditions. Thus, in most cases a disaster can probably be financially absorbed. On the other hand, if a disaster occurs in a distillation unit, the cost of repair may be proportionally much greater, especially since the equipment is normally built to last 15 to 20 years.

One of the advantages of reverse osmosis stems from its decentralized, modular technology. Small decentralized RO systems can avoid some of the potentially huge costs necessary for water transportation to or from a central processing plant. The modular construction of RO systems means that a small unit can be installed initially and additional capacity easily added as demand for water and finances dictate. This permits developing countries to develop localized water sources rather than invest in large centralized conventional water resource projects with wide distribution networks.

Apart from the large RO plants mentioned earlier, work is being carried out in developing countries with small-scale RO systems either for rural areas such as fishing communities along the sea-coast or in remote areas utilizing brackish water from wells. Small sea-water reverse osmosis systems have been built throughout the Mediterranean and Caribbean areas, principally by resorts for use during the tourist season.

Recent activity in the Middle East has focused some attention on RO as another viable option to use as part of the effort to fulfil the water needs of the region. Until about 1979 RO played a rather modest role in Saudi Arabia's desalination programme and was almost exclusively limited to brackish water applications and plants not exceeding a capacity of 3,800 m^3/d (1 mgd). However, with completion of the Riyadh and Jeddah plants, the situation has altered and observers expect plants of 19,000 to 95,000 m^3/d (5 to 25 mgd) capacity to be commissioned in the early 1980s. In 1983, the total production capacity of all desalination plants in Saudi Arabia was approximately 2.5 million m^3/d (660 mgd), of which 500,000 m^3/d (130 mgd) was accounted for by RO plants.

Saudi Arabia's first large sea-water RO plant is a 12,000 m^3/d (3.2 mgd) facility which came into full operational status at Jeddah in January 1979. The facility is located on the shore of th Red Sea and obtains its raw water supply from a sea-water intake offshore. It is a two-stage plant using thin film composite spiral-wound elements. After passage through the membranes, the product water is chlorinated for disinfection and stabilized by the addition of lime. The water is then transferred to the distribution system for the city of Jeddah.

Apart from the sea-water unit at Jeddah, most of the RO plants in Saudi Arabia are small units of 500 m^3/d (0.13 mgd) or less used for desalination of brackish waters and serving small communities, hotels, hospitals or industry. Around the city of Riyadh a number of larger RO plants have been built to treat the ground waters from local and nearby wells. Performance studies were carried out on the Salbukh plant from November 1979 to January 1982 and on the Buwayb plant from November 1980 to January 1982 (Wojcik, 1983).

The Salbukh plant, with 38,000 m^3/d (10 mgd) capacity, in general performed very well during the study period. Only a few stoppages occurred, which were mainly a result of non-delivery of chemicals. The on-line record of the plant was remarkably good, 98.9 per cent. The water recovery in the RO unit was 88 per cent, while the total plant recovery was 87.4 per cent.

The 45,000 m^3/d (12 mgd) Buwayb plant did not perform as well as the Salbukh plant. The main reasons for this were lack of adequate raw water supply and technical difficulties that delayed start-up and hindered performance. These included faulty relief valves, leaking high-pressure hoses and malfunctioning of meters. Such problems resulted in a rather poor 78.8 per cent on-line record of the unit and a rather high salinity content of the product water (about 1,200 ppm). Moreover, the cost of water at the Buwayb plant was much higher than from the Salbukh plant, for lower-quality water (Wojcik, 1983).

A Saudi Arabian company has begun to manufacture reverse osmosis systems. That company, Al-Kawther Water Treatment of Jeddah, established an affiliate in California, and is taking advantage of technology transfer between the United States and Saudi Arabia made to serve the special desalting needs of its markets in the Arab world.

The new company can design and fabricate both large and small standardized RO units from 25 to 1,000 m^3/d (6,600 gpd to 0.26 mgd) for municipal and industrial applications, as well as for hotels, hospitals, construction camps, high purity industrial processes, reclamation of polluted water and water reuse for agriculture.

In 1971, the Mexican Government established a central agency to direct its desalination programmes. That agency, originally known as Comisión para el Aprovechamiento de Aguas Salinas (Commission for the Improvement of Saline Water), was shifted, as part of a government reorganization in 1977, and renamed Dirección General de Aprovechamiento de Aguas Salinas y Energía Solar (DIGAASES) (Director General for the Improvement of Saline Water and Solar Energy).

During the 1970s that agency assembled and installed about 19 small RO plants of 15 m^3/d (4,000 gpd) capacity in rural communities, which were built with 65 per cent local materials, using imported membranes. DIGAASES experimented with the manufacture of tubular membranes for small-scale plants; it has also worked on the assembly of spiral-wound units. Those RO plants are relatively cheap, compact and do not require much infrastructure. DIGAASES has also built a 30 m^3/d (8,000 gpd) sea-water plant at Santa Rosalita and a similar 30 m^3/d (8,000 gpd) unit at Cozumel to treat brackish and polluted water. Both of these units use plate and frame membrane systems and were built under a technical co-operation agreement between the Federal Republic of Germany and Mexico. According to Mexican figures (Gibbs, 1982), the small-scale units could produce fresh water for approximately $1.90/$m^3$ ($7.20/1,000 gal), compared to a larger MSF unit (1,000 m^3/d (0.26 mgd)), which produced water at $4.50/$m^3$ ($17.00/1,000 gal). The lower costs of RO have accelerated its use in small communities in Mexico and other dry countries.

Mexico has also been an innovator in the use of solar technology for desalination. A prototype RO solar plant has been operating in the mountain village of Concepción del Oro since May 1980. Such solar plants are expensive to construct, but potentially have very low operating costs. They will only be competitive in remote areas where costs of bringing in conventional fuel (diesel) are very high. The key to using these solar reverse osmosis plants successfully in remote areas is to produce a unit that is very reliable and requires little maintenance. Whether the construction of desalination plants by DIGAASES has actually saved them money is not known with certainty, but it does provide them a chance to reduce the need for foreign exchange and to develop technology and fabrication techniques within their own country; this alone can have considerable value.

The largest RO plant in the world is being built at Yuma, Arizona, as a result of an agreement between the United States and Mexican Governments. The 370,000 m^3/d (98 mgd) plant is to reduce the salinity of Colorado River water entering Mexico for subsequent agricultural use in that country. The plant is to produce water with a TDS of between 300 and 600 ppm where the river enters Mexico.

Unfortunately, because of large budget cuts for desalination projects in the United States, construction of the Yuma plant has not been completed. For 1983 and 1984 work will continue at Yuma but construction of the facility to house the desalting equipment will not start until 1985 and full operation will be delayed until 1988 or 1989. On the other hand, because 1983 was a very wet year, desalination of the river water would not have been required even if the plant had been completed on the original schedule (Water Desalination Report, 7 April 1983).

5. Generalized costs for reverse osmosis plants

Precise capital and operating costs for a reverse osmosis system cannot be predicted without detailed knowledge of the specific application. In most cases, the cost factors for RO will be largely determined by the location of the facility, capacity of the installation, the level of dissolved solids in the feed water and the required quality of the product water.

The RO process is generally characterized by lower capital costs than similarly sized distillation plants. Moreover, an RO plant will generally consume less energy than a single-purpose MSF plant. Energy consumption can be further reduced if energy recovery techniques are used. A plant with a capacity of 19,000 m^3/d (5 mgd) requires about 7.9 to 10.6 kWh/m^3 of fresh water produced, based on 30 per cent recovery at standard conditions (Pohland, 1980). The major energy requirement is for high-pressure pumping to the membranes, although energy is necessary for other plant functions such as pumping of the feed water, chemical mixing and pumping, lighting, climate control, and pumping of product water. Electricity is commonly used as the primary energy source, but other sources such as diesel or steam engines with direct mechanical drives are also used.

With the development of sea-water reverse osmosis facilities in the 4,000 to 20,000 m^3/d (1.1 to 5.3 mgd) range, there is considerable discussion on whether reverse osmosis will also replace distillation for sea water.

In this regard, care must be exercised in examining the costs between reverse osmosis and distillation processes for treating sea water. The processes can utilize different types of energy which have different cost factors. The important objective is to determine the total cost of the energy and not necessarily the amount of energy used. At any rate, there will probably always be a place for distillation in the spectrum of sea-water desalination processes, especially since its operation is considerably less sensitive to the quality of the incoming feed water and it can utilize low-cost energy in the form of low-pressure steam from turbines, as well as other waste heat. However, in many single-purpose installations, sea-water reverse osmosis or a combination of reverse osmosis with distillation may be more economical (Sackinger, 1980). The actual economic feasibility of each process can only be determined on a case-by-case site specific basis.

The cost figures presented below are for plants located in the United States. A much more detailed analysis and discussion of those costs can be found in Reed (1982), which was the basis for the estimation of costs in the present section.

(a) Sea-water reverse osmosis

According to the cost up-dates prepared by Reed (1982), the total capital costs for SWRO plants in 1981 ranged from approximately $US 3,070 to $1,160/$m^3$/d ($11.63 to 4.40/gpd) of installed capacity for facilities with capacities from 38 to 19,000 m^3/d (0.01 to 5 mgd). Those values were based on equipment prices in the United States, including installation and indirect capital costs. In recent years, costs of SWRO systems have remained almost unchanged as a result of strong price competition among the equipment suppliers. Overall costs for representative SWRO systems installed in the United States are presented in table 5.

The operating costs for SWRO systems vary from approximately $1.45 to $0.85/$m^3$ ($5.50 to $3.20/1,000 gal) across the scale range of 38 m^3/d (10,000 gpd) to 19,000 m^3/d (5 mgd). Those operating costs are based on an electrical energy usage of 10 kWh/m^3 (38 kWh/1,000 gal). If energy recovery were incorporated into the system, the electrical usage could drop to about 5.3 kWh/m^3 (20 kWh/1,000 gal). At $0.05/kWh this would result in savings almost equal to the estimated membrane replacement costs. There is an interest among equipment suppliers to incorporate energy recovery devices within large reverse osmosis systems to reduce water costs, although this is countered by the fact that it would add to the capital cost and complexity of the facility.

It should be noted that the use of 10 kWh/m^3 as the basis for calculating energy costs is a conservative assumption. Energy usage is primarily a function of combined pump and motor efficiency and will vary according to plant size and other factors. Generally, the larger the plant the more likely that a good match can be found between the motor, pump and membrane modules.

Table 5 shows the total water costs for various sizes of SWRO in 1981, including operating charges as well as a capital charge based on equipment costs and installation. Based on this data, the total water costs for SWRO varied from $3.28/$m^3$ ($12.28/1,000 gal) for a small 38 m^3/d (10,000 gpd) system to $1.54/$m^3$ ($5.82/1,000 gal) for a large 19,000 m^3/d (5 mgd) system. For plants using energy recovery systems, the capital cost would probably be increased by 10 per cent, while operating costs (not including capital recovery) could be reduced by 15 to 30 per cent depending on the size of the plant, the type of energy recovery device used and the cost of energy.

Table 5. Reverse osmosis: a/ sea-water desalting cost estimates

(In thousands of US dollars)

	38 m^3/d (10,000 gpd)	380 m^3/d (100,000 gpd)	3,800 m^3/d (1 mgd)	11,400 m^3/d (3 mgd)	19,000 m^3/d (5 mgd)
Direct capital costs	94	673	4 270	11 172	17 260
Indirect capital costs:					
Interest during construction	2	15	114	528	825
Working capital	5	34	214	559	863
Contingencies plus A and E fee	16	115	740	1 961	3 032
Total capital costs	117	837	5 368	14 220	21 980
Annual O and M					
Labour b/	6	21	119	175	203
Electricity (at 5¢/kWh) c/	6	59	590	1 768	2 948
Membrane replacement	4	34	310	838	1 396
Chemicals and filters	1	10	80	223	372
Other	-	6	35	96	150
Total O and M costs	17	130	1 134	3 100	5 069
Fixed charges (18 per cent)	21	151	966	2 560	3 956
Total annual costs	38	281	2 100	5 660	9 025
Cost of water:					
$/m^3	3.28	2.41	1.81	1.62	1.54
$/1,000 gal	12.28	9.04	6.77	6.08	5.82

Source: Adapted from S. A. Reed, Desalting Seawater and Brackish Waters: 1981 Cost Update, op. cit.

Notes:

For the general assumptions used in establishing these cost data, see table 3.

All cost estimates are in 1981 United States dollars.

A and E: architect and engineering.

O and M: operation and maintenance.

a/ Sea-water reverse osmosis treating 35,000 ppm feed water, 30 per cent recovery, 85 per cent plant factor, 21°C (70°F) temperature.

b/ Labour includes an additional 40 per cent for general and administrative overhead.

c/ Electrical consumption for a 3,800 m^3/d plant assumed to be 10 kWh/m^3 (38 kWh/1,000 gal).

(b) Brackish water reverse osmosis

Table 6 shows equipment costs, operating costs and costs of product water for representative brackish water RO plants. The data were developed based on a feed water with salinity in the range of 2,000 to 5,000 ppm TDS which contains no constituents such as silica, barium or strontium at concentrations that would prevent operating the RO units at a recovery rate of 80 per cent.

The total capital costs for brackish water reverse osmosis systems varied from $318/m^3/d ($1.20/gpd) for a 3,800 m^3/d (1 mgd) system to $218/m^3/d ($0.82/gpd) for a 94,600 m^3/d (25 mgd) system. The trend of price stability observed with SWRO plants was also maintained for brackish water RO systems; the effect of competition counterbalanced inflation.

Operating costs varied from $0.24/m^3 ($0.91/1,000 gal) to $0.18/m^3 ($0.68/1,000 gal) over the same range of sizes. The primary area of cost increase from 1979 to 1981 was in the area of electrical energy costs, which doubled in the United States. Energy recovery is not nearly as important for brackish water as for SWRO systems, because brackish water plants operate at much higher recovery rates and at lower pressures than sea-water plants. In those estimations, a recovery rate of 80 per cent is assumed, with higher pressures assumed for higher TDS levels. A typical pressure used for brackish water desalting is 27 atm (400 psi), while operating pressures for SWRO currently range from 54 to 68 atm (800 to 1,000 psi). A major future trend for potential cost reductions in brackish water plants appears to be the development of new low-pressure (17 atm) membranes. The use of those membranes, where the feed water is appropriate, should lower energy costs because of the lower feed water pressures required, but at the same time will probably raise membrane replacement costs owing to the premium cost of those special membranes.

Total water costs (including capital recovery) for brackish water RO thus range from $0.41 to $0.30/m^3 ($1.54 to $1.11/1,000 gal) across the 3,800 to 95,000 m^3/d (1 to 25 mgd) plant size range.

Table 6. Reverse osmosis: a/ brackish water desalting cost estimates

(In thousands of US dollars)

	3,800 m^3/d (1 mgd)	11,400 m^3/d (3 mgd)	19,000 m^3/d (5 mgd)	38,000 m^3/d (10 mgd)	94,600 m^3/d (25 mgd)
Direct capital costs	976	2 487	3 841	6 867	16 086
Indirect capital costs:					
Interest during construction	16	68	107	275	860
Working capital	49	124	192	343	804
Contingencies plus A and E fee	167	429	662	1 198	2 840
Total capital costs	1 208	3 108	4 802	8 683	20 590
Total O and M					
Labour b/	60	74	119	147	189
Electricity (5¢/kWh) c/	139	416	694	1 387	3 650
Membrane replacement	62	158	233	465	1 163
Chemicals and filters	52	130	186	341	853
Other	3	8	12	26	62
Total O and M costs	316	786	1 244	2 366	5 917
Fixed charges d/	217	559	865	1 563	3 706
Total annual costs	533	1 345	2 109	3 929	9 623
Cost of water:					
$/$m^3$	0.40	0.34	0.32	0.30	0.29
$/1,000 gal	1.53	1.29	1.22	1.13	1.11

Source: Adapted from S. A. Reed, Desalting Seawater and Brackish Waters: 1981 Cost Update, op. cit.

Notes:

For the general assumptions used in establishing these cost data, see table 3.

All cost estimates in 1981 United States dollars.

A and E: architect and engineering.

O and M: operation and maintenance.

a/ Brackish water reverse osmosis; 2,000 to 5,000 ppm feed water: 80 per cent recovery; 21°C (70°F) temperature.

b/ Labour cost includes 40 per cent for general and administrative overhead.

c/ Electrical consumption for the 3,800 m^3/d plant assumed to be 2.1 kWh/m^3 (8 kWh/1,000 gal).

d/ Thirty-year capital recovery at 18 per cent interest.

E. Economic considerations

In any country, no matter what the level of development, the best selection of a desalination or any water resources system is one which is more than just economically reasonable in the paper study stage. It is a system which works when it is installed and continues to work and deliver a desired product at the expected quality and quantity for the planned life of the system.

The desalination of water is an excellent means to enable an area to utilize water sources that in the past were too saline for human consumption. However, a substantial capital investment is required, and the operation of the system will continue to require funds for energy, chemicals, labour, repairs and replacements. The potential initial and continuing costs must be kept in mind, because they can affect consumption and the local economy. Tables 7 and 8 show estimated capital and operating costs for various desalination processes treating sea water and brackish water with capacities of 3,800 and 19,000 m^3/d (1 and 5 mgd) in the United States in 1981. Data relating to other plant capacities were shown in sections B through D of the present chapter.

The data in table 7 indicate that for sea-water desalting the representative sea-water reverse osmosis plant has a cost advantage over both distillation processes at the 3,800 m^3/d (1 mgd) size. However, at the 19,000 m^3/d (5 mgd) size, the given multiple-effect distillation plant has a cost advantage over the SWRO example, while the reverse osmosis plant produces water somewhat cheaper than the same size MSF plant. However, these data must be viewed with extreme caution, as the economics could change easily, depending on assumptions. Particularly important are the costs assigned to energy and how such costs are allocated between electricity-generating and desalination plants in dual purpose facilities. Moreover, according to Reed's estimates (1982), MSF plants using fuels other than oil to fire their boilers seem to produce water cheaper than SWRO at the 19,000 m^3/d size.

Estimated costs of brackish water production for the representative plants are presented in table 8. These data indicate that electrodialysis and reverse osmosis are comparable over the two size ranges, depending on TDS and difficulty of treatment of the water. For lower TDS water, electrodialysis is less expensive per unit product. At higher TDS levels, RO has a cost advantage.

Overall, rough costs (including capital recovery charges) of $0.25 to $0.50/$m^3$ ($1.00 to $2.00/1,000 gal) for brackish water and $1.30 to $3.30/$m^3$ ($4.90 to $12.30/1,000 gal) for sea water will generally bracket the overall unit costs (capital charges, operation and maintenance) of desalination for plants with capacities in the range of 2,000 to 40,000 m^3/d (about 0.5 to 10 mgd) if built in the United States. For small units in developing countries, those operating costs could increase to over $1.00/$m^3$ ($4.00/1,000 gal) for brackish water and up to $8.00/$m^3$ ($30/1,000 gal) for sea-water plants. Items such as special feed water development (well fields, intake structures), water storage and brine disposal could add another $0.25 to $1.30/$m^3$ ($1.00 to $5.00/1,000 gal) to this cost. Costs in developing countries will generally be at least twice the cost in the United States, because of import duties and transportation of plant, more extensive site development, management fees and procurement of spare parts.

Whether consumers are asked to pay the full price or whether the cost is subsidized by the Government or someone else, monetary resources will have to be diverted from other economic priorities to be used for this purpose over the life of the project.

Table 7. A comparison of cost estimates for representative 3,800 m^3/d (1 mgd) and 19,000 m^3/d (5 mgd) sea-water desalination facilities

(In thousands of US dollars)

Plant capacity m^3/d	3 800	3 800	3 800	19 000	19 000	19 000
(mgd)	1	1	1	5	5	5
	MSF a/	SWRO b/	MED c/	MSF a/	SWRO b/	MED c/
Direct capital costs	6 024	4 270	5 110	19 726	17 260	15 385
Indirect capital costs						
Int. during construction	497	144	164	1 808	825	1 265
Working capital	439	214	89	1 926	863	303
Contingencies plus A and E	904	740 d/	741	2 959	3 032 d/	2 310
Proj. mgmt., overhead and profit	2 259	...	1 916	7 397	...	5 773
Total capital costs	10 123	5 368	8 020	33 816	21 980	25 036
Annual O and M costs						
Labour e/	238	119	217	305	203	252
Energy - steam	495		446	2 475		2 230
Energy - electricity f/	113	590	140	565	2 947	700
Chemicals and filters	57	81	28	286	372	140
Membrane replacement		310			1 396	
Other	36	35	84	86	150	270
Total O and M costs	939	1 135	915	3 717	5 068	3 592
Fixed charges g/	1 822	966	1 444	5 907	3 956	4 508
Total annual costs	2 761	2 101	2 359	9 624	9 024	8 100
Cost of water						
$/m^3	2.37	1.81	2.03	1.65	1.54	1.39
$/1,000 gal	8.90	6.77	7.60	6.20	5.82	5.22
Unit capital cost						
$/m^3	2 672	1 123	2 118	1 785	1 156	1 318
$/gpd	10.12	5.37	8.02	6.76	4.40	5.01

(Source and footnotes on following page)

(Source and footnotes to table 7)

Source: Adapted from S. A. Reed, Desalting Seawater and Brackish Waters: 1981 Cost Update, op. cit.

Notes:

The general assumptions used in establishing these cost data are listed in table 3.

All cost estimates are in 1981 United States dollars.

A and E: architect and engineering
O and M: operation and maintenance

a/ MSF plant: multistage flash unit using acid for scale control; performance factor = 12; maximum brine heater temperature of 121°C (250°F); recirculation with a concentration factor of 2; and an 85 per cent plant factor. Oil-fired boiler using steam at a price of $2.30/million Btu.

b/ Sea-water reverse osmosis facility; 35,000 ppm TDS feed water; 30 per cent recovery; 85 per cent plant factor; temperature 21°C (70°F); no energy recovery.

c/ MED: multiple-effect horizontal-tube unit using aluminum tubes, non-acid feed treatment; performance factor = 12; maximum brine heater temperature of 75°C (167°F); and an 85 per cent plant factor; oil-fired boiler using steam at a price of $2.30/million Btu.

d/ Includes management fees, overhead and profit.

e/ Labour cost includes an additional 40 per cent for general and administrative overhead.

f/ Electricity generated on site for a cost of 7.5¢/kWh for MSF and MED; purchased at 5.0¢/kWh for SWRO.

g/ Based on a 30-year capital recovery at 18 per cent interest.

Table 8. A comparison of cost estimates for representative 3,800 m^3/d (1 mgd) and 19,000 m^3/d (5 mgd) brackish water desalination facilities

(In thousands of US dollars)

Plant capacity m^3/d (mgd)	3,800 (1)	3,800 (1)		19,000 (5)	19,000 (5)	
	Brackish water RO a/	Brackish water EDR b/		Brackish water RO a/	Brackish water EDR b/	
		1	2		1	2
Direct capital costs	976	1 262	1 436	3 841	5 348	6 113
Indirect capital costs						
Int. during construction	16	26	29	107	177	201
Working capital	49	53	72	192	267	306
Contingencies plus A and E c/	167	214	245	662	927	1 059
Total capital costs	1 208	1 555	1 782	4 802	6 719	7 679
Annual O and M costs						
Labour d/	60	59	59	119	119	119
Electricity e/	139	96	179	694	479	893
Chemicals and filters	52	22	22	186	97	97
Membrane replacement	62	19	28	233	92	139
Other	3	4	5	12	17	21
Total O and M costs	316	200	293	1 244	804	1 269
Fixed charges f/	217	280	321	865	1 210	1 382
Total annual costs	533	480	614	2 109	2 014	2 651
Cost of water						
$/m³	0.40	0.36	0.47	0.32	0.31	0.40
$/1,000 gal	1.53	1.38	1.77	1.22	1.16	1.53
Unit capital cost						
$/m³	318	409	469	253	354	404
$/gpd	1.21	1.55	1.78	0.96	1.34	1.53

(Source and footnotes on following page)

(Source and footnotes to table 8)

Source: Adapted from S. A. Reed, Desalting Seawater and Brackish Waters: 1981 Cost Update, op. cit.

Notes:

The general assumptions used in establishing these cost data are listed in table 3.

All cost estimates are in 1981 United States dollars.

A and E: architect and engineering
O and M: operation and maintenance

a/ Reverse osmosis; feed water 2,000 to 5,000 ppm TDS; 80 per cent recovery; 95 per cent plant factor; temperature 21°C (70°F).

b/ Electrodialysis reversal; 80 per cent plant recovery; 95 per cent factor; temperature 21°C (70°F). Feed water No. 1: TDS 2,076 ppm; uses a two-stage system (referred to as water No. 3 in Reed, 1982). Feed water No. 2: TDS 3,475 ppm; uses a three-stage system (referred to as water No. 4 in Reed, 1982).

c/ Includes management fees.

d/ Labour cost includes an additional 40 per cent for general and administrative overhead.

e/ Electricity at $0.05/kWh. Electrical consumption for RO assumed to be 2.1 kWh/m^3; for EDR, 1.5 kWh/m^3 for water No. 1 and 2.7 kWh/m^3 for water No. 2.

f/ Based on a 30-year capital recovery at 18 per cent interest.

Investment in a water-short area could lead to the development for the first time of an abundant supply of water, and, as such, it is important that the development be carried out carefully. The key to the success of any major water resource development of this type is proper water management based on a thorough water resources study and the formulation of a realistic economic development plan. Proper water management includes the entire spectrum of water resources activities ranging from source selection and development through water usage and brine disposal.

1. Supply and demand evaluation

Generally, in carry out out a water resources planning study, the existing and potential supply is examined from the economic and technical sides and analysed along with the probable demand for the water from all users. The existing and potential water resources available in a given area, including all sources of fresh and saline water, need to be inventoried and evaluated. The quantity, quality, cost of development and consequences of development or diversion should be determined for all potential sources.

Demand must be estimated carefully, because the potential added cost of desalted water (if passed on to the consumer) can greatly affect water usage. Not only can this water be expensive for domestic consumption, but high costs can affect the type of industries attracted and the economic well-being of industries using the water. Obviously, industries requiring large quantities of low-cost water cannot readily survive if forced to pay the true cost of desalted water, especially water desalinated from sea water. Since demand will be affected by the perceived cost to the consumer, the policy that will be used to set the price that will be charged to the consumers for water should be ascertained early. Apart from the perceived cost to the consumer, the demand for water will depend on many factors, including climate, culture, distribution methods, uses (including agricultural, industrial and domestic uses), accessibility and availability. In some water-short areas it may be economical to develop a system with two or more grades of water distributed separately, providing distribution and usage of both potable and non-potable water. To analyse this potential, the demand for potable and non-potable usages should be projected separately.

2. Factors related to process selection

Following an evaluation of the overall water resource picture, the factors discussed in the following sections should then be examined and weighed before choosing desalination, the appropriate process and the capacity of the plant. There is no set way to arrive at the correct decision. As with any project that involves capital and operating expenses, an economic evaluation must play a significant role, but it should not be the only factor. Judgement based on a thorough review of the various factors, both objectively and subjectively, with a view to the long-term costs, benefits and consequences of a proposed project, must be exercised in making the final decisions.

(a) Raw water source

Identifying and characterizing the potential raw water source (or sources) is a basic part of process selection. The quantity and quality of a water source can change daily and seasonally, and knowledge of whether this does occur, and the extent of variations, is important in process selection, design and the successful long-term operation of the facility.

Unfortunately, many desalination projects consist of development of the feed water source and installation of a desalting unit simultaneously under the same concurrent contracts. In most cases, it would be far better to develop the feed water source first so as clearly to characterize it, and then move on to the final selection and/or design of the desalination facility, its procurement and installation. This may not change the process selected, but it may modify the pre-treatment and/or capacity required. Finalizing those changes before the contract bidding is almost always cheaper than trying to make alterations and chance orders in contracts at a later date. It has not been unknown for desalination plants to have been purchased and installed only to discover that the source of feed water was inadequate and/or unsuitable.

(b) Product water

Both the quantity and the quality of the water to be produced by desalination need to be determined. The quantity needed and plant production capacity will depend on the consumption demands in the system, storage capacity and whether the water is to be used to augment other sources.

Careful thought should go into specifying the quality of water desired from the desalination facility. Automatically assuming a TDS content of up to 500 ppm (World Health Organization standard for drinking water) might not be appropriate. In order to specify the proper TDS level, many factors should be considered, including the degree of blending with other water supplies, the taste preference of the population using the water, the type of post-treatment to be used, the potential for reuse of the waste water produced and special uses for the water, such as for industry or agriculture.

(c) Location and site development

The choice of a site for the desalination plant requires careful consideration, as an optimum location may result in a substantial reduction of costs. Some of the factors that should be taken into account include: raw water availability, brine disposal, conveyance of product water to the consumers, and the availability or fuel of other energy sources. Other considerations should include: geology of the site; exposure to winds, salt spray and flooding; and availability of cargo handling facilities, construction materials and labour. Usually, plants located on the coast present fewer problems than inland plants.

In addition to providing funds for the purchase of the site, additional funds will generally be needed for grading, drainage, sewers, fences and, if necessary, dock or railroad sidings and parking lots. It is desirable to provide for concrete or asphalt surface in working areas where they are needed.

Site development costs as a proportion of total direct capital costs decrease as the size of the plant increases. For example, for MSF plants, site costs fall from almost 5 per cent of total direct capital costs for plants with capacities ranging from 3,800 to 9,500 m^3/d (1 to 2.5 mgd) to only 1.5 per cent for large plants (380,000 m^3/d). The percentage for site development for SWRO units ranges from 6.5 for a 38 m^3/d plant to 2.5 per cent of total direct capital costs for a 19,000 m^3/d (5 mgd) plant (Reed, 1982).

(d) Raw water: intake and pumping

Substantial differences exist in the design and costs between plants on the sea-coast and inland plants using brackish water. On the sea-coast, the raw water intake can either be a head structure in relatively deep water or a number of intake wells near the coastline. The choice of intake depends on local conditions.

While sea water can occasionally be obtained using sea wells on the adjacent beach, the geology of the site or the quantity of water needed often does not favour that method of obtaining sea water for large plants. In those cases, a sea-water intake can be constructed which brings in the sea water directly.

The intake must be located in an area where it will pick up high-quality water and will avoid silts, sand, floating dissolved and suspended wastes, as well as marine life. The head structure requires protective screens to keep out the organic matter and sand. In considering the location of raw water intakes, possible pollution of the sea water from sewage discharge sites or by oil products should also be borne in mind; this will involve a study of currents, temperature, turbidity and biological aspects of the water. Proper location and construction can aid in obtaining suitable water in the desired temperature and salinity range.

For reverse osmosis plants, there is usually a definite advantage to using beach wells to provide feed water from the sea for desalination plants (Latour, 1980). Traditionally, water was supplied to distillation plants by pipes, lagoons or shore intakes. Beach wells were not used because the hydrogen sulphide in water drawn from the wells adversely affected the distillation equipment. With care this problem can be overcome for RO plants, however, and there are a number of advantages to using beach wells. Properly constructed, they can provide water that is low in substances such as marine life, trash and sand which can foul the membranes. The strata through which the water flows from the sea to the well filter the water and often reduce the need for pre-treatment (Pohland, 1980). If beach wells were the only method to obtain sea water for the feed, then their limited capacity or the existence of hydrogen sulphide might preclude the use of distillation, as some of the processes such as MSF and MED require large amounts of cooling water to operate.

The quality of the feed water can affect the process selection. With sea water, if it appears that a direct intake to the sea will be the only feasible method of obtaining feed water, then serious consideration should be given to using a distillation process that is more tolerant of suspended material in the feed water. Small vapour compression distillation units are often used at coastal resorts for this reason. The alternative to this, if reverse osmosis is to be used, is to provide for special pre-treatment processes. These will add to the cost and may change the economics of the project.

In considering the desalination of brackish waters, a thorough water quality analysis must be made as there are some constituents such as barium, strontium and silica which can adversely affect the recovery factor of a plant. Usually, the electrodialysis reversal process can maintain a higher recovery factor with difficult feed waters than the RO process. The recovery factor can have a significant effect on the economics.

In the desalination of both sea water and brackish water, the temperature of the water source is important. Although warm feed water theoretically has some advantages, most RO membranes experience structural problems in treating warm (above about 30°C (95°F)) water. However, warm water can be beneficial to desalination by electrodialysis as it reduces the amount of power needed, while not creating the same degree of structural problems. The temperature of feed water available for distillation can affect the efficiency of MSF units, since the same water is used as cooling water to establish the temperature differential between the brine heater and the final stages.

Total costs for intake and discharge facilities for a 19,000 m^3/d (5 mgd) plant in the United States in 1981 were estimated to range from about $280,000 for brackish water RO or electrodialysis reversal plants to $656,000 for an average MSF plant or $850,000 for an MED plant (Reed, 1982). The percentage of direct capital costs expended on intake and outfall facilities ranges from 4.0 to 7.0 per cent of total capital costs.

(e) <u>Size of units</u>

Desalinated water can be the only source, a major source or a complementary source of water supply within an area. When desalination is the only source of supply, careful studies will have to be made to see to what extent plant peaking capacity can be replaced by additional storage.

If desalinated water is the major component within a water supply system that also obtains limited amounts of fresh water from reliable underground sources, the optimum water mix cost will probably result from keeping the desalination plant at base load and meeting peaks with water from conventional sources. This would reduce the cost of water from the desalination plant and may reduce the need for maximum safe storage capacity to the extent that water is available from the conventional source.

For cases in which desalination is a complementary source of supply within a water system, running the plant at base load need not necessarily be the most economic solution. For example, the Lok-On Pai plant in Hong Kong is brought on stream only when there is a shortage of water from conventional sources. When the desalination plant is only used to meet peak load demand, annual fixed charges will weigh very heavily on the cost of desalinated water, making it relatively expensive. However, the overall cost of water in the water mix may still be relatively low.

Selection of the best plant for a given location will depend to a great extent on the relative availability of both capital and energy. In an area that has relatively low interest rates, or concessionary terms from a donor Government or international bank, and readily available capital, it may be desirable to build highly efficient plants with extra capacity to handle anticipated future growth in demand. Areas that are relatively short of capital but may have comparatively inexpensive subsidized sources of energy, may be justified in minimizing capital outlay through the design of a plant that is less energy efficient. Often the more energy efficient designs require more attention to operation and can have a tendency for increased down time (a lower plant factor), which can adversely affect production costs.

Existing desalination facilities have capacities ranging up to about 950,000 m^3/d (250 mgd). Economies of scale definitely apply to the large MSF plants. As can be seen from the table below, estimated total capital costs per m^3/d for MSF plants fall from $2,664 at the smaller end of the scale to $1,448 at the larger end. Predicted annual operation and maintenance (O and M) costs exhibit similar trends.

Cost component \ Size (m^3/d)	3 800	9 500	19 000	38 000	95 000	190 000	380 000
Total capital costs ($/$m^3$/d)	2 664	1 984	1 780	1 780	1 545	1 463	1 448
Annual O and M ($/$m^3$)	670	511	450	435	411	393	390

Source: Reed, 1982.

Economies of scale are not as evident in reverse osmosis plants, which are more modular in construction. However, savings are possible in any type of large-scale plant from relative reductions in personnel and other overhead costs. Increased costs might be incurred for conveyance of the product water from large plants located away from population centres.

The final size of the desalination plant that is required will depend on: (a) present needs, (b) population growth rate, (c) projected per capita consumption, (d) industrial growth rate and consumption, (e) relative costs of supplying water, (f) reduction in the overall efficiency of the plant over time, and (g) decisions with regard to a double piping system, with high-quality water for such uses as drinking and cooking and lower-quality water used for other purposes. Once all those factors have been taken into account, it is possible to determine the plant size and to make the necessary economic decisions required in selecting the process type and specific design of the plant.

Once the water needs of an area are established, the problem of meeting those needs becomes one of balancing the various factors to arrive at the most economic arrangement. In many instances, a water facility will be in existence, and it is the expansion and perhaps modernization of those facilities that are under consideration. Hence, the problem of meeting specific water needs range from complete replacement of an obsolete plant to those of incremental additions to existing facilities. In other instances, desalination plants will open up new areas and activities; thus, plant capacity will be strongly dependent upon the specific requirements of the area where the plant is to be located.

The demand for water at any given location varies within the 24-hour period as well as on a seasonal basis and from year to year. Daily variations do not create a serious problem since some storage is always necessary to cope with peak loads and maintenance shut-downs. Seasonal variations are more serious. For example, daily summer requirements in some areas may be double or triple winter demands. During the winter tourist season in the Caribbean islands or the summer tourist season in the Greek islands, for example, the demand for water is more than double that of the off-season. In general, residential areas show more variation than industrial areas with the same aggregate consumption.

In order to meet variations in demand, it is always desirable to strike a balance between the base plant's load factor, the storage reservoir size and the stand-by facilities available. If the new facilities are to be an incremental addition to existing facilities, it is likely that sufficient storage is already available. Operation of the water facilities thus becomes simply a matter of keeping the total costs to a minimum through the varied use of the total facilities. When a new plant represents an entirely new installation, storage must be balanced against plant load factors to arrive at the best combination for the specific area under consideration.

(f) Efficiency and reliability

The reliability required from a desalination plant will depend on local factors, particularly on whether there are complementary water supply facilities available that can be used for stand-by purposes. If complementary water resources are sufficient to meet peak demands when the desalination plant is out of commission, then it will be possible to reduce storage capacity that may otherwise be necessary as an insurance against breakdowns of the main plant. Where complementary water sources are not available, a more reliable plant combined with adequate storage capacity will be necessary.

The desalination industry is experiencing a continuous trend to increase the efficiency of the various desalination processes in order to reduce operating costs. Examples of this trend include distillation plants designed with higher performance factors and reverse osmosis facilities with energy recovery systems. Higher efficiency plants, however, tend to be somewhat more complex in design and operation, thus requiring more care in operation and maintenance. If this extra care is overlooked, serious operational problems could result which would reduce any expected benefits.

The reliability of a plant's operation should be of paramount concern because, regardless of a plant's efficiency when it is operating, it is zero when the plant is idle. This is especially important in developing countries, where it may be difficult to mobilize sufficient numbers of trained operating personnel, and particularly when an area relies mainly on the facility for its water supply. In such cases, alternative sources are usually difficult to obtain and very expensive. Reliability is generally increased by proper design, good materials and simplicity of operation.

A good indicator of plant reliability is the performance of existing plants of a given size and process operating under similar circumstances. Their performance, capabilities and problems can best be assessed by: (a) visiting plants in operation and examining operating data and repair records; and (b) discussing the facilities' operation with operating personnel and manufacturers' representatives.

The degree of reliability which it is necessary to provide will depend to some extent on the different categories of consumers connected to the water system. Reliability will be enhanced by the installation of a number of desalination units rather than one large unit. This would of course involve sacrificing some economies of scale, but this can be considered part of the cost of improving the reliability.

(g) Brine disposal

The desalination processes described in the preceding chapters treat saline water and produce a product stream, which has a low level of TDS, and a brine (or reject) stream, which has a much higher concentration of TDS than the feed water.

The brine stream must be discharged somewhere. For facilities located close to the sea, disposal does not generally pose a problem. An outfall must be provided for the discharge of brine from desalination plants located by the sea. The outfall should be sited sufficiently far from the raw water intake so that recirculation does not occur. This may require a study of the direction and strength of currents.

For facilities located inland, brine disposal can be a serious problem. Improperly discharged brine with its high salt content can contaminate existing ground water or surface water. It is generally too saline to be used for irrigation, so the disposal options are limited. Some methods that have been used include evaporation in solar ponds or by conventional thermal evaporators, injection into existing confined zones of very saline ground water, and transportation of the brine to a saline water body.

Discharge into a stream, even into a brackish stream, may cause chemical pollution problems that may extend for many miles downstream. Evaporation ponds are the most common method considered for safely disposing of brine, but they are costly and take up considerable space. The cost of the ponds needs to be weighed against the expense of using and operating a high-recovery desalination system, which will minimize the quantity of brine produced (but not the total amount of salt) and the size of the ultimate disposal system.

Impounding of the brine through injection wells is another option for inland plants. Not all areas are suitable for safe brine injection and a hydrogeological survey of the area would be needed if the plant is considering injecting brine underground through wells. If the injection facility is constructed improperly, it could contaminate the ground water over a large area. However, with proper construction and operation, the injection of the brine into underground strata may be the most feasible solution to inland disposal problems. It must be kept in mind during planning that there has not yet been a great deal of long-term experience in safely disposing of brines from inland desalination facilities.

No project should proceed unless an acceptable method of brine disposal has been determined. The economic evaluation of any desalination system is not complete without including the costs involved in brine disposal. When brine disposal is a serious problem, it has the potential to affect the ultimate process selection and the viability of the project.

The recovery of valuable chemical constituents from the brine may in some cases be possible. This depends on local market and climatic conditions. If by-product recovery is envisaged, it still may not be practical to use the desalination plant to achieve high concentrations of the residual brine, primarily because this poses handling and scale problems as solubility limits are approached. It would be better to pump the brine into ponds and let the final precipitation and drying occur by solar evaporation. As an example of the amounts of salt available, the brine stream from a 3,800 m^3/d (1.0 mgd) plant on the sea-coast could supply from 150,000 to 250,000 kilograms of salts per day.

(h) Conveyance and distribution

It is current practice to consider cost at the plant as the effective final cost of desalinated water. However, while this refers specifically to production cost, it does not make any allowance for the cost of conveyance from the plant site to the inlet into the distribution system. Apart from the fact that plant siting requirements may call for a considerable investment for conveyance, this item may become quite significant when comparing desalination to an alternative source that might be closer to or further from the consumption centre. It should therefore be included when computing the total cost of water from any source including desalination.

The question has arisen whether the costs of production and conveyance should be computed as a combined figure or separately when determining the cost of water delivered in bulk. If a comparison between different methods of production is desired and the cost of conveyance is a large item, it obviously should be computed independently. Moreover, the rate of depreciation is not the same for a pipeline as for a desalination plant and the same time interval is not applicable in both. A pumping station could be depreciated in 25 years, but a pipeline has a much longer useful life.

The cost of transporting the desalinated water can be a significant cost factor depending on the amount of water, distance and terrain and must be considered in the early stages of planning new or additional capacity.

Table 9 may serve as an illustration of how water conveyance cost might be calculated.

Distribution costs, on the other hand, may not have to be included in comparative calculations, since these would be the same regardless of source of supply, although in all cases they probably represent a substantial or major component in the cost of water delivered to the customer.

The distribution part of the water system can be as basic as handcarrying water obtained from a tap on a storage tank or as complex as a full piped-in distribution system. The type of distribution system should be known at the outset of the project, as it will affect the consumption.

Where the distribution will take place using an existing piped system, it would be prudent to determine how much of the water entering the distribution system is actually delivered to a consumer. A poorly designed, constructed and/or maintained distribution system could lose a substantial portion of the water entering the system. Some distribution systems in the Caribbean, which employ desalinated water as a major source, cannot account for 40 to 50 per cent of the water in the system. This is the result of a combination of leakage, unauthorized connections and broken meters, and it leads to lower revenues and increased unit costs.

A part of any distribution system should include sufficient storage to meet peak demand and/or allow for shut-down of the desalination facility to permit adequate planned maintenance and unplanned repairs.

Table 9. Water conveyance costs: method for calculation

a.	Average annual flow rate	____	m^3/d (mgd)
b.	Total friction head loss	____	m/km x number of km
c.	Net elevation difference	____	m
d.	Total head required (b + c)	____	m
e.	Energy required at 0.40 kWh per 3.8 m^3 (1,000 gal) for each 30.5 m of head $\frac{0.40 \times a \times d}{100}$	____	kWh
f.	Energy cost at y mills per kWh (y.e / a)	____	cents per m^3
g.	Total cost of pipeline	____	dollars per km x number km
h.	Annual fixed charges at z per cent (z.g / a) ..	____	cents per m^3 (1,000 gal)
i.	Total costs for distance involved (f + h)	____	cents per m^3 (1,000 gal)

Source: Adapted from Water Desalination: Proposals for a Costing Procedure and Related Technical and Economic Considerations (United Nations publication, Sales No. 65.II.B.5).

Note: Parameters such as annual fixed charges, cost of electricity and cost per km of pipe will have to be modified in each case according to local conditions.

3. Energy considerations

For most desalination processes, energy costs account for 45 to 85 per cent of the daily operation and maintenance costs of producing water, and from 15 to 40 per cent of total annual costs, including capital charges. The approximate percentages expended on energy by representative desalination plants in the United States are shown in table 10. As plants increase in size, the percentage of costs expended on energy increases. Thus, for very large size MSF plants, energy costs may be over 85 per cent of operation and maintenance costs. Although the energy utilized by a particular process to produce a given quantity of water can be estimated with some accuracy, the cost of that energy can vary widely among processes and locations, depending on the energy source, temperature levels, previous use and the method of accounting used. Energy costs thus have to be ascertained on a site-specific basis. True costs of electricity could easily be in the range of $0.10 to $0.30/kWh and more in developing countries, especially where small generators are utilized. In any case, a very careful estimate needs to be made of the costs of energy for a given plant and process, as this continues to be the most significant variable cost in producing water.

Table 10. Desalination plants: estimated percentage of costs expended on energy

Size of plant	380 m^3/d (100,000 gpd)		3,800 m^3/d (1 mgd)		19,000 m^3/d (5 mdg)		38,000 m^3/d (10 mdg)		190,000 m^3/d (50 mgd)		380 m^3/d (100 mgd)	
Type of plant	Percentage of O and M	Percentage of total annual costs	Percentage of O and M	Percentage of total annual costs	Percentage of O and M	Percentage of total annual costs	Percentage of O and M	Percentage of total annual costs	Percentage of O and M	Percentage of total annual costs	Percentage of O and M	Percentage of total annual costs
MSF												
oil-fired	...	...	65	22	82	32	82	33	85	34	86	36
MED												
oil-fired	...	...	64	25	82	36	85	39	...	...	...	...
SWRO (no energy recovery)	45	31	52	33	58	38	...	...	...	...	...	...
Brackish water RO	...	...	44	26	56	33	59	35	62	38	...	...
EDR No. 1	...	...	48	20	60	24	65	26	...	...	...	...
No. 2	...	...	61	29	70	34	74	36	...	...	...	...

Source: Adapted from S. A. Reed, Desalting Seawater and Brackish Waters: 1981 Cost Update, op. cit.

Note: For assumptions used, see table 3.

(a) Choice of energy source for desalination

The selection of a given desalination process is dependent upon many factors, but among the principal ones are the type of energy available and the purpose and required output of the plant. Some of the processes require energy in a specific form. Distillation plants (MSF, MED) use steam primarily provided by a boiler or other heat source, often in conjunction with a power-generating plant. RO plants generally operate on electricity as the primary energy source, while electrodialysis reversal uses direct current. Vapour compression evaporators operate on electricity, high-pressure steam or diesel drives.

Energy to operate the plant may be obtained from a variety of sources, depending on the design of the plant, its geographical location and other factors. A proper economic comparison of various energy sources should preferably be based upon the cost of energy, and not on the cost of fuel per ton. In this manner, adjustment will be made for variations of calorific value which occur not only between different fuel and energy sources, but also between different consignments of the same type of fuel.

Consideration must also be given to whether energy is purchased from an outside source for use in the desalination plant, or whether it is generated on site as part of a combined project. Those considerations also apply to the question of electricity supplies needed to drive the various plant auxiliaries. Frequently, large distillation systems use steam extracted from the low-pressure end of a turbine from an electricity-generating station where the steam for the turbine is produced by a boiler fired with oil, natural gas or coal. For membrane plants, electricity is more commonly purchased from a local utility at prevailing rates in the area, although direct drive diesels have been used to power some large SWRO plants. For purposes of costing, the cost of energy to be used should be the average annual cost of energy calculated from the total energy purchased and the total amount paid.

(b) Multi-stage flash versus reverse osmosis

The potential for lower energy usage is the main factor encouraging the use of SWRO over MSF systems for the desalination of sea water, especially for small plant sizes.

Although theoretically it appears that SWRO uses less energy than MSF to produce an equivalent amount of water, the subject is not that simple. SWRO uses rotating energy (usually a motor powered by electricity) to increase the pressure of the feed water to a point (between 54 to 68 atm (800 to 1,000 psi)) where it can effectively be desalinated by the membrane. Distillation with the popular MSF process requires thermal energy to increase the temperature and heat content of the feed water so that it will boil and produce vapour that can be condensed into fresh water.

If those energies are reduced to common terms such as kilowatt-hours, the energy requirement for SWRO will be about 9 kWh/m^3 (34 kWh/1.000 gal) and 63 kWh/m^3 (240 kWh/1,000 gal) for an efficient MSF plant. However, despite the apparent energy advantage of SWRO of about 800 per cent, the energies are not equivalent in cost. Thermal energy, especially low-temperature extraction steam from a turbine, can be considerably less expensive than electrical energy. If the selection of a sea-water desalination process is heavily dependent on the exact energy cost of each process, then this should be estimated by an expert in the field, as it is a complex matter.

If fuel consumption is to be minimized, as in fuel-importing countries, the purchaser may consider either a distillation plant with a high performance ratio or an RO plant with energy recovery. Initial capital costs would of course be higher, but operating costs would be lower. Where domestic fuel is available at a low cost or in the case of a dual purpose plant, the plant can be designed for lower thermodynamic efficiency, thus saving on capital costs, and particularly on foreign exchange.

4. Dual purpose versus single purpose plants

In many locations where there is an increasing requirement for water, there also exists a rising demand for electricity. In such circumstances, it may well be beneficial to combine the production of both products in a dual purpose plant. Most electric power plants, burning fossil fuels, utilize steam boilers and turbines to generate electricity. For example, fuel oil may be burned at 1,000° C (2,012° F) to generate steam at 540° C (1,004° F). The steam is then expanded through a turbine that drives an electric generator. When the energy has been expended and the temperature of the steam has dropped to about 50° C (122° F), it is rejected as waste in the power houses equipped with conventional condensing steam turbines. The condensed steam is then returned to the boilers as water for reheating. This low-grade heat, which is otherwise rejected in the cooling system, can be used as a thermal energy source in distillation systems. Steam turbines are built with extraction points so that steam at any desired temperature can be extracted from the side of the turbine. Once the turbine is built, those points cannot be easily changed. Thus, steam can be used twice, once to turn the turbine (to generate electricity) and a second time to raise the temperature of sea water to permit distillation. Normally, steam must be extracted for use above the condensation temperature. When this occurs, some energy that would otherwise be used in the turbine is lost. Often the value of this lost energy is the value placed on the steam used for the distillation unit. Facilities that use their steam for more than one purpose are referred to as dual purpose plants. A schematic of a dual purpose plant is shown in figure IV.

The one overriding advantage of the dual purpose plant is that it drastically reduces the consumption of fuel compared to two separate plants generating two different products. Where extraction steam from a power plant is used in a desalination plant, the cost of steam is 60 to 80 per cent less than for a water-only plant (Cox, 1979). Studies have shown that savings can add up to 25 per cent when the overall costs of a dual purpose plant are compared to those arising from a desalination plant and a power station operated separately on the same site under the same conditions and producing the same amount of electricity and water (Kuenstle and Janisch, 1979). Savings on both investment and operating costs can be obtained from the joint use of common facilities, labour and plant administration.

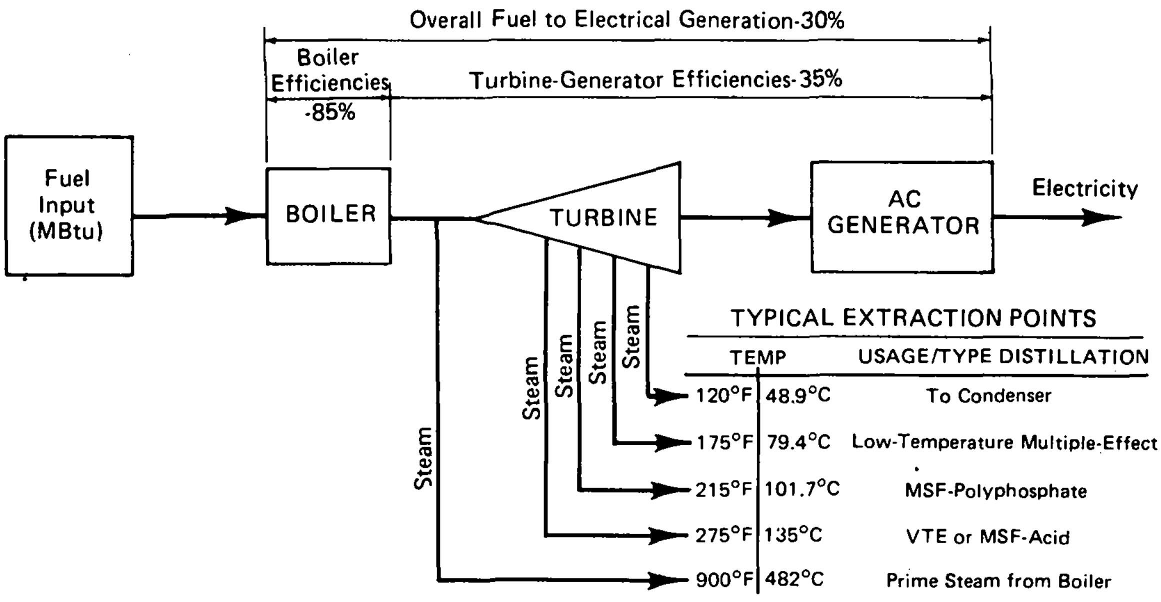

Figure IV. Schematic of a dual purpose plant

Source: This figure courtesy of the United States Agency for International Development. From O.K. Buros and others, The USAID Desalination Manual (Washington, D.C., prepared for USAID by CH2M Hill International Corporation, 1980).

Dual plants most often combine an electric power station with a multi-stage flash distillation plant. These have found widespread application in the Middle East and North Africa.

It is essential that before a dual purpose plant is installed, the separate demand characteristics for both electricity and water be examined with a view to assessing their suitability for inclusion in a combined system. Once a dual purpose system has been designed and installed, the proportions of water and electricity output are substantially fixed, and changes in either can only be achieved at additional expense. The principal disadvantage of dual purpose plants is that the plants become interdependent. If the power plant does not operate, there is no steam for the desalting plant. If the desalting plant does not operate, there is no condenser for the steam. To keep both plans operating regardless of what happens to one or the other, it is therefore necessary to install auxiliary or stand-by equipment. It is also good practice to increase reliability by installing multiple units rather than one single large unit.

The location of a dual purpose plant may be greatly influenced by the site selected for desalination; this may not necessarily be the most suitable for electricity production. In those circumstances, costs may arise due to the provision of additional facilities for the transmission of electricity from the dual purpose plant site which would not have arisen had the electricity-generating plant been located according to power station criteria. Again, a survey of current and future demand for water and electricity should help in choosing the optimum location.

In assessing the economics of a dual purpose plant, the main difficulty is allocating various joint costs between water and electricity. Often the decision is arbitrary; this may greatly affect the respective costs of the two products and distort comparisons. One approach to this problem is to assume that one product (that is, electricity) is the primary output of the installation and that the other product (that is, water) is a by-product. In this extreme case, an assigned value would be given to the electricity, determined by the estimated production costs of the cheapest alternative means of producing the same amount of electricity. The cost of producing the water would then be the total annual plant production costs less the assigned annual value of the electricity (United Nations, 1965).

A procedure formerly used by the Office of Saline Water for their cost studies was much more complicated. The OSW method required that two separate, complete plants be designed and costs assigned to each. Then the two plants were combined into a dual purpose plant and the costs for jointly used components (such as sea-water intake and discharge, control rooms, piping and instrumentation systems, and operating and maintenance labour) were distributed as a function of their separate costs.

Another method of joint cost allocation is pro-rating the cost on a thermal basis, in which total annual costs are allocated to power and water on the basis of the percentage of thermal energy used by each. This or a similar method should at least be used to assign a fair value to the steam used by the desalination plant, in order to make comparisons with alternative types of plants. The steam, which is extracted at a reduced pressure for use by the desalination plant, has already performed considerable work. One way to value it is according to the work it can still perform, based on its heat content. The higher the temperature of the extraction steam, the more it costs. This method is illustrated in table 11.

Table 11. A method to calculate dual purpose steam costs a/

1		2	3		4
Extraction steam temperature		Steam enthalpy	Usable work above condensing temperature		Extracted steam value as percentage of steam cost
(° F)	(° C)	Btu/lb	Amount Btu/lb	Percentage of total	
900	482	1 448	516	100.0	100.0
275	135	1 133	201	39.0	39.0
215	101.7	1 057	125	24.2	24.2
175	79.4	1 020	88	17.1	17.1
120	48.9	932	0	0	0

Source: R. B. Cox, "Energy costs of various desalting processes", Pure Water, vol. 8, No. 4 (Englewood, New Jersey, 1979).

a/ This table shows a typical calculation of extraction steam cost based on the usable work (enthalpy) available. Other methods can and are being used to assign costs of extracted or back-pressure steam in a dual purpose plant.

However, higher temperatures allow the distillation plants either to reduce capital costs or to produce more water. The optimum extraction temperature is, therefore, an economic compromise between an increased cost for the extraction steam coupled with either a reduced cost for the desalination plant or an increased output. When steam is extracted from the power plant, there is some sacrifice in the quantity of power that can be produced per unit of fuel. However, this is still far less than the 200 per cent required for two separate plants.

It must be remembered that the turbine extraction must be designed for the temperature used by the desalination plant. This is an especially important consideration when installing a new desalination plant that will use steam from an existing electricity-generating plant. Steam is generally valued at the saturation temperature (at a given pressure) at which it is extracted from the turbine, and not the temperature at which it is used by the desalination plant (Cox, 1979).

Other methods of costing could be based on: pro-rating on the basis of the ratio of power generated before exhausting steam to the water plant to the additional power that could have been generated without the water plant; and pro-rating costs on a revenue basis, when rates for both water and power are pre-determined. This method raises difficulties, however, where there is an established structure of power or water rates which bear little relationship to production costs.

5. Special considerations in developing countries

(a) Sources of finance and foreign exchange

The financing of a desalination project in a developing country is sometimes split between two agencies or organizations where one, such as a foreign assistance agency or a development bank, contributes to the purchase of the unit and the recipient government agency has to fund its operation. In such cases, the purchaser must assess realistically the future financial support of the donor for up-keep of the facility before finally selecting the type of process and capacity of the unit. Moreover, repayment of loans to development banks must of course be costed into annual payment calculations.

An analysis of the local agency that will operate the desalination facility and its proposed operating budget is necessary to estimate the level of technical supervision, spare parts and operating supplies to be allocated in the years to come and to select the plant wisely. Even the agency's philosophy with regard to the stocking of spare parts and its procedures for procuring parts, technical services and/or repairs (which could be time-consuming) should be considered in plant selection and specification.

In developing countries there often arises the problem of availability of foreign exchange. If a foreign assistance agency donates funds for the purchase of the plant, the immediate foreign exchange requirements may be taken care of. However, purchase of spare parts and repair needs will require foreign exchange over the life of the project. It will be possible to control to some extent the relative amounts of foreign and local currency required during both the construction and operating phases of the programme through the choice of plant design and process.

As for covering daily operation expenses, the policy for charging consumers - municipal, industrial and agricultural - should be determined to some extent before construction of the plant and explained to potential customers. In many cases, customers in water-short areas are already paying high prices for unreliable water supplies delivered intermittently. In such situations, they would be willing to pay for a reliable and clean source of water.

(b) Labour and personnel requirements

Labour required by the plant will vary depending on local situations. Depending on wage scales, labour can often amount to up to one third of the annual costs excluding capital recovery. This can be a critical investment of funds for a desalination facility. A good operating staff can often make the poorest plant perform to some degree and a decent plant perform excellently. An incompetent staff can usually destroy or severely damage almost any desalination plant produced. The degree of investment to obtain a good operating staff is a site-specific determination. The added production (or higher plant factor) obtained by using a competent, and often highly paid, staff usually keeps the costs per unit of production reasonable and far more predictable.

Personnel requirements also depend upon the nature of the plant and whether it constitutes an addition to an existing facility or whether it represents a complete replacement or an entirely new installation. Requirements will be considerably less in the case of small incremental growth as compared to a major new installation. In addition, some savings in labour are incurred in the dual purpose plant. This is particularly true of supervision, since the same management will be used for the production of both electricity and water.

Where possible, the technical skill required for the operation and maintenance of a plant should be matched to that available (within the future operating budget) in the locality of the proposed plant site. The presence of local personnel with experience in operating desalination plants is a factor in favour of using desalination where technical experience is scarce.

Frequently, in developing countries skilled labour will not be available to the standards required by the complex modern desalination plants. This problem can be alleviated through the establishment of training programmes during the construction and start-up periods. Operating and maintenance personnel can be selected ahead of time and sent to existing plants for training and thus be available when the new plant goes into operation.

More skilled personnel are required for maintenance than for operation. Maintenance personnel must be capable of repairing and replacing the individual items of equipment and instrumentation. Experience with boilers, steel work, steam and welding is useful in conjunction with distillation plants, whereas the membrane processes usually require skills with plumbing, pumps and electric motors. Operating personnel need a more limited training dealing with the specific problems of plant performance.

Proper training of operating personnel is a necessity, and training will need to be repeated in the future as personnel are replaced or need additional training in specific skills. A long-term training programme should be planned and included in any acquisition of new equipment.

When the plant represents a small incremental expansion or is part of a dual-purpose plant, there will be savings in both supervision and maintenance personnel requirements. If the plant is part of a large existing facility, no additional supervisory people may be needed. Also if instrument technicians, pipe fitters, painters and so forth are already part of the maintenance staff, the incremental plant may only require the addition of one person to the total maintenance staff. On the other hand, if the same plant is to stand alone as a new or single unit, it will be necessary to have a manager and several maintenance people in addition to the operating staff.

Unskilled labour versus automation

There are a number of cases in which it would be desirable to balance the degree of plant automation against the availability of skilled and unskilled labour. This is particularly true when many delicate control instruments that need frequent maintenance and calibration can be replaced by simpler devices operated and read by relatively unskilled personnel. Automation ordinarily requires considerable capital and permits labour requirements to be reduced to a minimum. This is particularly attractive in areas where capital is readily available at low interest rates and where labour is relatively expensive.

Relatively small savings in capital cost can be accomplished through the replacement of some of the automatic equipment with manual control. In any case, not all of the automatic devices can be replaced without serious threat to plant efficiency. In each specific instance a study should be made to determine the best combination of manual and automatic control for a given job.

(c) Operating materials, spare parts and power

The availability, quality and cost of power and materials necessary for operation of a desalination facility are also important considerations. These must be determined on a site-specific basis to evaluate the status of power, chemicals, spare parts and outside technical expertise for future operations. Site location, transportation facilities, taxes, customs duties and handling, climate and local demand all affect the cost and availability of fuel, chemicals and spare parts.

In developing countries where it may require many weeks or months to obtain replacement parts, it will be advantageous to make a detailed study of the desalination process to determine what spare and replacement parts ought to be kept on hand. The adequate provision of those materials can result in considerable savings in costs and minimize plant down time. This item should also be included within the specifications of the plant.

For some processes chemicals can constitute a significant operating expenditure. More importantly, they are used continuously and hence are noticed since they are constantly being purchased. There can be a considerable variation in the cost and availability of chemicals in any area. Potential delays in transportation would require appropriate storage facilities to keep a sufficient stock available so as to permit continued operation. The overall availability of chemicals can be a factor in process selection. One of the advantages of the electrodialysis reversal process is its minimal use of chemicals, which can be extremely important in reducing costs or transportation problems in many isolated areas.

For membrane processes, it is important to know the normal time interval for membrane replacement. Three years has been commonly used as the life of reverse osmosis membranes. Some manufacturers have extended this up to five years for brackish water applications. Which time estimate is used will have a significant effect on the cost allocated to this category. The assumption should be clearly stated and should correspond to the membrane life that the manufacturer guarantees. For electrodialysis membranes it averages about 5 to 10 years.

The need for locally available components is not confined to the specialized desalination equipment, but also covers fuses, bolts, screws, bearings, pumps, electrical systems and tools. Problems can arise with something as basic as metric or English parts, threads or tools being used where the other system is usually found. If basic parts and tools are not available locally, either large inventories must be financed or long down times can be anticipated while even the most common parts are procured.

The source of energy is important as well. In some areas, they may be considerable merit in building a dual purpose (electricity and water) plant as part of a national or local development programme. In other areas, waste heat may be available for a low-temperature distillation process. Where existing steam and/or electrical power is to be used, its type, cost, adequacy and reliability should be determined. For larger facilities that are to produce water only, there are some interesting dual purpose combinations that could be considered. An example of this for sea-water desalination might involve using a high-temperature boiler to produce steam. The steam could operate a turbine which directly runs a reverse osmosis unit while the turbine's back-pressure or extraction steam is used to operate a multiple-effect plant. A variety of those types of combinations is now being explored.

(d) Transport

The additional investment required for the transportation of equipment from the country of origin to the plant site should not be overlooked when assessing plant costs.

Movement of equipment for construction and maintenance replacement can pose a problem in areas that do not have adequate transportation facilities. By planning ahead and scheduling deliveries, it is possible to overcome or anticipate difficulties that may arise as a result of transportation problems. Before construction, a detailed critical scheduling should be arranged at an early date so that orders and contracts are let and monies committed in such a fashion as to provide for the smooth operation of the construction crew and facilities. This scheduling should be part of the specifications of the plant.

In some instances it may be necessary to build transport facilities such as docks and highways. This could result in substantial increases in capital costs, especially for a developing nation. It will also be necessary to provide fuel transport facilities for the operating plant.

6. Cost evaluation

In evaluating costs formulated by others, a good general approach is to take the stated costs and break them down into the components shown on the worksheet below, based on assumptions for each component such as plant life, plant factor, capital recovery, labour and energy. Components that are missing or not specified should be identified. The breakdown should be compared to those for equivalent equipment from information obtained from data available from other sources, such as the study by Reed (1982). Items that are at obvious cost variance with those established by previous studies or by basic common sense should be carefully investigated. Certain variances may be justified, but the use of data comparison allows potential problems to be spotted and encourages investigation of the basic cost assumptions.

Some of the data presented in literature on operations and/or projections of costs are given as costs only, without the basic assumptions clearly stated. It is important to ascertain those assumptions, since they can affect the costs and possibly the conclusions.

There are two major cost components to be computed and considered: capital costs and annual costs.

(a) Capital costs

The elements that usually make up the capital costs of a desalination facility are divided into direct, indirect and non-depreciable capital costs.

(i) Direct capital costs

These are the costs of equipment and/or construction services and for desalination facilities. They generally include:

(a) Installed desalination equipment, including piping, electrical equipment, drains etc.;

(b) Site development - buildings, roads, fences, grading etc.;

(c) Development of the raw water source and its conveyance to the facility;

(d) The equipment and/or structures associated with brine disposal;

(e) Development of the power source and/or power conveyance to the site.

(ii) Indirect capital costs

These are capital costs that do not involve the purchase of equipment or construction services. They include:

(a) Interest costs incurred during construction start-up;

(b) Contingencies;

(c) Architect/engineer study design, construction project management and other fees.

(iii) Non-depreciable costs

These expenditures must be made to begin the project and/or operation but the materials purchased remain (or are replaced) during the project's life so that they are on hand at the end of the project. These costs include:

(a) Working capital, which includes on-hand fuel, chemicals, materials, other supplies and operating capital;

(b) Land costs.

(iv) Evaluation of capital costs

In evaluating or estimating capital costs, the two major items of concern, apart from the basic equipment costs, are: (a) realistic definition of the assumptions for interest charges, contingencies and working capital; and (b) inclusion of all the needed major capital development costs. The latter could include special source development, brine disposal and special site work.

Capital costs for dual purpose (electricity and water) plants must be developed carefully so as to allocate capital costs fairly between the two components. Care needs to be exercised in interpreting or evaluating the cost of the desalination portion of already built (or priced) dual purpose facility. One method used to estimate the capital cost of the desalination facility (in dual purpose plants) is to select a unit cost for the generating portion (MW of installed capacity) and to use this cost to arrive at the capital cost of the desalination facility by subtraction.

Obviously, the assumed unit cost for the generating facilities can greatly affect the desalination cost. If the unit power cost is high, the desalination cost is low; if it is low, the desalination unit cost is high. In such situations, it is prudent to investigate the premise on which unit costs are calculated.

(b) Annual costs

The elements that usually make up the theoretical annual operating costs are: recurring costs, operating expenditures and expendables and the fixed charge to cover capital depreciation. Those costs are combined with the annual plant factor to compute the annual unit operating cost in terms such as dollars per m^3 or per 1,000 gal.

(i) Recurring costs

These include costs such as insurance and taxes which continue year after year. In comparing processes for future installation, the recurring costs are often not considered since they often are equivelent for all of the options.

(ii) Operating costs

Almost all of these costs occur steadily during the operation of the plant. They include: labour (both salaries and administrative costs), supplies and maintenance materials, energy, special repairs, chemicals and filters, and membrane replacement.

Each of these components has been discussed separately above. Labour and energy costs are particularly site-specific and will account for a major portion of the operating costs. Assistance in estimating the necessary number of staff and appropriate salaries and the costs of energy might be needed from professionals familiar with similar plants operating under similar conditions and cultures.

(iii) Capital recovery

Standard tables and programmes for calculators are available for computing capital recovery. An interest rate must be set and a plant life estimated. A period of 20 years seems to be a realistic plant life for well designed and constructed desalination facilities. For poorly designed and/or constructed plants, 5 to 10 years might be more realistic.

(iv) Summary

The major cost items are capital recovery, energy, labour, and membrane replacement (for the membrane processes). The evaluation or estimation of those items should be performed carefully since they have a major impact on the annual costs. The assumptions behind those values should be clearly understood and stated.

(c) Unit production costs

(i) General

Unit production costs translate all the above cost elements into a cost per unit of production such as $\$/m^3$ or \$/1,000 gal. Such a parameter is useful in performing cost comparisons and enabling people to understand project costs. Apart from the capital and operating costs enumerated above, the most important item in the calculation is the plant factor.

(ii) Plant factor

The determination of the plant factor should play an important role in both the economics of a desalination facility and in the selection of an appropriate process.

$$\text{Plant factor} = \frac{\text{Actual production}}{\text{Rated (design) production}}$$

The plant factor is often considered on an annual basis. If during a year a facility is producing water continuously at the design capacity, it would have a plant factor of 1, or 100 per cent. If it either did not produce at the design capacity or was shut down for some reason (such as general cleaning or repairs), the factor would fall accordingly.

Investigators and manufacturers often use plant factors in the range of 0.80 to 0.95 in making cost estimates. A 0.9 plant factor means that a plant producing at its design capacity would be shut down for about 36 days a year (or 10 per cent of the time). At plant factor of 0.95, the shut-down would be for only 18 days (or 5 per cent of the time). Many plants can maintain this type of performance, but other cannot. A major distillation complex in the Caribbean reported an average annual plant factor of about 0.30 over the three-year period 1977 to 1979. This, of course, would have a profound effect on its overall economics of operation if the original predictions were based on a 0.85 or 0.90 plant factor.

The plant factor is used to determine the annual unit production cost (such as $/1,000 gal or $/m^3) for water in the following manner:

$$\text{Unit water cost (\$/unit)} = \frac{\text{Annual recurring costs + annual fixed charges}}{\text{Design capacity (units/day)} \times \text{365 days} \times \text{plant factor}}$$

It is this cost that is usually used to select a process or design. Since the plant factor affects this cost directly, the assumptions behind its selection are extremely important.

Apart from the overall, generally predictable, technical reasons for plant shut-down for cleaning, inspection and schedule maintenance, there are site-specific conditions that can greatly affect the plant factors. Familiarity with those local conditions is required to generate realistic predictions and to ascertain how they will affect plant operation, maintenance and performance.

Innumerable factors can affect the actual operation of the plant and the plant factor to one degree or another: local residents; their desire and support for the project; climate; labour conditions; the degree of operator training; technological capacity; economic conditions; transportation systems; availability of power, chemicals, spare parts, service, and tools; past experience; and the degree of planning systems integration carried out. A lack of consideration of these items will only change the economic evaluation and selection, it will not prevent them from ultimately affecting the project. As these factors are integrated into the economic evaluation, the theoretical cost figures will approach the actual number.

Unfortunately, this process requires that subjective information be translated into an objective number. This process can be open to question and criticism, especially by those whose interest may be affected.

Whatever the plant factor, its accurate prediction will play a major role in arriving at a final selection. It is one of the key factors in an economic evaluation. Its selection should be carefully justified and thoroughly documented, as any change in the plant factor can have a significant effect on the unit production cost.

7. Process selection

The actual selection of a desalination process, its production capacity and variations in its design should be undertaken with the help of a qualified consultant or other qualified assistance. It would also be useful for a potential purchaser to look through the USAID Desalination Manual (Buros and others, 1980), especially table D-1, "Summary of guidelines for desalting process selection". Moreover, the Saline Water Conversion Corporation of Saudi Arabia has devised a method for choosing among alternatives based on the country's requirements, including projected power and water demands. The attributes considered in the Corporation's multi-objective decision analysis include reliability, operability, maintainability, manpower requirements and utilization of natural resources. Thus, government decisions can be made on the basis of objective criteria, rather than only on salesmanship or cost estimates. The methods for estimating costs and conclusions are outlined in the article by Adil A. Bushnak and others (1979). Discussions with manufacturers' representatives can be helpful, but it should be realized that they may tend to recommend a process which they can furnish.

It is generally accepted that the following process applications are currently viable in most cases:

Sea water: Distillation and reverse osmosis;

Brackish water: Electrodialysis and reverse osmosis.

This may change for some cases involving difficult feed waters, problems in brine disposal or other special local conditions. If the freezing process ever becomes commercially available, it will normally be used for sea-water applications.

Economics always plays an important part in the ultimate process selection. In economic optimization between capital and operating costs, changes in interest rates (for capital recovery) and energy costs (for operating expenditures) will affect the ultimate choice. As fuel costs increase, the optimal solution, all other things being equal, tends towards a higher efficiency design.

When setting the capital recovery interest rate, a higher interest rate will (if fuel prices stabilize) optimize the selection at a lower energy efficiency or performance factor. As noted by the developer of the multi-stage flash process, Robert Silver (1979), the rise in both interest and energy costs has tended to keep the optimum performance factors of distillation plants about the same over the past few years. Wherever the optimal solution occurs, it is important to keep in mind how it is derived so that when assumptions such as those regarding interest rates or energy costs are made, the consequences are understood in advance.

Another aid to process selection and evaluation is contained in the desalination project information form and cost summary sheet at the end of this chapter. Those forms include a series of questions on conditions, assumptions and data which are useful in approaching a project and determining whether sufficient data (with reasonable assumptions) exist in order to reach a conclusion. They should be used in project reviews and in making cost estimates of various processes as part of process selection and evaluation. By completing the information for several processes (such as electrodialysis and reverse osmosis for a brackish water application), an estimate of relative costs can be obtained. This can furnish much of the initial objective input into the selection of the process.

The selection and operation of desalination facilities in developing countries requires consideration of many additional factors that are essentially subjective in nature. They concern past experience, available technological expertise, availability of materials, cultural characteristics and special local conditions. There are two ways to handle those considerations within the scope of an economic optimization of a solution. The first is to use a normal cost analysis and then to list the subjective conditions as a form of back-up for the selection recommended (which may not appear to be the lowest-cost solution). The other method is to translate those subjective considerations into a reasonable plant factor to be used in the optimization process. There is little experience in doing this, but it can be important as it will require some thought on ways and means by which local conditions might logically (or illogically) affect the continued operation of a desalination facility in that area.

Unfortunately, without special consideration of those characteristics or situations of local significance, an economic analysis could lead to the selection of a process that might look good on paper, but be less than satisfactory in long-term operation. Thus, theoretically the most energy-efficient process may contain components or require operating and maintenance procedures that create difficulties in a particular local environment and result in excessive down time, unexpectedly low plant factors, high unit production costs, and possibly a non-functioning plant. This can be particularly problematic when introducing a process or design which has minimal realistic commercial operating experience. Without data (except those under controlled or theoretical conditions), it is difficult to assess accurately the long-term plant factor. This then introduces a degree of risk or uncertainty which must be factored into the selection process.

In addition, there must be an evaluation of the future financial, manpower and facilities support that a desalination project will have once installed. Some of the financial risk associated with any of the uncertainties discussed above can be offset by requiring long-term performance guarantees and/or placing the plant under contract operation and/or management. The latter is a common practice in many areas of the Middle East, especially in isolated areas.

Generally, manufacturers are very reluctant to grant long-term overall guarantees on a facility unless they operate it. If they do not operate the facility, the guarantee is apt to have conditions and/or penalties that can negate much of its meaning. It is wise to examine and evaluate carefully any agreement concerning guarantees.

Procurement

Although desalination equipment can be purchased and installed through direct negotiations with the various vendors, it is usually good practice to utilize a qualified consultant or other independent agency to assist the owner in the transaction. The consultant can aid the owner in process evaluation and selection and then draw up appropriate specifications and bid documents.

The specifications and bid documents should be used to reduce the uncertainties associated with the future costs (and plant factor) of the desalination unit. This could include specifying the process, standards, materials of construction, performance, spare parts, guarantees and construction schedule.

Evaluations of the bids, especially where exceptions are taken and alternatives priced out, form an important part of the procurement process. The specifications should be written with sufficient care that the low bid is actually a good long-term investment and not a potential disaster. An ever-present danger in the bidding process, especially on large projects, is a bid that is too low to cover the actual reasonable costs of the contractor. This is generally no bargain, because all parties are likely to suffer in this type of situation.

Desalination cost summary sheet and project information form.

Location ______ Capacity ______ mgd [m³/d]
Type of Plant ______ Plant Life ______ Years Plant Factor ______
Source of Feedwater ______ TDS Level ______
Recovery or Performance Factor ______
Energy Source(s): Fuel (______ type)/Electricity/Steam (Circle Sources)

CAPITAL COSTS

DIRECT CAPITAL COSTS

1.	Feedwater Supply Development	$______
2.	Feedwater Treatment	$______
3.	Desalination Equipment	$______
4.	Site Development	$______
5.	Energy Source Development	$______
6.	Electrical Equipment (switchgear)	$______
7.	Brine Disposal	$______
8.	Product Water Storage and Treatment	$______
9.	Other	$______
	SUBTOTAL DIRECT CAPITAL COSTS (1-9)	$ ______ (A)

INDIRECT CAPITAL COSTS

10.	Interest During Construction	$______
11.	A/E, Project Management Fees	$______
12.	Contingencies	$______
13.	Startup Costs	$______
14.	Other	$______
	SUBTOTAL INDIRECT CAPITAL COSTS (10-14)	$ ______ (B)

TOTAL DEPRECIABLE CAPITAL COSTS (A + B) → $ ______ (C)

OTHER CAPITAL COSTS (NON-DEPRECIABLE)

15.	Land ______ acres [m²]	$______
16.	Working Capital	$______

TOTAL OF OTHER CAPITAL COSTS (15-16) → $ ______ (D)

TOTAL OF ALL CAPITAL COSTS (C + D) → $ ______

UNIT CAPITAL COST ($/GPD [m³/d] INSTALLED CAPACITY) → $ ______ /gpd [m³/d]

ANNUAL COSTS

Recurring Costs

17.	Taxes	$______
18.	Insurance	$______
19.	Other	$______

TOTAL ANNUAL RECURRING COSTS (17-19) → $ ______ (E)

OPERATION & MAINTENANCE (O&M) COSTS

20.	Labor–Salaries	$______
21.	Labor–General & Administrative Overhead (______%)	$______
22.	Chemicals	$______
23.	*Supplies and Maintenance Materials*	$______
24.	Membrane Replacement (______yr Life)	$______
25.	Special Repairs or Overhauls	$______
26.	Energy–Fuel/Steam (Circle one) cost/unit ______	$______
27.	Energy–Electricity ______ $/kWhr	$______
28.	Other	$______

TOTAL ANNUAL O&M COSTS (20-28) → $ ______ (F)

ANNUAL FIXED CHARGE

______% Interest & ______yr Plant Life   Capital Recovery Factor (CRF) ______

($______ (Depreciable Capital) (C) × ______ (CRF)) + (______ (Nondepreciable) (D) × ______ (CRF))* → $ ______ (G)

TOTAL ANNUAL COSTS (E + F + G) → $ ______ (H)

***** *In many analysis the capital recovery is not computed for nondepreciable capital (D).*

UNIT PRODUCTION COSTS

Annual Production ______ kgal [m³] ☐ Design ☐ Actual

Operating Units

UNIT COST = Total Annual Cost (H) / Actual Annual Production = ______ → $ ______ /kgal [m³]

For Estimating Costs

UNIT COST = Total Annual Cost (H) / Annual Design Capacity x Plant Factor = ______ → $ ______ /kgal [m³]

Cost Estimator ______ Date ______ Project ______

Attach the Desalination Project Information Sheets

Source: O.K. Buros and others, The USAID Desalination Manual (Washington, D.C., United States Agency for International Development, 1980).

1. Location ______________ Design Capacity ______ mgd [m /d]
2. Type of Plant ______________ Est. Plant Life ______ yrs
3. Source of Feedwater ______________
4. Feedwater Characteristics—Is a Complete Analysis Available? ☐ Yes ☐ No
   TDS ______ mg/l max ______ mg/l min
   Temperature ______ max ______ min
   Source of Feedwater Data ______________
   How many of the feedwater analyses have been performed? ______ When? ______
   Where? ______________
   How reliable is this feedwater data? ______________
   What feed and/or cooling water temperature was used for plant design? ______
5. Description of Plant ______________
   ____
6. Recovery Factor ______________ (Membrane Plants)
7. Performance Factor ______________ (Distillation Plants)
8. How many plants of this design and equivalent capacity have been built previously? ______
   Where? ______________
9. Are any plants of this design and capacity operating under similar conditions? ☐ Yes ☐ No
   Where? ______ Any in the Same Country or Region? ______
   With what results? ______________
   ____
10. Who will operate this plant? ______________
11. What is the expected level of technical expertise of those who will operate the plant? ______
    ____
12. What experience have they in operating desalination or similar equipment? ______
    ____
13. Will there be an adequate budget available for operation and maintenance of the plant throughout the project? ______________
    ______________ Is a training program planned? ______
14. What is the design plant factor? ______________
    Based on local conditions of funding, technology, climate, support facilities, etc., is this a realistic plant factor? ☐ Yes ☐ No Explain ______________
    ____
    If not, what would be? ______________
    ____
15. Will there be a problem disposing of the concentrated brine discharge from the plant? ☐ Yes ☐ No
    How will it be disposed? ______________
16. What permits, licenses, ordinances, financing, etc., need to be obtained or passed before the desalination facility can be procured and operated? ______________
    ____
    ____

PROJECT DESCRIPTION ______________________ Page 2

17. What is the estimated construction period? ______________________ months
When will design begin? ______________ Bids be requested? ______________
Contract be awarded? ______________ Construction Begin? ______________
______________ Plant begin operation? ______________

CAPITAL COSTS

DIRECT CAPITAL COSTS

18.

Type	Description	Source of Cost Estimate	Cost	Cost Index		Est. Indexed Cost
				Time	Locality	
Feedwater Supply Development						
Special Feedwater Treatment						
Desalting Equipment						
Site Development						
Energy Source						
Electrical Equipment (Switchgear)						
Brine Disposal						
Product Storage and Treatment						
Other						

19. The cost index(es) used: ______________________
A local cost index factor for the area under study must be determined and must include transportation factors. This local index is ______________________

INDIRECT CAPITAL COSTS

20. Interest during construction: ________%. Basis for calculation is: ______________
______________________ Interest is: $__________

21. A/E and project management fees: ________% and/or basis for calculation is: ______________
______________________ Fee is: $__________

22. Contingencies: ________% and/or basis for calculation is: ______________
______________________ Contingency is: $__________

23. Startup costs: ____________ Basis for calculation is: ______________________

OTHER CAPITAL COSTS

24. Land area needed: ______________ Unit cost of land: ________ Total cost: ________
Basis for unit cost of land: ______________________________

25. Working capital: __________ Basis for cost is: ______________________________

ANNUAL FIXED CHARGE

26. Has this been included? ☐ Yes ☐ No Rate of interest: ________% Time Period ________ yrs
Capital recovery factor: ______________ If no charge is to be made, why? ________
____

O&M COSTS

LABOR

27. How many hours per day will the unit run? ______________________

28. How many hours per day will the unit be attended? ______________________

29. The anticipated staff is:

Job Description	No. of Positions	Annual Salary	Annual Cost
Administrator/Superintendent			
Process or Plant Engineer			
Mechanic—General			
Mechanic—Electrical			
Mechanic—Instruments			
Chemists			
Laborers			
Driver/Guard			
Secretary/Clerk			
Shift Supervisor			
Shift Operator			
TOTAL ANNUAL COST			

If there is no idea of the staff required nor the salary levels, then use a general estimated of overall labor costs. This estimate is $________ and ☐ Does ☐ Does Not include G&A.

30. What level of general and administrative (G&A) overhead is to be used? ______________%
The basis for this percentage is: ______________________________
The annual G&A cost is: $__________

CHEMICALS, SUPPLIES, AND MAINTENANCE MATERIALS

31.

Chemicals and Filters Description	Annual Quantity Needed	Local Unit Cost	Total Cost

32. Are there anticipated difficulities in purchasing, delivering, storing, and/or handling these materials during the life of the project? ☐ Yes ☐ No Details: ______________________

33. Cost of supplies and maintenance materials $__________ Basis ______________________

MEMBRANE REPLACEMENT

34. What type or configuration of membranes ______________________

35. Will spares be kept on hand? ☐ Yes ☐ No If yes, how many? __________
What membrane life is being used? __________ years. For RO membranes, what is the guaranteed productivity at the end of that period versus at startup? __________

Annual replacement cost $__________ Basis ______________________

SPECIAL REPAIRS

36. Will any major repairs or equipment replacement going to be required during the life of the project?
☐ Yes ☐ No Describe: ______________________

Estimated annual cost $__________ Basis ______________________

ENERGY

37. Source(s) ______________________

38. Dual- or single-purpose plant ______________________

39. Cost of Electricity __________/kWh; Electric usage __________kWh/kgal [kWh/m^3]

40. Does the electricity consumption include all pumping into and out of the plant? ☐ Yes ☐ No
If not, how much additional pumping energy will be required? __________kWh/kgal [kWh/m^3]

41. If fuel is required what type? __________ Heating value __________

42. Fuel usage (for diesel- or gas-operated plants) __________ gal fuel/kgal [l/m^3] water

43. Steam (for distillation plants)
Plant performance factor __________ Operating temperature ______°F [°C]
Steam requirement __________ MBtu/kgal [GJ/m^3] or ______/______
Single-purpose steam cost ______/MBtu [GJ] for prime steam @ ______ psig [atm] ______°F [°C]
Dual-purpose steam cost ______/MBtu [GJ] at operating conditions ______ psig [atm] ______°F [°C]

F. Desalination with renewable energy sources

Recently, considerable attention has been directed towards the use of renewable energy sources for desalination, especially in remote areas, because of the high costs of standard fuel, difficulties in obtaining it, attempts to conserve fossil fuels and the lack of power in rural areas. Renewable sources of energy, such as solar and wind power, require no further investment in power once the proper energy collection system is installed.

Apart from the basic solar still, the development of renewable energy sources for desalination is still in its infancy. The need for those sources is recognized by many throughout the world, but their commercial development and large-scale application, especially in developing countries, can be expected to take some time to implement. Most alternative energy sources take a considerable capital investment per unit of power to develop, and their interface with desalination equipment can be complicated.

Currently, practical applications of renewable energy supplies combined with desalination are limited almost entirely to solar stills used in locations around the world. Numerous experiments have been carried out with other types of combinations, but these have been supported by Governments or research institutes and have seldom been commercially competitive with desalination facilities powered by conventional means.

Efforts are being made in Australia, Egypt, France, Greece, Italy, Jordan, Mexico, the United States of America and other countries to work on matching up alternative energy sources to desalination processes, but generally on a very small scale (20 m^3/d or less), because of the high capital costs involved. As will become apparent, renewable energy sources are likely to become competitive with conventional sources first in small-scale applications at remote sites. Those applications, which are of special interest to developing countries, will offer the main scope for renewable energy desalination systems in the next few years.

1. Solar energy

(a) Historical background

Of all the renewable energy sources available, solar energy has received the most attention in connection with desalination. Using solar energy for desalination was mentioned as early as the seventeenth century by the Italian scientist Della Porta.

Various experimenters have mentioned and tried solar distillation for at least the past four centuries (Nebbia and Menozzi, 1966). One of the first successful, well-documented solar stills was built in Chile's northern desert at Las Salinas in about 1872 by Carlos Wilson. It used plate glass, which was then a recent invention, and is a necessity for most modern solar stills. Other stills were built at about that time and in the years that followed. They were used in various arid areas such as Chile, the Sahara and other locales in North Africa. During the Second World War, efforts were increased to produce a solar still that could be utilized on life-rafts for ships and aircraft. Maria Telkes invented a small inflatable plastic unit for that purpose and hundreds of thousands of the units were produced. Her research efforts in this field continued after the war.

Interest in the field increased so that more and more independent research and development were conducted around the world.

In the 1960s, the United States Office of Saline Water undertook an extensive programme to investigate the potential use of solar energy for distillation. A significant part of the OSW programme consisted of construction and field testing at a station operated by Battelle Institute near Daytona Beach, Florida. Various designs of solar stills included glass-covered basins, inflated-plastic basins, tilted wicks and trays, and all-plastic double tubes. The OSW solar still programme, conducted from 1952 to 1970, produced design data that have been used in numerous solar stills built around the world since 1960 (Eibling, 1980).

The OSW programme was terminated in 1970, when it was concluded that the required reductions in capital costs could not be achieved. Based on this, it was concluded that the high fixed charges associated with the cost of still construction would not be offset by the savings resulting from free solar energy (Mattson and Lundstrom, 1979). Talbert, Eibling and Löf summarized and reviewed efforts in the field of solar distillation in the Office of Saline Water's publication, Manual on Solar Distillation of Saline Water (United States Department of Interior, 1970). This reference text contains information that should be examined by any agency, group or individual contemplating work on solar distillation. Other valuable publications that should be consulted are: Solar Distillation as a Means of Meeting Small-scale Water Demands (United Nations, 1970), the United States Agency for International Development's Fresh Water from the Sun (Dunham, 1978) and Brace Research Institute's Systems for Solar Distillation (Lawand, 1975).

(b) Technical considerations

Solar energy varies during the day and from day to day, and depends on location and atmospheric conditions. Although general averages can be calculated, the exact amount of energy available at any one place at a specific time is dependent on atmospheric conditions. Obviously, owing to the diurnal nature of solar radiation, applications using it must either gauge their operations to the varying energy supply or provide some type of storage to lessen the variations and deliver power for a longer period than that provided by actual sunlight.

(i) Energy converters

A variety of mechanisms are used to convert solar energy directly to other forms of energy - either heat or electricity. Among the commonly employed devices for heat conversion which are commercially available now are flat plate collectors, focusing collectors and solar ponds.

Flat plate collectors are made from flat metal plates that have been blackened to maximize their absorption of solar energy. The temperature of the plates rises as they are exposed to incoming solar energy. The heat generated can be transferred to another location by circulating a fluid (usually water or air) along the plates to pick up the heat energy. Usually, tubes or pipes are fastened to the plates to channel the fluid and provide good heat transfer from the plates to the fluid. Heat loss is controlled by the flat glass (or plastic) window covering the absorber plate and by thermal insulation behind the plate. Flat plate collectors usually operate in the temperature range of 40° to 90°C (104° to 194°F) and are only marginally suitable for desalination applications.

In evacuated tube collectors the finned absorber tubes are contained in evacuated tubes to control heat loss. They reach a temperature of up to 150°C (300°F) and are more suitable for solar distillation than flat plate collectors.

Focusing collector systems can achieve much higher temperatures by concentrating the solar energy at a point focus (parabolic dish mirrors or fresnel lenses) or along a line (trough-type reflectors). It is also possible to build systems consisting of large arrays of mirrors surrounding a central tower with individual mirrors (heliostats) computer controlled to track the sun and focus its energy on an absorbing cavity atop the tower. Focusing collectors operate in direct sunlight and are suitable for desert regions where they might find application for desalination, either as a source of heat and/or electrical energy.

A variety of solar ponds may be used to convert solar energy to usable heat. The most important are non-convecting solar ponds which are usually 1 to 5 metres deep and are stabilized against convective heat loss by means of a salt concentration gradient. The operating range of solar ponds is usually from about 30° to 90°C (86° to 194°F) depending on the location and design of the pond. There has been some research in Israel and elsewhere on using those ponds. The heat output of solar ponds could be used for powering heat engines and/or used with low-temperature distillation units.

Photovoltaic cells convert light (the visible portion of the spectrum) from solar radiation directly into electricity. The conversion involves no moving parts, other energy or special machinery. However, the manufacture of those cells is rather sophisticated and expensive. They have been used since about 1955, at first for space applications. More recently they have found widespread use for powering small devices such as navigation aids, lights and pumps.

The photovoltaic cells produce direct current and are arranged in flat panels or modules and arrays of panels. The modules respond to both diffuse and direct radiation and are normally deployed as stationary units tilted at the latitude angle that will optimize electrical energy production throughout the year. Sun-tracking of concentrating systems has also been demonstrated.

Photovoltaic modules, which were priced at $15/peak watt in 1978, had become available for $6 to $7/watt by late 1983. Current photovoltaic cells are based on monocrystal or polycrystal silicon semiconductor wafers. However, further technical developments, especially based on amorphous silicon thin film solar cells, are expected to reduce module costs to less than $2/watt by the early 1990s, corresponding to total photovoltaic system costs of approximately $4/watt.

For desalination applications, photovoltaic cells could be used to produce electricity to operate motors, controls and instrumentation in distillation and membrane desalination equipment.

Some type of energy storage system is often required, since solar energy is subject to fluctuations owing to atmospheric conditions and its diurnal nature. Two basic systems that are often used are: (a) insulated hot water (or other fluid) or rock bed storage for heat-producing systems and (b) batteries for photovoltaic systems. Other more complex storage systems involving molten salts etc. are also available.

(ii) Solar stills

Solar stills operate on the principle of using solar energy to increase the relative humidity in a confined area and, in effect, distilling the feed water without boiling. The classic still is a form of solar basin in which solar radiation increases the temperature of the water to be desalinated. The resultant water vapour produced is allowed to contact a coller surface, where it condenses (as fresh water) and is then collected for use. This is, of course, the same basic principle as the conversion of sea water to rain water in nature.

There are several factors that affect the performance of a solar still (Rajvanshi, 1979). Among those factors are: solar radiation, depth of brine in the basin, cover material and its shape, ambient temperature, wind velocity and temperature of the condensing surface.

Some of these are related to local conditions, while others are dependent on the physical design of the still. Although most solar stills are similar to the basic one shown in figure V, it seems that the subject has captured many a scientist's fancy and imagination. The result has been the production of a wide variety of designs and pilot plants (often just one-of-a-kind) which have been able to desalinate sea or brackish water.

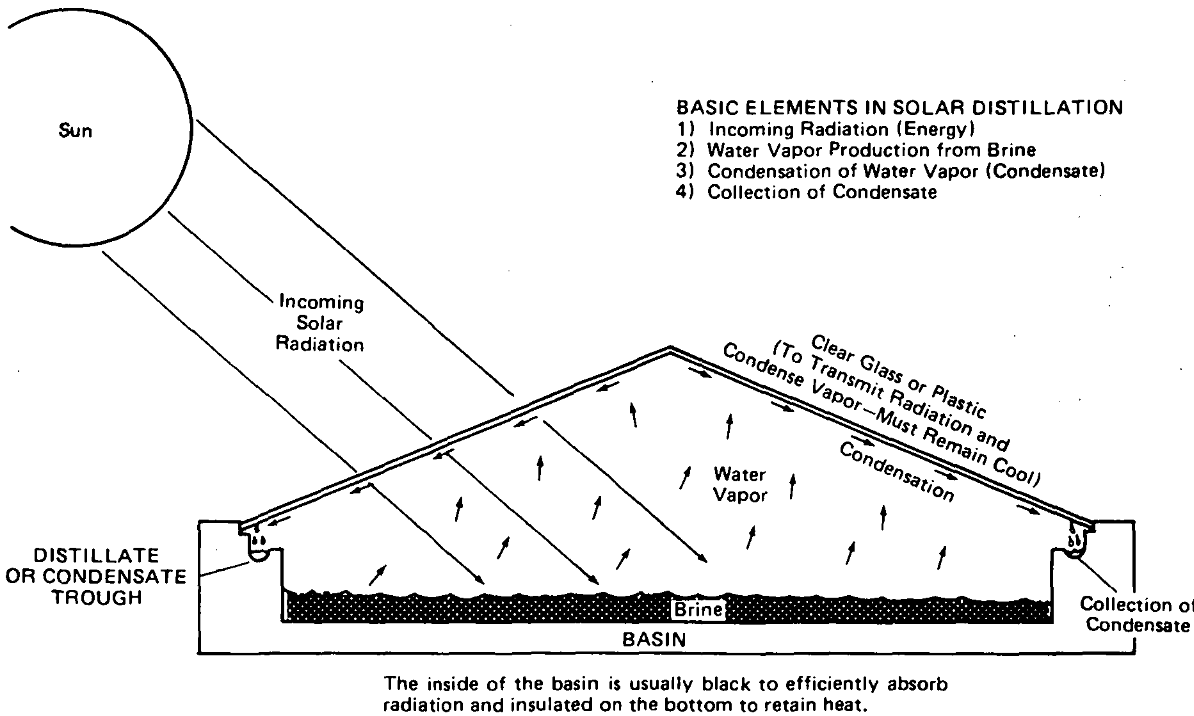

Figure V. Basic elements of a solar still

Source: This figure courtesy of the United States Agency for International Development. From O.K. Buros and others, The USAID Desalination Manual (Washington, D.C., prepared for USAID by CH2M Hill International Corporation, 1980).

A wide variety of construction materials can be used in building the basin, walls, frame, and condensate collector of a solar still, and those portions lend themselves to construction with locally available materials.

The key material is the transparent coverings for the solar stills, which have been made from glass and plastics (both films and rigid or semi-rigid sheets). Glass has proved to be an excellent material but is often very costly and subject to breakage during transport, installation and use. Compared to the other coverings, films are lighter, usually cheaper, and easier to transport but appear to be subject to greater wind and rain damage during use and to degradation in sunlight.

Several types of rigid or semi-rigid plastic sheets have been used as covers for solar stills, primarily on an experimental basis. Depending on their chemical composition and method of manufacture, their characteristics (strength, thermal conductivity, aging) for still applications vary. The advantages of plastic sheets include their light weight, their ability to be formed into self-supporting shapes and (compared to glass) their higher impact strength.

Disadvantages include their low thermal conductivity, high thermal rate of expansion, high transmittance of infra-red radiation, soft surface (scratchability), and high cost or non-availability in developing countries (Dunham, 1978). The use of plastic sheets may indeed be an attractive prospect for certain locations, but it should be approached with caution and field testing.

As a rule of thumb, a well-designed solar still located in an area of good insolation may produce daily about 2 to 4 litres of water per square metre of basin area. This varies with still design, season, location and weather, but is a good average rate. Stills may produce less than 2 litres/m^2, but claims that a still will produce significantly more than this should be regarded with caution. Such production is possible, but it warrants careful investigation and verification - preferably field verification. Tleimat (1978) indicated that the following features seem to lead to high efficiency in stills: low heat capacity, low air content, vapour-tight cover, water-tight basin, and good insulation around the basin.

Given a good basic solar still design, there appear to be two major technical causes of problems in operation: water vapour loss and reduced heat absorption capacity.

Water vapour loss will occur as a result of any leaks in the unit. Although adverse weather can cause the transparent cover to be ripped or broken, a great deal of breakage results from human or animal intervention.

Another serious cause of vapour leakage is improper sealing of the joints between the glass and the frames. Since glass expands and contracts with alternate exposure to heat and cold, it must be sealed with a material that will flex and still remain sealed. Unfortunately, the perfect sealing material, which will hold up under conditions of direct sunlight or heat, has not yet been found. Those materials that do have most of the necessary qualities (such as silicon sealing agents) are very expensive.

The second major operational problem is a reduction in the efficiency of heat absorption by the water to be desalinated in the basin. It is usual practice to coat, paint or otherwise colour the bottom and sides of the basin black to increase heat absorption. However, if the water in the basin is allowed to dry out, or become very concentrated, there is a tendency for the precipitated minerals to form a white coating on the basin's surface. This white coating can severely reduce the absorption of heat.

A related problem is the growth of algae and micro-organisms on the surface of the brine or the basin. It is important that the basin be built so that it can be cleaned and washed and that areas on which salt deposits have formed can be repainted. In some units the glass panels can be removed to permit access for maintenance and cleaning.

(iii) Other desalination processes

The concept of using solar energy for the standard distillation processes (multi-stage flash, multiple-effect etc.) rather than solar stills (actually solar humidification) has been evaluated for a number of years. Most of the discussions, studies and bench-scale experiments have centred around using solar energy as an energy augmentation to those units. That is, solar energy would be used to heat feed water and to reduce overall fuel consumption, but the remainder of the motors, pumps, instruments and controls would be conventionally powered. Some of the many variations of this work are described in United Nations (1970), Howe and Tleimat (1974), Tleimat and Howe (1977), Klaxen and Pieper (1978), Mustacchi and Cena (1978), Gasparini and others (1979) and McCarthy and Leigh (1979).

In recent years there has been an interest in distillation plants that are completely solar powered. Such arrangements would eliminate all need (except perhaps for stand-by facilities) for fossil fuels and/or outside electric power. Installation of such a unit might be appropriate for isolated, high-fuel-cost areas. Many distillation processes are quite sensitive to the mechanics of starting and stopping; hence, field work and testing are necessary to avoid problems in this area.

Electrodialysis is just beginning to be seriously investigated for solar energy applications. The process has the following characteristics which lend themselves to use with solar energy:

(a) The productivity of an electrodialysis cell is proportional to the current flow, and indeed even improves at low current levels. This precisely matches the power characteristics of solar photovoltaics for which current varies (at constant voltage) with the insolation (solar irradiation), thus permitting utilization of the solar power system even at low levels of sunlight, without the need for batteries;

(b) The major energy requirement of electrodialysis is for direct current, which can be obtained directly from photovoltaic cells. Other processes which require alternating current lose 5 to 10 per cent in the conversion systems;

(c) The electrodialysis process is amenable to shut-down and start-up;

(d) Any heating of the feed water by solar energy or other inputs improves the overall efficiency of the membrane stack operation.

Solar-powered reverse osmosis is a relatively new application. Energy must be furnished either as electricity or mechanical shaft power. Where electricity is produced, it can be used to power a standard electric motor to drive the high-pressure pump. Where rotating power is available, it can be used to drive the pumps directly; however, even some electrical energy is usually needed to operate controls, other pumps and instruments.

Owing to the high pressures involved and the potential for membrane fouling by precipitation, reverse osmosis installations do not perform well over the long term if they are continually subjected to start and stop operation, unless they are specially constructed to do so. Thus, a workable system should have provisions to handle interruptions in energy generation. Whether to operate continuously or only during daylight hours is a decision that must be made based upon economics, site requirements etc.

(c) Recent technological advances

A number of prototype solar desalination plants have been constructed and operated on a pilot basis. All have provided useful experience, but are still extremely expensive and unlikely to become commercially viable in developing countries in the near future. Some examples of solar plants using the range of desalination processes are described below.

(i) Multi-stage flash

There has been very little experience with completely solar-operated distillation facilities. However, an important 10 m^3/d pilot plant was installed at the city of La Paz in the arid peninsula of Baja California, Mexico, in 1980. The facility is a joint research effort of Mexico's DIGAASES and the Federal Republic of Germany.

The purpose of the project is to gain field experience with the use of solar energy in conjunction with a multi-stage flash distillation plant. Of special concern is the ability of the unit to operate in a stable condition with a variable energy supply.

The solar section of the facility consists of flat plate collectors (for low temperature) and parabolic concentrators (for high temperature). A heat storage system capable of storing sufficient thermal energy to provide a stable energy source for about 28 hours is provided. The plan is for the distillation unit to operate 24 hours per day.

The flat plate collectors are divided into three groups, one to provide energy for day time operation and two to provide energy storage for night-time operation. Total flat plate collector area is about 520 m^2. The parabolic concentrators will have a total collection surface area of about 158 m^2.

The distillation unit, designed by DIGAASES, is a 10-stage multi-stage flash plant using brine recirculation and has a design performance factor of 130 kWh/m^3 (Manjarrez and Galvan, 1979).

(ii) Multi-effect distillation

Extensive experiments are currently being carried out by Japan's Water Reuse Promotion Centre on a high-efficiency multi-effect solar distillation plant. One distiller unit is made up of 10 cells, and solar energy is collected on the plate of the first cell. Sea water flowing through the wick on the back surface of the collecting plate is distilled. The vapour generated on the surface of the partition plate of the second stage cell is condensed and collected as fresh water. This continues up to the tenth stage.

Twenty-four units of this 2.4 m^3/d pilot plant were installed on Okinawa in 1983 and testing is to run for two years. The heat receiving area of each unit is 100 m^2 and the reported capacity of the unit is 20 to 30 litres/m^2 per day, depending on global solar radiation. Those capacities are about eight times as large as a conventional basin-type solar distiller (Water Desalination Report, 15 December 1983).

(iii) Membrane distillation

The recent development of the membrane distillation process appears to hold promise for solar thermal desalination. Hot brine in contact with a suitable membrane (teflon fabric) evaporates through the membrane and condenses on a second similar membrane cooled by cold brine. Modules are now being tested which are capable of producing 1 m^3/d or more of distilled water from brine heated to 85°C by waste heat, solar thermal collectors or a solar pond. These reportedly can achieve a performance factor of 10 or better by using an energy recovery system. Capital costs of $10,000 per m^3/d capacity with relatively simple and reliable systems (all plastic materials) seem potentially attainable.

(iv) Vapour compression distillation

Water may also be distilled at relatively low temperatures with recovery of the heat of condensation in a heat exchanger. A vapour compressor can be used to raise the pressure and temperature of the condensing vapour above that of the incoming salt water stream.

The process is particularly suited to small systems that can be powered by solar photovoltaics. Temperatures can be as low as 55° C (130° F), and external heat is not required other than that provided by the compressor. Moreover, a minimum of pre-treatment would be required, especially compared to membrane desalination processes. Its low energy requirements, which can be as little as 10 to 12 kWh/m^3, also make it compatible with expensive solar photovoltaics for which the only competitive processes are reverse osmosis and electrodialysis.

The first solar-powered vapour compression unit is now being built by AEG-Telefunken under a co-operative project of the Government of Egypt and the United Nations at Abu Ghosun on the Red Sea coast. It will have a capacity of 2 m^3/d and includes some 8kW of solar photovoltaics. The capital cost of the chosen vapour compression system will be about $75,000/$m^3$/d, of which about half is for the photovoltaic system. Because of limited photovoltaic and battery storage, it will operate only six to eight hours daily. Future systems would have sufficient battery storage to permit 24-hour daily operation. With reasonable reductions in costs of photovoltaic and vapour compression technology, direct capital costs might be reduced to perhaps $25,000/$m^3$/d.

Because vapour compression distillation is less sensitive to feed water quality than membrane processes, it is expected to be more promising for small-scale solar desalination of sea water in remote areas. However, membrane processes would still probably have an economic advantage for brackish water applications, where they benefit from lower energy requirements.

(v) Reverse osmosis

A prototype 60 m^3/d (16,000 gpd) reverse osmosis unit was built at Cadarache, France, and is operated by the French Atomic Energy Centre for Nuclear Studies (CEA). Detailed experiments were conducted to simplify the pre-treatment system so that the complex chemical addition pumps and mixing tanks could be eliminated. In addition, an energy recovery system using a Pelton turbine on the brine stream was incorporated into the design.

The energy to operate the unit comes from flat plate collectors. There are about 223m^2 of collector area in south-facing collectors set at 45° to the horizon. These heat water which either goes to storage or is used to power a heat engine using Freon as the expanding fluid (organic Rankine cycle (ORC) engine). The engine's condenser is cooled by saline well water pumped from the same sources as the feed water.

The unit operated on an experimental basis from 1978 to 1980 using brackish water. However, because of the inherently low efficiency of ORC engines with flat plate collectors, and problems of reliability, the system is not likely to prove economic. A larger system, also built by CEA, has been installed in Egypt, but has not become operational.

(vi) Electrodialysis

Although there has been little or no field experience with solar-powered electrodialysis, the now-disbanded United States Office of Water Research and Technology had financed an interesting and detailed study on the subject. A facility was designed to operate in a remote location in the south-western United States. Brackish water with a TDS of 2,000 to 2,500 ppm would be treated with an average production of about 15m^3/d (4,000 gpd). A water analysis for the town of La Luz, New Mexico, was used for design purposes. The plan was designed to operate using photovoltaic cells as the source of power. Because of the high calcium sulphate content of the proposed feed water, the recovery was limited to about 50 to 60 per cent without chemical treatment. To keep the unit operations as simple as possible, the recovery had been limited to 50 per cent, and no chemicals were added during pre-treatment.

The plant was designed to operate 10 hours per day, with the batteries acting to smooth out transients rather than to provide long-term energy storage. To minimize the solar energy collection system and yet maximize output, the facility had two distinct modes of operation, full and half flow. The half flow mode was used during periods when sunlight was reduced by clouds or other atmospheric conditions and when the well pump was operating.

In addition, the flow regulators and variable valves were to be instrumented so that the flow and recirculation through the membrane stack would be regulated to match the resistance in the stack (based on flow and TDS level) with the amount of incoming energy from the photvoltaic cells. This not only served to conserve pumping, but also heated the feed water and improved the efficiency of salt removal in the membrane stacks.

For sea-water desalination, existing electrodialysis systems have a higher specific energy consumption (about 15kWH/m^3) than reverse osmosis or distillation processes, and a correspondingly higher direct capital cost when powered by solar photovoltaics. However, for treatment of brackish water at low TDS levels, electrodialysis seems to be competitive with RO.

(d) Units located in developing countries

While the main experience in developing countries has been with solar stills, there are scattered examples of individual units using the range of desalination processes combined with solar energy, as described below.

(i) Working solar stills

Although there has been extensive discussion about solar stills a number of pilot units and a scattering of installations around the world, there are not many documented cases of long-term operation. The 4,500 m^2 still constructed at Las Salinas, Chile, operated from 1872 to 1912, one of the longest operating histories on record. The still was abandoned when a freshwater pipeline was installed to Salinas. Few other stills have equalled the longevity of the Las Salinas plant. However, some stills have been reasonably successful, as discussed below.

In 1978, the Central Salt and Marine Chemicals Research Institute (CSMCRI) of Bhavnagar, India, installed a 1,900 m^2 still at the village of Awania in Gujarat State. This village of about 1,400 people had no electricity and used brackish ground water as a source of potable water.

This was a bay-type still, in which the brine pool was continuous beneath the glass covers. The facility had an average production of about 4.9 M^3/d, and was operated on a batch basis. When the level of brackish water dropped below a certin level in the pools, more water was added. CSMCRI reported that the plant operated quite well and that the villagers were able to operate and maintain the facility, although they did not readily volunteer to do so. Some problems were experienced with vapour leakage owing to the sealant used and with lost efficiency as a result of algae build-up in the brine pools. Glass breakage was caused by animals and by stones thrown by villagers, but those problems have diminished (Natu and others, 1979b).

A smaller solar still of 0.95 m^3/d (250 gpd) capacity was built on the semi-arid island of La Gonâve off the west coast of Haiti in 1969. The still was installed with the co-operation and assistance of the Eglise méthodiste, the Oxford Committee for Famine Relief (OXFAM), the Brace Research Institute and the Haitian Government. While the design and construction were under the direction of the Brace Research Institute, local labour and materials were used as much as possible for the completion of the still.

Brackish feed water with a TDS of about 8,000 ppm is hand-pumped to a raw water tank, from where it flows by gravity to the bays. The still is operated on a batch (as opposed to continuous feed) basis. Both the rugged construction and practical design of the still have been demonstrated. In 1978, the installation was revitalized by the Eglise méthodiste through consultation with the Brace

Research Institute. That work consisted primarily of replacing butyl rubber lining to correct an original design fault. Upon completion of the repairs, the average daily production of the still was about 0.95 to 1.1 m^3/d. The unit serves a varying population of from 250 to 1,000 persons (Alward and Lawand, 1980).

The Mexican Government's desalination agency, DIGAASES, has used a variety of desalination processes, including solar distillation, to provide water to villages in the very arid areas of Baja California. A solar still of 1.0 m^3/d capacity was installed at Puerto Chale in 1973 and was still operating in 1980. The facility serves about 100 inhabitants, mostly fishermen, who live along the coast.

Such DIGAASES installations use many small modular units connected together, whereas the two examples cited above feature units constructed in large bays. The agency's solar distillation programme is based on using the modular approach for all its installations. The basic still is manufactured from fibreglass, which is lighweight, watertight and corrosion resistant. Those units are designed for ease of rapid installation in isolated areas where materials are not available. To do this, the stills are constructed and shipped in four major components: one-piece fibreglass basins, including end walls; a ridge pole made from aluminium; glass panes; and miscellaneous piping. The formed basins are designed so that when the ridge pole and glass are removed, the fibreglass basins will nest when stacked on top of each other. This allows a great many basins to be packed into a relatively small volume, greatly decreasing transportation costs and problems. The remaining glass, ridge pole and piping are easily packed and shipped, to be assembled at the site.

(ii) Reverse osmosis

In 1980, the Mexican Government's desalination agency, DIGAASES, in co-operation with the Federal Republic of Germany, installed a 4.4 m^3/d (1,200 gpd) solar reverse osmosis facility at the mountain village of Concepción del Oro in Zacatecas State.

The facility is powered by electricity generated by photovoltaic cells and is designed to desalinate braskish water eight hours per day during the daylight hours using both the photovoltaic cells and batteries. The batteries allow power to be delivered at a more constant rate despite variations in insolation during the day. They are not meant to be used to operate the unit for night-time operation. The project is geared ultimately to mass manufacture for distribution to rural and coastal areas.

The first solar-powered sea-water reverse osmosis facility was installed in 1981 at a community outside Jeddah, Saudi Arabia. The plant is powered by an 8-kilowatt (peak) photovoltaic array which is about 93m^2 in size and provides about 2 m^3/d of high-quality drinking water. A battery bank acts as a short-term energy buffer between the photovoltaic array and the electrical load. Sea-water RO technology, using hollow fine fibre membranes made from Kevlar polyaramide plastic, was chosen for its low energy consumption, which was estimated at less than one half that of thermal desalination units (Solar Energy Intelligence Report, 28 September 1981).

Subsequently, a 6 m^3/d unit based on an 11.2 kW (peak) array was built at Qatar, incorporating an energy recovery pump, which is crucial to achieving a reduced energy demand of 10 kWh/m^3 of product water. Even lower energy consumption is believed to be possible with newer hollow fibre materials currently under development. This system was developed to pioneer solar desalting for widespread usage throughout the Middle East and similar desert coastal areas. Using 42,000 ppm TDS Red Sea water, the plant consistently produced water of less than 200 ppm TDS (Water Desalination Report, 13 May 1982).

(iii) SOLERAS (Saudi Arabia-United States Joint Desalination Project)

In October 1977, Saudi Arabia and the United States signed a project agreement for co-operation in the field of solar energy (SOLERAS). The objectives of the agreement were to co-operate in the field of solar energy technology, advance the development of solar energy in the two countries and facilitate technology transfer between the two countries.

The Solar Energy Research Institute (SERI) at Golden, Colorado, is responsible for implementing the SOLERAS programme. One area in which the SOLERAS programme has started to operate is solar desalination. In March 1980, SERI accepted proposals concerning studies on the technical and economic feasibility of large-scale desalination of brackish and sea water using solar power exclusively. Those proposals were the initial part of a three-phase activity.

Phase I included preliminary designs and cost analysis for both a 6,000 m^3/d (1.6 mgd) base plant and a 100 to 400 m^3/d (26,000 to 106,000 (gpd) pilot plant for brackish and sea water. By the end of phase I, in August 1981, all the estimated costs submitted in bids from five companies were considered too high. Therefore, the SOLERAS executive board extended phase I to allow the pilot plants to be redesigned to fit into the SOLERAS five-year budget.

The work was completed in June 1982, and in October 1982, the contract was awarded for phases II and III to the Chigago Bridge and Iron Company. Phase II consists of detailed design and actual construction of the pilot plant, while phase III will cover operation and evaluation of the pilot plant.

The 200 m^3/d pilot plant design chosen is a solar system using an indirect freezing technique to desalinate the water. The test facility is to be constructed at Yanbu, Saudi Arabia, as a joint project between the United States Department of Energy and the Saudi National Centre for Science and Technology. It is being built alongside the Saline Water Conversion Corporation's existing Yanbu desalination plant (Wiseman, 1983).

2. Wind energy

Wind power has been used in windmill-type devices for several thousand years. The main functions of those devices have been to grind, pump water and (most recently) to generate electricity. In the United States and Europe, various types of wind machines were commonplace at the beginning of the twentieth century but, with the advent of rural electrification and dependable gasoline engines, they were largely displaced.

Windmills with a horizontal or vertical rotating axis produce rotary mechanical energy (shaft power). The machines can be coupled directly to a pump, saw or grinding wheel or used to generate electricity. Some improvements in wind machines have occurred in the past 50 years with attention being paid to their aerodynamic design. As with solar stills, the potential for wind power has intrigued man and has stimulated numerous variations on basic designs and materials of construction.

Efforts have been made by various organizations, such as Intermediate Technology Power, the Steering Committee on Wind Energy for Developing Countries, Brace Research Institute, the Indian Institute of Science, the United States Energy Research and Development Administration, and Volunteers in Technical Assistance, to design efficient but simplified wind machines that can be built in developing countries.

Several types of wind energy collectors, including horizontal and vertical axis turbines capable of producing up to as much as 4 MW, are commercially available or under development, and several hundred MW of grid-connected wind power from "wind farms" are now operational in the United States. Wind energy systems coupled with VC, RO or electrodialysis desalination plants may be economical in arid areas where the wind velocities are relatively high, and where conventional energy sources are in short supply.

Any consideration of wind power for desalination must take into account the fact that wind speed and continuity are site-specific. Data need to be obtained on those meteorological variables so as to determine if wind power is possible, and if it is, to optimize the system design. An important factor is that the wind does not always blow, and when it does, the velocity might be either too low to permit the machine to begin to produce power or too high so that the blades must be furled to prevent damage to them.

The economics of individual situations revolve for the most part around a balance of: (a) the capital costs for wind machine capacity, (b) energy storage, (c) desalination plant capacity, and (d) water storage to satisfy base and peak water demands.

Because the availability of power from the wind follows a cube law with wind velocity, economic costing is particularly sensitive to site. Nevertheless, taking an average wind speed of 6 m/s, which is on the low side for acceptable wind power, there are now machines on the market with rotor diameters of 7 to 9 m capable of generating from 50 to 100 kWh/d or about 1.5 kWh/d of electrical energy (in stand-alone as distinct from grid-connected operation) for every $1,000 of installed cost. The costs of such a unit will vary strongly with wind speed, with size of plant and with the development of both wind and desalination technology.

The use of wind power for desalination is only beginning to be explored. As far as can be determined, there are only a few experimental units being built and none that are actually operating under realistic commercial conditions.

(a) Reverse osmosis

The combination of reverse osmosis with wind power is a fairly new application. In theory, power would need to be furnished either as electricity or rotating energy. If electricity were produced, it would power motors to drive the pumps, while rotating energy would drive the pumps directly, although some electrical energy would usually be needed to operate controls and instruments. Most often wind power has been used to produce electricity, which is then used to power the motors which drive the pumps.

Brace Research Institute (Canada) conducted experiments over a period of years using a simulated windmill to run a standard reverse osmosis unit on brackish water. The varying flow rates had no significant effect on long-term performance.

As discussed above in the solar power section, reverse osmosis units need to be specially designed if they are going to be subjected to constant start-stop operation. Thus, a workable system should have provisions to handle transients in energy generation.

The use of wind power for reverse osmosis applications has been discussed (Cadwallader and others, 1977), but very few units have been built. One 10.4 m^3/d unit was built for use on an island off the North Sea coast of the Federal Republic of Germany. The wind machine drives a generator, which produces a three-phase alternating current at 380 volts. This is rectified to a variable voltage direct current, which is used to operate the pumps in the reverse osmosis system.

The reverse osmosis unit is a plate and frame system which operates on North Sea water with a recovery of about 40 per cent and a membrane pressure of 80 atm (1,200 psi). The specific energy consumption is about 11 kWh/m^3 of product. Pre-treatment consists of mechanical filtration with the potential for backwash and the addition of acid (Petersen and others, 1979).

A second unit was installed on Planier Island in the Mediterranean Sea off the coast of Marseilles, France. It was designed and tested by the French Atomic Energy Centre for Nuclear Studies at Cadarache.

As with the CEA solar unit, this system has been designed for simplified pre-treatment and the use of energy recovery to reduce the power consumption. The pre-treatment consists of electrochlorination, a settling tank, a two-stage sand filter, an activated charcoal column, and a cartridge filter. It uses an efficient high-pressure displacement pump and a Pelton turbine for energy recovery. The total energy usage, with recovery, is expected to be 7.5 kWh/m^3 of product including the low-pressure and high-pressure pumps (Maurel, 1979). Hollow fine fibre reverse osmosis modules are used, and the design recovery is 25 per cent. The unit was tested at the CEA Research Centre at Cadarache before installation at Planier during 1980.

(b) Distillation

There is some potential for using the rotating energy from a wind machine for operation of a vapour compression unit. Careful design and consideration of the interface between the two systems, however, would be required.

Units with this type of application have received little or no field testing. The concept had been discussed in theory, however, in 1961 by Lawand, who performed extensive studies on a 1.9 m^3/d (500 gpd) vapour compression unit to test its performance with a varying energy source.

(c) Electrodialysis

There is some potential for running an electrodialysis system using wind power. This type of system can tolerate the variable energy output of wind generators better than the other processes, but design work remains to be done to account for energy transients and power variability.

Little or no field work has been done with wind-powered electrodialysis, although it has been considered in theory in reports (Cadwallader and others, 1977).

3. Ocean energy

The desalination of thermal brines is being investigated. Several proposals have been forwarded to use ocean thermal energy conversion (OTEC) for direct desalination of ocean water. The principle behind OTEC is to utilize the temperature difference between the colder, deep ocean water and the warmer water on the surface. This requires an area where deep sea water is available, normally near to a coastal site having a demand for power. In the closed cycle system, which is the subject of most current investigations, the warm and the cool water are used as a heat source and sink, respectively, to drive a Rankine cycle turbine using ammonia or an organic fluid as the working fluid. However, in the open cycle system, which is also being investigated, the water itself would be used as a working fluid. In this case, large quantities of distilled water would become available as a by-product of the power cycle. It is as yet too early to evaluate the feasibility of this system.

The idea of harnessing the kinetic energy of the oceans has also long fascinated man with its potential as a source of free power. Investigations into recovering energy have been concentrated in two areas: (a) employing energy derived from tides and currents and (b) recovering energy contained in wind waves. Wind waves are non-tidal in nature and are generated by winds sweeping across the sea's surface. These can be either local winds or winds from storms or hurricanes.

The trapping of tidal water at high tide in a reservoir and releasing it through turbines at low tides has been discussed and investigated in various parts of the world. This requires a specialized site and massive structures.

The major problems with harnessing wave energy are associated with the changing wave patterns and the tremendous force that can be contained in some waves. A device needs to be designed to work with varying wave patterns and yet be rugged enough to withstand a massive wave that might only occur once every year or so. Research is continuing on the subject of waves and their inherent characteristics and potential use for energy, much of it focusing on offshore structures such as drilling platforms, which must withstand the force of waves. The loss of some of these massive rigs indicates that there probably is still much to be learned about waves and appropriate construction techniques.

In wave energy, as with some of the other alternate energy technologies, there is still a great deal of research, development and field testing necessary, both in providing reliable economic power and in combining it with desalination.

As far as is known, there is no commercially operating desalination unit employing wave energy as its power source, even though several proposals have appeared on a small scale. Wave energy is not currently considered a promising energy source for the near future.

4. Human energy

The direct use of hand power is probably the earliest renewable energy source used by man. Some attempts have been made to utilize hand power for desalination in reverse osmosis applications. One of the first applications used was in life-rafts to desalinate sea water. This recalls the work of Maria Telkes on devising solar stills for life-rafts during the Second World War.

A Canadian corporation, Seagold Industries, has developed a desalination unit operated by a hand lever, which can be used on both brackish and sea water. Salt rejection varies depending on the rate of pumping. A fine mesh suction strainer is used for pre-treatment, but it is recommended that a special fine filtration device be used in addition to protect the unit in all but survival applications. According to the manufacturer, the unit could be used to supply water while travelling in areas where water sources other than fresh water are available. The reverse osmosis membrane provides an added benefit in that it affords some protection to the product against microbial contamination.

A bicycle-pedal-driven reverse osmosis unit (PEDRO) has been developed by the non-profit government-financed GKSS Research Centre at Geesthacht, the Federal Republic of Germany. The unit consists of a pre-filter, a piston pump with fly wheels and pedals and an RO plate module with 1.7 m^2 of sheet membranes. With an input level of 100 watts, which can easily be sustained by an adult for 10 minutes, PEDRO can produce 0.75 litres/minute of potable water from sea water and, in the two-stage procedure, 0.4 litres/minute of potable water using commercial cellulose acetate membranes.

A similar development of mini-RO modules has been carried out at the Indian Institute of Technology at Bombay. The Indian Institute of Technology model is based on spiral-wound modules, which are said to result in a better flow rate and product quality. The pumping capacity is limited to man's maximum power output, which is about 100 watts, giving one litre of product water per minute (United Nations Children's Fund, 1982).

The present section is limited in extent and has covered only some of the many alternate sources of energy that could be used with desalination. Some others include geothermal energy, low-head hydropower and biomass conversion.

5. Application in developing countries

Although the use of renewable energy sources offers the potential for drastically reducing energy costs, its use for desalination in developing countries needs to be approached with caution and good judgement. The idea of renewable energy sources may convey the sense of going to a simpler way of life, but the fact is that there are still some very complicated elements involved in selecting reliable units and properly interfacing them with desalination units. There has been very little experience in this regard, and most of it is taking place under highly supervised and well-financed conditions.

Long-term commercial experience is needed in this field to work out the problems in design, operation and materials. That experience will not be gained without considerable expenditure, since units fail, need to be modified or repaired and, in general, require special attention during this phase of development. Whoever finances such projects must be able to afford unexpected expenses.

In the long term, there is certainly a potential for desalination using renewable energy sources in selected developing areas where conditions of climate, topography, technology and economics are suitable. The test units described above will aid in clarifying some of the opportunities and problems that exist in the field. However, it appears that each type of technology will require more work before units are ready for reliable commercial (versus research or experimental) operation in developing areas. At present, it might be counterproductive for both the concept of renewable energy sources and desalination to place those units routinely in villages, where maintenance capability is lacking. For any application involving desalination by renewable energy sources, consulting someone with professional knowledge and experience would be prudent.

6. Economic considerations

In contrast with other desalination processes in which the cost of fuel is a very important, if not the major, element in the total, desalination with renewable energy sources involves virtually no fuel cost. Experience has shown that the cost of operating labour is minimal, in comparison with conventional desalination processes. Thus, the cost of investment in plant and other related direct capital costs are the controlling expenses in desalination with renewable energy sources. This means that the total capital investment per unit of distiller production capacity, coupled with the interest charges on this investment and the amortization rate (depending on the useful life of the installation) are the primary and controlling elements in the cost of water produced by such processes.

The capital investment in equipment designed to harness the "free" solar or wind energy is very high, however. In relation to the heat recovered by solar energy, for example, the equipment can be quite expensive, because solar energy is diffused, and considerable equipment is needed to collect it in significant amounts. After several years of development effort, the United States Office of Saline Water concluded that solar distillation processes would be limited to the production of small amounts of water in areas of high solar intensity where fossil fuels were not readily available. To date, this conclusion still remains valid.

As can be seen from table 12, which indicates only orders of magnitude of costs from prototype desalination plants associated with renewable energy sources, water could cost anywhere from $3/m^3 ($12/1,000 gal) for desalting brackish water by electrodialysis to over $27/m^3 ($100/1,000 gal) for a vapour compression system associated with solar photovoltaics and desalting sea water. However, while the capital costs discussed below reflect 1984 sub-system equipment prices, complete systems can still be obtained only on a prototype basis and actual turnkey system costs are likely to be higher. It should also be remembered that those systems are too small to achieve economies of scale and auxiliary items such as water pumps and water treatment equipment can add significantly to costs. On the other hand, once those systems become available commercially, engineering and development costs will be lower, and overall costs will decrease.

Table 12. Estimated range of capital costs and water costs from experimental desalination plants using renewable sources of energy

	Total capital cost, 1984 ($/m^3/d installed capacity)		Annual capital cost (amortized at 12 per cent for 20 years and 18 per cent for 10 years)	Cost of Water (90 per cent plant factor) $/m^3 ($/1,000 gal)
	Sea water	Brackish water	($/yr)	
Solar still a/	32 000		4 300 - 7 100	13.00 - 22.00 (49.00 - 82.00)
Multiple-effect solar still b/	16 000		2 100 - 3 600	6.50 - 11.00 (25.00 - 41.00)
Vapour compression c/	20 000			
plus solar PV d/	20 000			16.00 - 27.00
Total	40 000		5 400 - 8 900	(60.00 - 100.00)
Small multi-stage flash e/	10 000			
plus solar thermal f/	18 000			11.00 - 19.00
Total	28 000		3 800 - 6 200	(43.00 - 72.00)
Membrane distillation j/	5 000			
plus solar thermal k/	12 000			7.00 - 12.00
Total	17 000		2 300 - 3 800	(26.00 - 44.00)
Reverse osmosis g/	12 000	4 000	SW: 3 800 - 6 200	SW: 11.00 - 19.00 (43.00 - 72.00)
plus solar PV d/	16 000	4 000	BW: 1 100 - 1 800	BW: 3.00 - 5.00
Total	28 000	8 000		(12.00 - 21.00)
Electrodialysis h/		5 000		
plus solar PV i/		3 000	BW: 1 100 - 1 800	BW: 3.00 - 5.00
Total		8 000		(12.00 - 21.00)

(Footnotes on following page)

(Footnotes to table 12)

Notes: The desalination equipment cost estimates are based on 1984 price quotations for 10 m^3/d desalination plants assumed to produce only 4 m^3/d when powered by solar energy sources without storage, plus corresponding solar thermal or photooltaic energy subsystems. The estimates indicate very approximate ranges of costs, which could easily change depending on assumptions and technological breakthroughs. They are based on experimental prototype or subsystem costs and should therefore not be considered actual commercial costs.

PV: photovoltaics SW: sea water BW: brackish water

a/ Solar still producing 3.3 $l/d/m^2$ is based on recent Australian prices of $100/$m^2$.

b/ Improved multi-effect solar still is a 10-stage unit producing 26 $l/d/m^2$. Energy equipment costs are estimated at $400/$m^2$.

c/ Specific energy consumption for vapour compression unit estimated at 10 kWh/m^3.

d/ Solar PV energy equipment costs based on $12/W with some battery storage.

e/ Small multi-stage flash unit has estimated energy consumption of 130 kWh/m^3 for 10- to 12-stage unit.

f/ Solar thermal parabolic trough (or evacuated tube) energy equipment costs estimated at $300/$m^2$; 120° C brine temperature with 50 per cent collector efficiency.

g/ Reverse osmosis energy consumption estimated at 8 kWh/m^3 for sea water and 2 kWh/m^3 for brackish water.

h/ Energy consumption for electrodialysis brackish water applications estimated at 1.6 kWh/m^3.

i/ Solar energy equipment costs based on $10/W without storage.

j/ Membrane distillation equipment costs are estimated as this technology is not yet available for sale. Estimates based on energy consumption of 70 kWh/m^3.

k/ Solar thermal flat plate collector system based on equipment costs estimated at $300/$m^2$; 85° C brine temperature and 30 per cent collector efficiency.

Generalized costs

According to an example from Australia, solar stills cost about $100/m^2$. From a study of those solar stills for which performance has been reported, a typical average daily productivity is about 1 m^3 of water from a 400 m^2 still, corresponding to a capital cost of $32,000/$m^3$/d of capacity. The costs per m^2 of those stills are low, but their efficiency is also very low.

The weakness of solar stills is that heat required to evaporate the water is rejected to the outside and lost when the water vapour condenses. In large conventional multi-stage flash and multiple-effect distillation plants, using conventional fuels, the heat of condensation in one stage is recovered in heat exchangers and used to distill (at lower temperatures) the saline water in subsequent stages.

Large distillation plants with capacities of 100,000 m^3/d and more take advantage of significant economies of scale and can achieve energy efficiencies of 60 to 70 kWh/m^3 for capital costs of somewhat more than $1,000/$m^3$/d installed capacity. However, small plants in the range of 10 to 1,000 m^3/d have higher capital costs reaching $3,000 to $5,000/$m^3$/d capacity and lower energy efficiencies.

High-temperature distillation plants can use industrial-type solar heating installations instead of conventional fuels. Using evacuated tube collectors, or possibly high-performance plate collectors with selective coatings or simple line focusing trough-type tracking collectors, all of which have current installed costs of about $200 to $400/$m^2$ and collection efficiencies of about 50 per cent at the required temperatures (about 120° C), heat costs are in the range of $10 to $20/GJ according to certain assumptions. This compares with costs of about $5/GJ for fuel oil at $30/barrel.

However, since many large conventional desalination plants are part of dual purpose power/water systems, using waste heat, it is likely that high-temperature solar distillation would be limited to small-scale systems in the range of 10 to 1,000 m^3/d in areas where conventional fuel costs are relatively high. For solar collectors with 5 kWh/m^2/d insolation and energy efficiency of 50 per cent, the collector area requirement would be 60 m^2 for every m^3/d capacity; this corresponds to direct capital costs for the solar thermal subsystem of about $18,000/$m^3$/d of installed capacity. To this must be added at least 25 per cent to cover the cost of thermal storage to permit continuous system operation. Including other equipment, the direct capital cost of a thermal solar distillation system would probably be of the order of $28,000/$m^3$/d. Such large collector systems would involve complex plumbing and maintenance problems, and there is relatively little scope for cost reduction.

A promising direction for distillation systems would be to combine them with solar ponds, which would greatly simplify the problems of collection and storage. Assuming a cost of $40/$m^2$ and a collection efficiency of 20 per cent for solar ponds leads to a requirement of 150 m^2 of pond area per m^3/d capacity and a specific capital cost of about $6,000/$m^3$/d. This would mean a total direct capital cost including distillation plant and interface with the pond of about $12,000/$m^3$/d for those sites at which a solar pond may eventually be technically feasible. Solar ponds may provide an excellent heat source for membrane distillation in suitable locations, which could in turn provide lower costs than conventional multi-stage flash or multiple-effect distillation plants combined with solar collectors or ponds.

For a modern vapour compression system, the specific energy consumption is about 10 to 12 kWh/m^3, implying direct capital costs for the solar photovoltaic system of about $20,000/$m^3$/d, plus $20,000/$m^3$/D for the desalination plant. However, it is estimated that those costs could be reduced in the future to a system cost of about $25,000/$m^3$/d capacity. The reverse osmosis process would have a proportionally lower energy consumption for brackish as compared to sea water and would therefore be less expensive than distillation processes at lower TDS levels.

Electrodialysis is competitive in capital costs with reverse osmosis for brackish water applications. However, because it can utilize the direct current electrical output of a photovoltaic array directly without power conditioning, and because it does not require high pressures and is more tolerant of water quality, it would probably be preferable to RO for certain brackish water applications.

The decreasing cost of photovoltaic arrays offers the promise of ultimately cheaper desalination in locations where insolation intensities are moderately high. If present cost and size predictions are confirmed, it is feasible that, by 1990, solar photovoltaic systems capable of generating a few kilowatts of power at costs of about $4 per peak watt will be available. The amortized cost of such devices at present values still represents a significant charge for water, however.

Although such costs are still high, those photovoltaic systems associated with reverse osmosis, vapour compression or electrodialysis should become competitive with or cheaper than diesel systems in remote areas where fuel costs are high (above $0.80/litre) and in regions of reasonably good sunlight (5 kWh/m^2/day) at production levels of less than 10 m^3/d of water.

Wind-powered systems have not been included in table 12, although they may be attractive in cases where average wind speeds are 6 m/s or better. For example, with a 6 m/s average wind speed, an 8 m diameter wind machine with some battery storage and costing about $40,000 installed can provide about 30 to 40 kWh/day of useful energy, equivalent to a 6 kW solar photovoltaic system costing about $72,000. For higher average wind speeds the energy output will be considerably greater (it increases as the cube of the wind speed). However, even in those places with good wind, it is likely to be less reliable than solar energy and a diesel generator back-up may be required. Solar photovoltaics has a number of advantages over wind, especially for small systems.

G. Small-scale desalination units in rural areas

The technical aspects of desalination are rather specialized and, although most countries do not have many desalination facilities, where they do exist they represent a sizeable investment in funds as well as a vital part of the national economy.

In many countries, the functions associated with planning and/or operation of desalination facilities are grouped within one governmental department and/or agency. This centralizes technical expertise and aids in co-ordinating planning, purchasing, maintenance and training. Occasionally, other agencies may share in this role as their activities warrant. For example, some representative national governmental agencies that deal with desalination are the Saline Water Conversion Corporation (Saudi Arabia), the Ministry of Electricity and Water (Kuwait), the

Secretariat of Electricity (Libyan Arab Jamahiriya) and the Directorate General for the Improvement of Saline Water and Solar Energy (Mexico).

One question that a desalination agency must deal with is the degree to which it will subsidize water sales to the public. If little or no subsidy is given, then desalination facilities can be expanded as localized economic conditions warrant, since those regions will be financing their own operations. Where high subsidies are employed, future expansion (and in fact all operations) must depend on continued and increased financing from the central Government.

Because of its high cost, desalination is generally used only for domestic purposes and some industrial uses, rather than for agriculture. At the village level, there is often a great need for desalination just to supply basic drinking water and sanitation needs for people and livestock. There are many areas in developing countries, such as in the villages of Rajastan and Gujarat States in India, where only brackish water is available for drinking purposes. Therefore, there is considerable scope for introducing small-scale desalination plants treating brackish water in rural or remote areas where alternative supplies are extremely limited. Such programmes may be related to national plans under the International Drinking Water Supply and Sanitation Decade (1981-1990).

1. Village desalting programmes

Programmes for village desalting require considerable planning to achieve long-term success. If they are to be accomplished with the co-operation of the villagers, and not by fiat, they demand considerable time and substantial funds. The cost per person served is bound to be considerably higher than for desalination projects in urban areas, where many thousands of people can be serviced with one installation. The programme that was being carried out by the Mexican Government in the late 1970s and early 1980s had the elements necessary for success. It was not inexpensive, but it served a social and technical function that was desired by the central Government. That programme is discussed below.

(a) Constraints

There are several constraints to introducing a new technology such as desalination to a village environment. Villagers tend to be conservative and shy away from risk. They tend to be sceptical about changing habits and traditions that have endured, especially at the urging of a stranger who may know little about their way of life. Risk-taking is difficult and dangerous when there is little with which to gamble and the penalties for failure are severe.

Thus, if desalination is to be introduced as an improved water supply to a village, it should be done with care and attention to the particular culture if it is to meet with long-term success. The villagers should want the improvement, approve of the idea of desalination and participate in discussions about the capacity of the proposed plant, where it will be located, and what will happen to the brine. Additionally, they should participate in the construction and/or installation of the unit and its subsequent operation. They need to identify with the unit in order to be willing to keep it running.

It is crucial that adequate supervision be provided during the installation and initial operating period. If the unit, for even the most insignificant reason, stops operating in the beginning, the villagers may become extremely sceptical of the whole concept. After the initial operating period, additional visits should be made to monitor the plant's performance and assist in its operation and maintenance.

There are often considerable financial constraints at the village level, and it is often difficult to mobilize the necessary funds to pay for fuel and spare parts. If the villagers are expected to finance the operation and maintenance costs, a system must be devised for collecting fees and a respected village leader or committee should be appointed to be responsible for that collection. If the costs are to be paid by the central Government, it is important that the parts and fuel arrive in a timely fashion so that the unit continues to function. If it ceases to function at a time when the water is needed. the villagers may consider the unit undependable and return to their previous methods of obtaining water.

Problems with introducing desalting units in villages can be both technical and sociological. Technically, a unit must function extremely dependably, with minimal maintenance and operator attention. Although energy efficiency is a consideration, it is not as important as reliability.

Sociological problems are very site-specific and vary considerably. However, they have to be taken into account if the unit is to function properly. Most important is that the desalination plant be introduced with a minimum of disruption to village life. Some examples of social disruptions that might occur are the following:

(a) The introduction of strangers (possibly central Government employees) into the village to install, operate and service the unit;

(b) The change in patterns of meeting, working and talking that might occur if the source of water for the village is changed in type and/or location;

(c) The question of who should service and operate the desalting unit. In many societies, obtaining water is traditionally a woman's job, whereas operating machinery is a man's. It might be preferable to train women to operate a solar still or other small-scale desalination unit, because it is in their interest to keep it running;

(d) The installation of a community unit where traditions are not oriented towards community organization;

(e) The decision or mechanism involved in allocating water produced by the desalting device among various users.

(b) <u>Village desalting equipment</u>

The type of equipment used will vary with the characteristics of the specific location and the amount and type of technical and financial support available. If technical support is generally good (as in Mexico), rugged standard units of the best process for the application can be used.

However, if the intention is to let the villagers operate the unit themselves, with minimal assistance after installation, serious consideration should be given to the use of solar stills where feasible. Although the capital cost is rather high and the structure requires considerable space, a solar still is technically rather straightforward in construction and operation. It also allows for maximum local participation, operation and repairs. Various designs construction techniques and pitfalls are discussed in Fresh Water from the Sun (Dunham, 1978) and in section F of the present chapter.

Another potential apparatus for village desalting could be a specially designed reverse osmosis unit. This would have a low efficiency and low recovery, but would require minimum attention and chemicals. A commercial unit of this type that has been thoroughly proven in the field does not exist at present, probably as a result of the lack of a significant market for this type of unit; hence, manufacturers have little incentive to design or manufacture such a unit. If there were a substantial market, it is very probable that a unit would be developed.

It should be remembered, though, that reverse osmosis units continue to require fuel, filters and other expendables for the life of the facility. Although alternate energy sources such as wind, solar and wave energy can replace the fuel component, those technologies are not yet widely available at the village level. However, progress is being made in developing those technologies for village applications, and it is important to keep abreast of long-term developments.

2. Examples of country programmes

(a) Mexico: village desalting

In Mexico, DIGAASES is the central agency that directs the desalination programme. DIGAASES has placed particular emphasis on developing desalination facilities in small villages. By 1982, it was estimated that the agency would be operating approximately 100 desalination plants serving over 260,000 people (with a total installed capacity of about 21,000 m^3/d), plus a number of experimental units. Most of the installations produced between 38 and 95 m^3/d (10,000 to 25,000 gpd). To service its units and carry out experimental and research work, DIGAASES had centres in four areas outside Mexico City, where its headquarters were located.

The agency realized that a successful programme of desalination in the village required a special approach. DIGAASES would begin with a study of the village, in which both the source of feed water for desalination and any other potential sources of potable water were evaluated. The study would also cover economic, social and technical aspects to determine if there was a true desire for that type of facility, whether it would fit into the village social milieu, what its impact would be, and what type of local financial support, power sources and operator potential were available. Usually the local schoolteacher was an excellent source of information on many of the social and economic aspects. During this investigation period, DIGAASES tried to maximize local involvement in the project, realizing that in the end the project would succeed only if the villagers wanted and supported it.

A typical DIGAASES installation in a village included: (a) a raw water source, (b) the desalination equipment in a building, (c) a power-generating system (if power was not available), (d) a product water tank, and (e) a house for the operator (and family). For example, an installation in a village in the State of Coahuila served about 470 people and produced approximately 8 m^3/d (2,100 gpd). One woman operated the plant, which was a reverse osmosis facility treating brackish water with a TDS of approximately 3,000 ppm. The water was distributed by villagers picking it up in buckets that were fulled from taps in the product water tank.

Under current policy, DIGAASES tries to restrict its activities to desalination and does not become involved in subsequent water distribution within the villages. The agency does attempt to encourage the villagers to organize in communities or co-operatives to handle the distribution of the water. In many cases, the most economical method is to use buckets. Generally, the local water committee supervises the collection of fees for the water. The fees are nominal and defray only a small portion of the total cost of the service. Success in fee collection varies greatly from region to region.

An important part of the success of DIGAASES in the village programme was its periodic assistance during operation. As part of the initial study, DIGAASES personnel would select a local villager as an operator for the facility. The operator was given training to carry out the basic functions needed at the plant and was placed on the DIGAASES payroll. After the plant was put into operation, an engineer or technician from DIGAASES would usually visit the village about once a month to pay the operator, collect data on operation, assist in making repairs or modifications, deliver parts and chemicals and generally assist the operator with the plant. DIGAASES personnel used the data collected to monitor the plant's performance, enabling them to spot and correct problems early and to use the information (especially on problems) to modify future designs, construction and/or purchase specifications. At present, DIGAASES continues to profit technically from the experience gained in the operation of their field units, while providing a high standard of service.

(i) Mobile units

In addition to the many small permanent units in villages, the Mexican Government has begun work on using mobile desalination equipment. This will enable technicians to service a number of smaller villages with one unit. A typical unit has its own power-generating facilities and is mounted on a trailer. It employs reverse osmosis for desalination, and the trailer includes all the necessary pre-treatment equipment. The unit can be towed into a village and operated to fill up a fresh water tank with several days' supply. The unit then moves on to the next village, where it repeats the operation. In this way, a number of small villages can be successfully supplied with fresh water with a minimum number of operational personnel and problems with power. As a result, all maintenance and repair work can be centralized.

In designing its plants, DIGAASES has tried to adapt the equipment to local operating and construction conditions and to minimize foreign exchange expenditures. The percentage of parts for each process that can be fabricated in Mexico range from 60 per cent for vapour compression processes to 100 per cent for solar stills. Reverse osmosis and MSF fall in the middle of this range.

For MSF plants, DIGAASES has developed a special design that can utilize available fabricating machinery and a high percentage of locally made materials. That design allows for easy transportation of fabricated components to isolated locations where cargo handling and assembly facilities are severely limited. After initially working with carbon steel, DIGAASES now uses 90/10 copper-nickel almost exclusively for its multi-stage flash plants. The agency has also assembled an experimental heat recovery evaporator and a vapour compression unit.

(ii) Technical co-operation among developing countries

The national desalination programme organized by DIGAASES has considerable merit. It has been accomplished with a moderate budget and has attracted a staff of competent, dedicated personnel. Developing countries that are interested in organizing a national programme of this type would do well to study the DIGAASES programme to see if portions of it are suitable for their situation.*

(b) Village programme in India

The ground water in the arid and semi-arid States of Gujarat and Rajastan in India is widely used for irrigation, and saline intrusion has become a major problem in much of the area. The salinity problems, in turn, have affected village water supplies, especially during periods of drought. In the mid-1970s the Central Salt and Marine Chemicals Research Institute, in the State of Gujarat, constructed and installed several desalination units in various small villages in the region as a practical demonstration of their utility in providing good water to the villages. Those units included electrodialysis, reverse osmosis and solar stills.

For example, at Motagokharwala in Gujarat, a 12 m^3/d (3,100 gpd) electrodialysis unit was installed and operated for about one year, serving a population of about 1,000. The unit used interpolymer type membranes manufactured in India. Brackish feed water was obtained from the village well, and the product water was distributed by means of large water pitchers in the village. The level of TDS of the feed water was in the range where either electrodialysis or RO could be used. The Institute had both types of units available for its research work and placed them in selected villages as available.

The 12 m^3/d unit reduced TDS from 4,000 ppm to 1,000 ppm, with an energy usage of about 3 kWh/m^3. Intermittent dosage of the concentrate stream with acid was used to control scaling. The plant was operated by a villager who was trained by the Institute. There was reported to be no acceptance problem among the villagers, who approved of its use for drinking and cooking (Central Salt and Marine Chemicals Research Institute, 1980).

A 15 m^3/d reverse osmosis unit was installed in the village of Rajasthali, serving a similar population of 1,000. That tubular RO unit, which was designed, manufactured and operated by the Institute, was installed for about six months. As at Motagokharawa, the village well produced brackish water which had been used by the inhabitants. The unit used cellulose acetate tubular membranes, which were mounted in parallel holders and stacked above a central collection tray. The permeate moved through membranes and porous supports and dripped into the collection tray, where it was transferred by gravity to a small product storage tank.

The unit was operated by a villager who was trained by the Institute. The energy usage was about 7.1 kWh/m^3 of product water produced. TDS was reduced from 4,000 ppm to about 600 ppm. Acid dosing was used intermittently to control scaling in the membranes (Central Salt and Marine Chemicals Research Institute, 1980).

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* Further information can be obtained from: Director General, DIGAASES, Boulevard del Pípila No. 1, Lomas de Tecamachalco, Mexico City, D.F., Mexico.

The villagers were reported to be enthusiastic about the quality of the water. They remarked on the reduced quantities of soap used for washing and sugar used for their tea (Mehta and others, 1976).

As the above examples illustrate, there may be a potential for providing drinking water from desalination to villages in remote areas that have to depend on brackish water supplies. This could be introduced as one component of national programmes in arid or semi-arid countries under the International Drinking Water Supply and Sanitation Decade (1981-1990), which aims at supplying water to all people by 1990. It will entail considerable investment in equipment, but may prove to be economic, since existing sources of brackish water can be used and no new sources have to be developed. Moreover, it may prove to be cheaper than what the villagers have to pay now to vendors who bring water by truck in times of drought. With support at the national and international level, agencies in developing countries may choose to fabricate small-scale units themselves for widespread distribution to remote rural and coastal areas. Systems for involving villagers in operation and for establishing monitoring and repair networks are integral components of such a programme. There is also considerable scope for technical co-operation among developing countries in this field.

II. TRANSPORT OF WATER

A. Introduction

Water is commonly transported from source to end-user at locations throughout the world. Except for those people who live on or along the shore of a river or lake, most consumers are dependent on water that has been transported some distance from its origin.

There are three essential elements in a water transportation system: a source of water, a container and the means of transportation. If any of these fail, then the system ceases to function. A common means of transport in industrial countries is a pipeline. Water is collected and treated at its source, such as a river or reservoir, and it is pumped through a pipeline that forms the container as well as the means of transport. This is a convenient, although rather capital-intensive, method of supplying water, and it allows the continuous availability of water to the user. In some developing areas, water is provided by a village well (the source), which supplies the water to people (the means of transportation) who carry it to their homes in buckets or jars (the containers). Although this does not require a lot of capital, it is labour-intensive and delivers water to the point of consumption in discreet units where it must be stored until used.

The present chapter discusses methods of providing water supply to an area which involve transportation of water on a large scale. The methods described are more closely related to hauling water in buckets than to transporting by pipeline as the water is conveyed to an area in large individual units. Those methods involve the use of tankers and icebergs to transport water across a sea or ocean to the place where it will be used.

The first section discusses the use of tankers of various sizes to transport water from a place with a surplus of water to places with a shortage. The source might be a river or a city, such as Rotterdam, where surplus water exists. The tanker is the container, which also acts as the means of transporting the water to the area of need. Depending on the tanker or barge selected, up to about 250,000 m^3 (60 million gallons) can be hauled in a single trip.

Since time in port is an important economic consideration in ocean shipping, efficient water transport requires port facilities at both the source and receiving ends which can deliver or store large quantities of water. This usually means modern docking or mooring facilities, large pumping stations and storage tanks.

The use of tankers for the long-term supplying of water to an area is not widespread but it has been done. From 1965 to about 1980 barging of water between Puerto Rico and the Virgin Islands supplied the island of St. Thomas with the major portion of its municipal potable water supply. For about five years oil tankers have transported fresh water as ballast between New York and the Netherlands Antilles. Other instances can be cited, although large-scale use of very large tankers exclusively for water transport over a long period of time has not been tried.

The second method dealt with in the present chapter involves the transport of icebergs. Icebergs are made up of high-quality fresh water and can be found floating near the polar regions. The concept is simple - to transport an iceberg to an area where water is needed, melt it and use the melted water. In this case, the iceberg is the source and the container and all that is needed is some form of power to transport it.

Unfortunately, to be economical, massive icebergs must be used and this requires large powerful tugs to move and manoeuvre them. Additionally, facilities must be available at the receiving end to moor the iceberg, melt it and store the water produced. Since an iceberg floats with over 80 per cent of its volume below the surface, it is possible that an iceberg would require a draft of 100 to 500 m (300 to 1600 ft) or more to float, hence limiting its passage and approach to shore.

The use of icebergs as a source of water is an interesting but basically conjectural concept, as it has really never been commercially undertaken.

B. Tankers

1. Historical background

The carriage of fresh water by ship as an exclusive cargo is not a recent development. Vessels dedicated to the exclusive carriage of water had been built for short-haul transportation of fresh water towards the end of the eighteenth century. Those sailing craft were built of wood and were conventionally rigged, containing two or three large circular, covered tanks built of cast iron and were termed "water hoys". Because of the awkward nature of their oval, squat hull, the water hoys were incapable of deep-sea navigation; they were used principally in protected areas for the watering of ships at anchor, their carrying capacity being on the order of 150 m^3 (39,600 gal).

Long-haul carriage of liquids, on the other hand, began with the switch to oil as a motive fuel in the industrial countries in the early twentieth century. The original oil tankers were classical deep-sea sailing vessels indistinguishable from their dry cargo carrying counterparts. As steam drove the sails from the seas, the purpose-built oil tanker - at first outwardly identical to any other steamer - began to emerge, evolving gradually during the First World War and the 1920s into the "all aft" look that it still retains to this day.

Inevitably, with the cyclical ups and downs of merchant shipping, the boom that followed the First World War turned into an unprecedented market depression, during which people began looking for alternative uses for surplus oil tanker tonnage. The Italians were the first to notice in the 1920s that the surplus of water in northern Italy could be transported to water-short areas in the south and the islands by means of surplus tanker tonnage. Thus, a social need could be fulfilled by supplying surplus water to compensate for its lack, while unemployed vessels were once again put to good, if unprofitable, use.

Greece followed, and by the 1930s a small-scale trade had developed, in both cases State-organized and operated chiefly by naval auxiliary services for the regular supply of fresh water to areas of shortage in ships of up to 3,000 m^3 carrying capacity. While this type of service continued, the quantities involved were small and unit costs therefore high. Despite this, a method had been established and shown to be feasible.

Because of regional water shortages, the trade expanded during the 1950s and 1960s using larger vessels that could carry 25,000 to 30,000 m^3 of water, going between, for example, China and Hong Kong, or Central America and the Caribbean islands, often using chartered vessels built originally as oil tankers.

In the mid-1980s there has been renewed interest in fresh water transportation by tankers because of a combination of circumtances that can be summarized as follows:

(a) Surplus oil tanker tonnage currently out of service which could be applied to dedicated fresh water transport;

(b) Operational oil tankers now travelling from oil-exporting to oil-importing countries which could transport fresh water in the ballast back hauls;

(c) Availability of fresh water in areas near major tanker trading routes;

Historically, there have been sporadic local, subregional and regional ventures in marine transportation of water. The technological developments and structural changes that have occurred in maritime transport in general, and tanker fleet in particular, are indicative of the successful application of economies of scale, resulting in lower unit costs of transportation. Accordingly, marine transport of water stands a good chance to affirm itself as a viable alternative option to augment local supplies of water. Needless to say, such an option should be considered on its own merits, in competition with other sources of water supply.

2. Technical considerations

(a) Uses of transported water

There are various ways in which tanker-hauled water can be used, depending on the quality of the water at the point of delivery and any changes that might occur while being transferred or stored in tanks on board the ships. The water available for shipment may be either raw and untreated or treated, and its quality and sales price will vary according to location. Common contaminants picked up in passage include oil, salts and corrosion products.

(i) Agricultural use

The water imported for irrigation can have a range of quality, including treated waste water, depending on the crops to be irrigated. Some quality standards must be set to ensure that the water is free of chemicals and organisms above a level that would be harmful to plants or people handling the water. Contaminants can be tolerated, but the permissible limits of contaminants must be defined.

When applying oil-contaminated water for irrigation, a new factor of uncertain dimension is introduced, the importance of which can only be determined by experimentation. Some introductory research has been undertaken with regard to the effect of oil-contaminated irrigation water on the growth of some vegetables. Those trials have been performed since 1978 in Norway under greenhouse conditions where some chemical analyses of aromatic compounds were performed on the fruit of sweet pepper and tomato. The results of those analyses showed that there were only traces of hydrocarbon compounds taken up by the plans. Similar tests performed by the Nodai Research Institute of the Tokyo University of Agriculture have so far been encouraging. Water with an oil content of 50 ppm or less seems to cause no problem with regard to absorption of metals or hydrocarbons (Meyer, 1983). However, determination of limits must be based on a site and plant specific basis.

(ii) Industrial use

There are many ways in which water is used in industry, the quality requirements depending on the nature of the process. It is understood, however, that an oil content of up to 1 ppm would be acceptable for many industrial processes. Oil-free water can, if required, be provided by using onshore treatment or by carrying the water in segregated ballast tanks. New regulations require all new tankers to be built with segregated ballast tanks.

(iii) Potable use

Water for drinking and other domestic purposes can be transported relatively simply as ballast by tankers equipped with clean ballast tanks. As water of the desired quality can be provided for shipment, consideration must be given to possible changes of water quality during transportation. Every precaution will have to be taken to avoid contamination en route (Meyer, 1983).

Water can also deteriorate in quality owing to corrosion in the tanks. The existence of an oil layer in cargo tanks can provide a film that may be an effective protection against corrosion. When water is carried in clean cargo tanks, the situation will be similar to conditions in segregated water ballast tanks, although corrosion is possible. The upper layers and underdeck areas of the tanks can be coated in a way that will prevent corrosion and excessive degradation of the water quality during transportation, although cleaning those surfaces of oil can sometimes be difficult.

(b) Geographical considerations

Tankers can be most effective when they are used to supply water to coastal regions or islands where there are facilities for unloading the cargo of water and where there is a local demand that does not require significant additional transfer of the water. Since there is a considerable area of arid land located along coastlines,* the potential for the effective use of tankers exists. Table 13 lists some of the countries with significant coastal arid or desert zones throughout the world. Those areas are also indicated on map 1.

Structural changes that have occurred in maritime transportation have lessened the disadvantages of large distances for hauling bulk cargoes. The increased size of carriers has resulted in economies of scale in maritime transport, and improved port and infrastructure facilities have reduced costs of loading and unloading.

The economies of scale in maritime transport have influenced the choice of port locations and development zones, which also entail consideration of technical, operational, financial, economic and political issues. The large-sized vessels need deep-water berthing facilities and special bulk handling equipment for the fast turn-round of vessels at both terminals.

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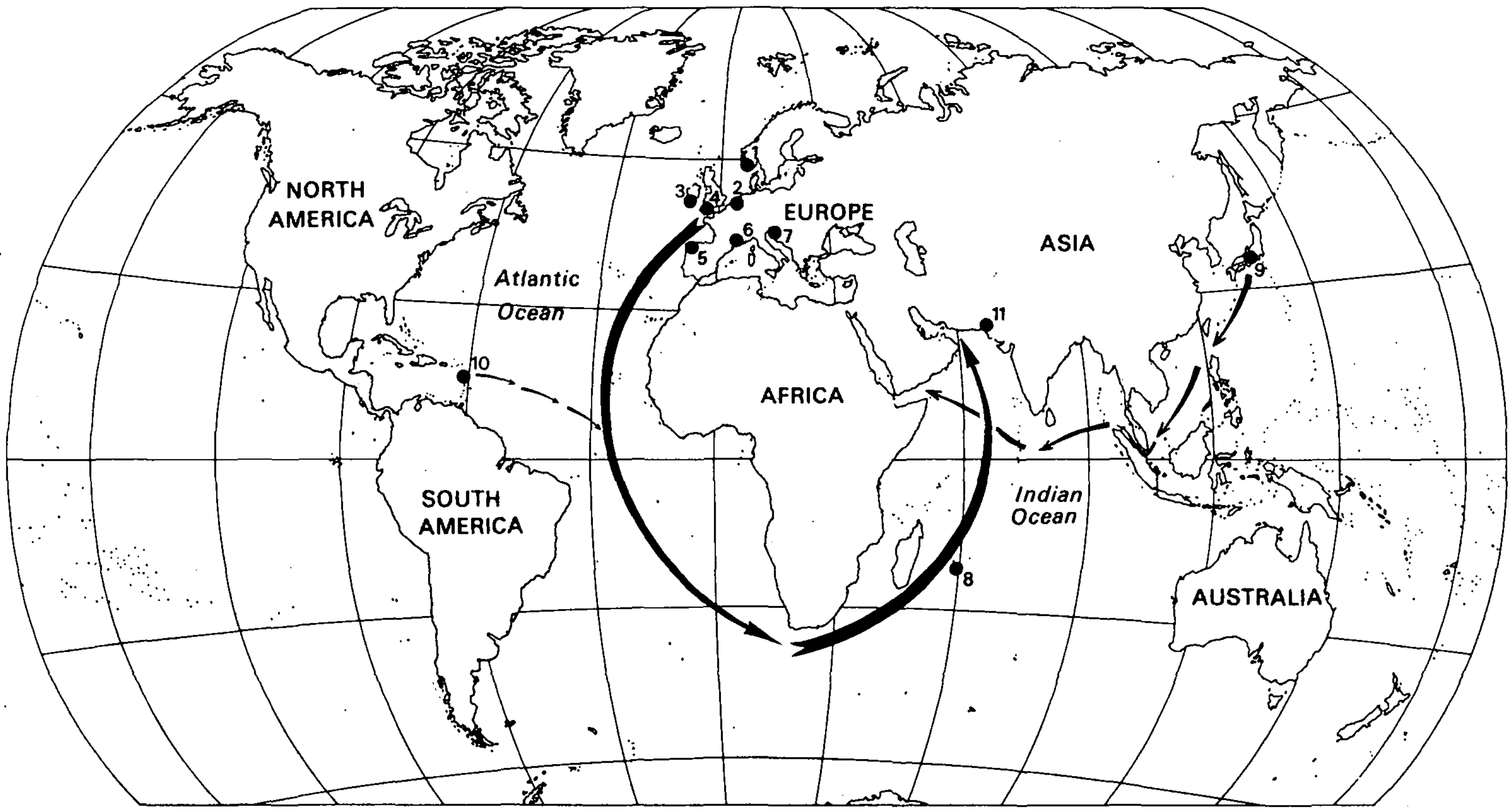
* Of the approximately 450,200 km (280,000 mi) of coastline in the world, about 34,800 km (21,650 mi) are considered to be desert or arid coastal areas.

Table 13. Countries and areas with significant lengths of very arid coastlines

Country	Location on map I	Estimated length of arid coastline (km)	(mi)
Africa			
Afars and Issas	4	244	152
Egypt	4, 6	2 420	1 505
Ethiopia	4	1 010	628
Libyan Arab Jamahiriya	6	1 685	1 047
Mauritania	7	666	414
Morocco	7	452	281
Namibia	8	1 385	861
Somalia	5	2 955	1 837
Sudan	4	716	445
Tunisia	6	500	312
Western Sahara	7	907	564
Subtotal		12 940	8 046
Australia	9, 10	4 700	2 921
Subtotal		4 700	2 921
Asia			
Democratic Yemen	3	1 211	753
India	1	1 105	687
Iran, Islamic Republic of	1, 2	1 834	1 140
Pakistan	1	753	468
Saudi Arabia	2, 4	2 437	1 515
Yemen	3	451	280
Subtotal		7 791	4 843
Central and South America			
Argentina	14	1 700	1 056
Chile	13	1 574	978
Mexico	11	3 800	2 362
Peru	12	2 329	1 448
Subtotal		9 403	5 844
Grand total		34 834	21 654

Source: Adapted from table 1 in J. Z. Bradanovic, "Certain considerations and criteria for possible development of coastal desert and/or arid areas in developing countries", Alternative Strategies for Desert Development and Management, vol. 4 (New York, Pergamon Press, 1982), pp. 1017-1041.

Map 2. Potential water transportation routes



MAP NO. 3289 UNITED NATIONS
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Source: Adapted from Trygve A. Meyer, "Freshwater ballasting as a means for the conservation of energy and natural resources", in *Proceedings of the International Seminar on Fresh Water Ballasting,* Tripoli, Libya, 31 May to 1 June 1983 (London, International Maritime Organization, 1983).

Note: Numbers refer to locations listed in table 14.

The economics of serving specific coastal areas is greatly enhanced if they are located along the world's major ocean trading routes, that is, in the mainstream of the maritime traffic. The maritime traffic is generally along certain basic east/west and north/south direction trading routes.

The east/west direction may be defined as primarily using the Mediterranean/ Red Sea maritime transport route. This route has Gibraltar on the western end and Bab el Mandab Strait on the eastern end, with the Suez Canal linking the Mediterranean and the Red Seas.

The alternate east/west direction is, in fact, the north/south trading route around the Cape of Good Hope and along the West African coast.

In relation to those routes the desert or very arid areas can be identified as being located in the south-western and western parts of Africa, a few Mediterranean countries on the African continent, and practically all countries riparian to the Red Sea, Gulf of Aden and the Persian Gulf, Pakistan and part of India. Those areas are identified in map 1. The north/south trading route on both west coasts of North and South America would have primarily hemispheric maritime traffic connotations.

Regarding marine transportation of water, the main coastal desert areas of interest would be those where there are human settlements, trade, industrial, agricultural or other resource development potentials.

Three situations may give rise to marine transportation of water by tankers from water surplus to water deficit areas. These are: (a) unpredictable emergencies, requiring short-term import of water to meet emergency requirements, (b) predictable and/or seasonal increases in demand for supplementary water (heavy tourist season) and (c) long-term increases in demand for imported water in very arid or drought-prone coastal areas.

Certain general criteria outlined below seem to be applicable for areas that might benefit from water transportation schemes:

(a) The area must be accessible from the sea;

(b) If no suitable harbours exist, the sea-bed should not be excessively steep in order to enable an offhsore mooring system to be established in reasonable water depths and be linked to land with an underwater pipeline;

(c) The area should have a permanent rather than a temporary water shortage warranting long-term supply arrangements. This does not of course exclude temporary supply by tanker or barges to areas where unusual crises may occur; on the contrary, water supply by tankers or barges may offer the most reliable and flexible solution;

(d) The coastal area or its immediate hinterland must be the location where the fresh water is required; alternatively, the infrastructure for its further inland distribution must be available in order to pump it to the various areas required;

(e) Financial resources, from whatever source, must be available for the operation to be carried out.

(c) Infrastructure

Infrastructure needed for the marine transportation of water will differ according to location; therefore, only generalized alternatives will be considered below. Before resources are committed for the marine transportation of water, it must be determined whether separate terminal facilities will be needed or whether the existing port outlet facilities at both place of origin and destination can be used. In addition to many other considerations, prudent attention must be given to the overland distance from the marine facility to the source of water and reservoirs as well as to the marine distance between the loading and discharging terminals. Development of new terminal facilities requires a careful investigation of the future port sites and a study of the physical features of the area, including hydrography and topography, meteorological and oceanographic influences and coastal hydraulics.

(i) Berthing systems

The extensive transport, terminal and port facilities developed by the oil industry could in many cases be adapted to handle export and import of water by means of separate water manifolds connected to piping systems and reservoirs. The possible berthing systems for tankers are briefly described below.

Among the floating systems, the main types are: the single buoy mooring system, the exposed location single buoy mooring system and the multi-buoy mooring system. The single buoy mooring system is said to be the most common of the floating systems. The capital cost of that system is relatively low. However, with all the additional equipment such as anchors, hose connections, floating and underbuoy hoses and the bottom manifold, the total cost may be several times the capital cost of the single buoy. Nevertheless, the cost is still considerably less than an onshore terminal with equivalent accessibility. One advantage of the single buoy mooring system is that, thanks to its swivel top, a vessel can move around the buoy once it is moored, and loading operations can take place with waves up to 4.5 metres.

The exposed location single buoy mooring system is generally better able to cope with severe sea conditions than the single buoy system. However, this rather sophisticated system, first put into operation in 1975, is much more expensive than the single buoy mooring system. On the other hand, the multi-buoy mooring system is said to be less expensive than the single buoy system. In this system, several buoys are placed in a semicircular pattern. The ship is moored in a fixed position and must drop two anchors successively during the mooring manoeuvres. The main disadvantage of this system is that the mooring procedure requires much more time than for the single buoy system.

Among fixed berthing structures are the onshore and offshore terminals. The traditional one is the onshore terminal, but the increasing draft requirements of very large tankers have led to the building of offshore systems, or "sea islands". A detailed analysis of the conditions that prevail in a specific area can determine which of the two alternatives is preferable.

Naturally sheltered harbours may provide the required depth for a defined optimal tanker size to be used in the transportation of water. In many instances, however, naturally sheltered water may not be available. In order to provide protection for the berthing facilities, one or two breakwaters may have to be constructed. The cost per metre length of a breakwater may average from $US 15,000 to $20,000, but adverse conditions may push the figure up much higher.

(ii) Channel approach

The basic aim of the approach channel is the safe passage of all vessels. The depth must be sufficient to allow vessels with the deepest draft to pass through the shallowest reach of the channel at some stage in each tidal cycle. The width and depth of the navigation approach channel to the harbour are major economic considerations. Unless there are severe economic constraints, a two-way channel should be provided in order to offer unrestricted access to the port.

In many instances in order to provide sufficient water depth in the harbour for an optimal size tanker, an approach channel and the port turning basin as well as the water loading berth have to be dredged. Dredging is essentially an excavating operation, but the selection of the correct equipment is vital to achieving economy. All dredging activity calls for special consideration of the nature of the ground to be dredged, the best means of removing the soils and the optimum work programme. Both capital and maintenance costs must be considered in dredging.

(iii) Shore-based and shipboard system

The economics of shipping operations in general and tanker operations in particular are greatly enhanced by a vessel's fast turn-round in ports which, in turn, increases both carrier capacity performance and the berth's throughput. Therefore, in the context of any development scheme for the transportation of water, the handling system for the tankers has to be designed for a high throughput rate at both loading and discharging terminals. This will be achieved by harmonizing the capacities of loading and discharging facilities, reservoir system capacities and pipeline capacities.

The dockside handling equipment is mainly composed of loading arms that are designed to connect the hoses to the ship's manifold. The cost of the system depends on its designed capacity. The loading operations can be carried out either by gravity or with the help of pumping systems. The actual pumping rates depend on the pumping capacities of the tanker and/or shore-based pumping systems, all of which when harmonized contribute to much higher tanker handling rates.

A water terminal is designed for receiving, treating and distributing water for different purposes. A typical water terminal may be composed of the following elements: supply pipes with pumps, receiving and storage reservoirs, purification or treatment plants, and the distribution system for treated water.

Few existing crude oil loading facilities are designed to receive large quantities of water ballast simultaneously with loading an oil cargo. If the vessels carry large quantities of fresh water, piping must be provided for pumping ashore. Therefore, existing facilities have to be modified to be used for water importation, or the vessels should empty their water ballast into separate receiving facilities.

(iv) Deballasting facilities

The Mediterranean Sea, the Red Sea and the Persian Gulf have been declared special protected areas by IMO conventions. In those areas oil transportation by tankers must be a closed system. Deballasting facilities will be required at oil-exporting terminals in those regions in order to eliminate the discharging of oil-contaminated ballast water from oil tankers into the port's waters. When such new facilities are constructed, they should be dual purpose in nature, as fresh water used for ballast could be used onshore.

Fresh water ballast backhauling is feasible if there is a market for the fresh water. The fresh water is loaded in the oil-importing port and discharged in the oil-exporting port. The introduction of fresh water ballast schemes could, therefore, give added incentives to installing adequate reception facilities for oil-contaminated ballast water in accordance with international regulations.

Tanker fresh water backhauling schemes, where the full cargo carrying capacity is being utilized for fresh water, could most easily be implemented with separate large capacity reception facilities, storage tanks and a distribution network. However, such facilities have not necessarily been located at the oil-loading terminals.

In an interim period, converted tankers may very well serve as docked reservoirs for storage and as water treatment plants. Tankers designed for the treatment of oil-contaminated ballast water have already proved to be feasible in Greece, Singapore, Sweden, the Union of Soviet Socialist Republics and the Persian Gulf (Meyer, 1983).

3. Recent technological advances

The major development in marine transportation over the past 20 years has been the spectacular quantum jump in the size of tankers, which has had technical and operational, financial, economic and political ramifications. The economies of scale resulting from this size increase have made maritime transport the cheapest mode of bulk cargo transport in terms of unit costs, except for pipelines.

(a) VLCCs and ULCCs

In the latter half of the 1960s and in the 1970s there was a tremendous expansion in construction of very large crude carriers, which range in size from 100,000 to 250,000 dead weight tons (dwt), and ultra-large crude carriers, ranging in size from over 250,000 to 500,000 dwt.* From 1971 to 1975 over 500 VLCCs and ULCCs, amounting to some 145 million dwt (nearly half of today's world fleet), were delivered or contracted (Wilson, 1983).

Those supertankers were constructed to carry crude oil on long hauls from the Persian Gulf to Europe and North America around the Cape of Good Hope, particularly

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* Dead weight tons is the actual carrying capacity of a ship expressed in long tons, which is equivalent to metric tons (each equivalent to 1,000 kg or 2,240 lbs). It includes cargo, crew, fuel, supplies and spare parts.

during the period when the Suez Canal was closed (1967-1975). The transportation costs relative to the prices of oil are currently only about 3 to 4 per cent of the oil price. This percentage had fallen steadily from 110 per cent of the oil price in 1957 to 52 per cent in 1970 and 4.7 per cent in 1980 (Meyer, 1983), primarily as a result of the increase in oil prices. However, what amounts to a small percentage of oil costs will be a high price to pay for transporting large quantities of water (that is, over $11.00/m^3$). Therefore, unless lower rates for water transport are introduced, it would be most economical to use a portion of the large tankers for backhaul ballasting of fresh water in a situation where the return voyage would normally not produce any revenue. Since the large tankers are generally used for long-distance runs, the backhaul system would probably be the most feasible water transport system.

The supertankers, being larger and deeper than conventional vessels, use proportionally less steel, personnel and equipment per ton of carrying capacity. The economies of scale derived from those VLCCs, as well as the increase in oil prices, have substantially changed the effect of geographic location of natural resources and have proven to be a decisive factor in the development of lower-quality resources.

Since the late 1970s, the reduction in oil shipments from oil-exporting countries has caused a large surplus tonnage of tankers. During 1982 the estimated tonnage requirements fell as low as 150 million dwt. To put this figure in perspective, the available tonnage capacity (excluding vessels employed for oil storage) amounted to about 302 million dwt. Hence, during the second quarter of the year the estimated gross surplus capacity reached the record figure of 152 million dwt. equivalent to 50 per cent of the potential capacity of the oil-carrying fleet. It is this tremendous surplus capacity that has made the transport of water by tanker economically feasible. Water is a low-cost commodity which could economically be carried over long distances by supertankers, if they did not have alternative sources of income on the ballast portion of the voyage.

At the beginning of 1983 the world tanker fleet included 630 VLCCs and ULCCs, of which 180 were laid up, 43 were being used as storage vessels, and about 30 were idle or awaiting employment. The remaining 377 were employed for long haul oil transport from the Persian Gulf countries to the east and west.

(b) Fresh water ballasting

A dedicated oil tanker (a vessel used solely for the transportation of oil) is generally used at only 50 per cent of its total round-trip carrying capacity, since on its return voyage it carries no oil, but only sea water as ballast. Tankers could maximize capacity utilization by carrying a revenue-earning cargo on the return voyage. By using fresh water for ballasting, the tanker's carrying capacity for oil would serve as the primary revenue-producing service and fresh water on the return voyage would be a secondary source of revenue.

The use of a portion of the carrying capacity for fresh water is encouraged by the International Convention for the Prevention of Pollution from Ships (MARPOL 73/78), which came into force on 2 October 1983. That Convention, under the International Maritime Organization, lays down certain requirements for construction and equipment aimed at reducing operational oil pollution. The Convention requires that VLCCs and ULCCs reserve up to 30 per cent of their carrying capacity for fresh water ballast. Several alternatives have been suggested for reserving part of the carrying capacity, the most promising of which are the segregated ballast tank system and the clean ballast tank system.

The segregated ballast tank system would set aside a portion of total space (about one third of dead weight) to be used exclusively for fresh water transport. For new tankers the segregated tanks must be arranged in a protected location.

The clean ballast tank system is an interim measure for existing tankers whereby certain tanks are designated as clean ballast tanks for the sole carriage of fresh water ballast. The clean ballast tanks have to be thoroughly cleaned, inspected and certified for the transportation of fresh water. In those schemes it is vitally important to comply with certain internationally recognized water standards and to give the receiver full information on the quality of water being delivered.

Special equipment and scientific techniques are required for the maintenance and/or upgrading of the water while en route to the destination. Whether the segregated or clean ballast tank system is chosen, the fresh water carrying vessels will have to have been modified in advance and be staffed by at least one qualified water engineer.

With the coming into force of MARPOL 73/78, owners now face the choice of upgrading vessels at high costs to the international standards for inert gas, crude oil washing, and/or segregated ballast tanks. Alternatively, tankers will be sent to demolition yards or find alternative employment and conversion projects. The age and technical standards of vessels vary, but most of them would be suitable without conversion for transportation of water for many years to come. The hulls can also be used as water-receiving, storage, treatment and distribution plants (Meyer 1983).

(c) <u>Dedicated water carriers</u>

(i) <u>Large tankers</u>

In early 1983, over 200 VLCCs were laid up without prospects of employment. All these vessels are suitable candidates for dedicated water transportation service. Such vessels as are appropriate will, apart from all other routine recommissioning procedures, require a thorough cleaning of all cargo spaces and the installation of water treatment equipment and piping on deck. It is generally accepted that transport of water by large dedicated tankers would be economic mainly for short-distance shuttle runs.

Dedicated service has certain advantages over the transportation of a combination of water and oil. First, the trade is oriented towards identified demand and supply of a single commodity. The water delivered will not therefore depend on fluctuations in the trade of oil. Accordingly, a fresh water transportation programme can be established and delivery commitments can be met over a long period without operational risk. Secondly, there is no risk of admixture or contamination of water from residue of an oil cargo which would necessitate special treatment onshore. Thirdly, dedicated service allows permanent contractual arrangements to be made between the end-user and the supplier of suitable water, whereby the end-user has exclusive rights over the quantities of water required and is officially given access and official title to it. Fourthly, the dedicated tanker could have on board its own individual water treatment plant.

With this it would be possible to load fresh water of somewhat lower quality and upgrade it during passage to the desired standards. Consequently, the end-user would not be limited to obtaining water at the purest source, but would have the flexibility if circumstances required to switch sources and yet maintain timing and quality of the supply.

The negative aspect of dedicated service is that the tanker must make the backhaul carrying non-revenue producing ballast.

(ii) Tug and barge systems

One specific dedicated water transportation scheme may involve tug and barge combinations in a relatively calm sea or oceanic environment, such as for inter-island short hauls or between the mainland and nearby islands. Prevailing meteorological and oceanographic conditions are primary considerations in such a scheme and in some areas restrictions may be imposed as safety precautions. A system of this type was used for almost 15 years to transport water from the Caribbean island of Puerto Rico to St. Thomas, a distance of about 100 km (60 mi).

Various options are available in a tug and barge water transport operation. For small-scale short hauls, a one tug and two barge system would usually require one loading berth and two berths at the discharging terminal. The most efficient use of a tug is with three barges: the first at the loading berth, the second in transit being towed by the tug and the third at the discharging terminal. Barge down time is higher but, because the barge is less capital-intensive, this alternative is usually acceptable. Two loading and two discharging berths would be required for an efficient operation.

The next level would involve two tugs and five barges. While the tugs are fully utilized, some barge down time would be incurred. The loading port would require two berths, while the discharge port would require three berths.

(d) Oil removal

Analysis of arrival ballast water transported in cargo tanks, which have been properly crude-oil washed and water-rinsed, shows that about 90 per cent of the water can be discharged with less than 15 ppm oil content. The oil remaining in the last portion of the fresh water to be emptied from the oil cargo tanks can be removed by gravity separation in a special receiving tank to achieve an oil content of less than 10 ppm in the water. This simple and cost-effective method of separating oil from water is most encouraging for water transported by crude oil tankers. By comparison, oil-water separators on the market will reduce the oil content in treated water to around 25 ppm.

New techniques for oil and water separation have been developed, using ceramic oil absorbent or filter granulate absorbent materials. Those two systems can lower the level of oil in water to less than 5 ppm and, at the same time, the recovered oil can be used. Laboratory research has shown that fresh water contaminated by crude oil passing through multi-oil absorbent filters will have its level of oil contents reduced further to less than 1 ppm. These are relatively low-cost methods of removing pollutants from water.

Polluted fresh water can be further upgraded to potable standards, using water treatment by slow sand or activated carbon filters or chlorination.

4. Application in developing countries

Although there may be some long-term potential for establishing water transportation schemes among developing countries, the trade that has so far developed generally involves European countries as suppliers and arid areas around the Mediterranean or Persian Gulf as markets. As was shown in map 1, most of the arid coastal areas of the world are located in developing countries. These areas, especially those located along the main tanker routes, are the major potential markets for transported water.

(a) Potential markets

As with markets for other non-conventional water sources, the main buyers of transported water would tend to be water-short countries and island nations which derive their income from such sources as petroleum exports and tourism. Obviously, the countries around the Persian Gulf are along the main tanker routes. An average of 625 VLCC oil cargo loads (average 250,000 dwt each) is required each year to supply European ports from the Persian Gulf. All those trading vessels are capable of returning with fresh water, either as partial or full cargo (Meyer, 1983). The transportation by sea of oil from the Persian Gulf countries to the United States averages about 160 VLCC cargoes (250,000 dwt) per year. Vessels discharging at United States gulf ports and the Caribbean area are in a good position to transport fresh water either within the Caribbean area or from Caribbean or South American ports to the Persian Gulf on their ballast voyage.

Japan and other Asian countries import about 134 million tons of oil each year from the Persian Gulf countries. This represents 536 VLCC voyages to Asia every year. About 80 per cent of those vessels are in a favourable position to carry fresh water on the ballast journey (Meyer, 1983). Many of the Asian countries along the tanker routes have large surpluses of fresh water, particularly during the monsoon season. Those resources could be harnessed for export to the Persian Gulf, possibly under swap arrangements with the oil exporter, as long as the tanker operator is compensated for the loss of alternative earnings.

The total oil exported in oil tankers from the Persian Gulf countries is at present about 360 million tons per year, out of which about 220 million tons are carried in VLCCs and ULCCs. Thus, a considerable potential exists for fresh water backhauling to Persian Gulf countries in large tankers. If dedicated tankers were used in a water shuttle supply system on short-distance runs, the importation potential would be even further increased (Meyer, 1983).

(b) Fresh water ports

Fresh water supplies of good quality are already available in large quantities from several ports, some of which are identified in table 14. Most of those potential fresh water export ports are strategically located along major tanker routes (see map 2). Many major oil-importing ports have fresh water available at the port or at a nearby source. In some locations, deviations to pick up water would be necessary, but could be minimized to reduce costs.

Table 14. Some potential fresh water loading ports

1. Norway

Kvina-Sira. The run-off to the sea from the water system supplying the hydroelectric power stations is approximately 3,600 million m^3/yr. Water in large quantities of excellent quality is available. The chloride content is less than 3 ppm. A sheltered deep water port to accommodate large tankers can be built. Close to tanker routes.

Hardangerfjord. Mountain surface water of excellent quality. Officially tested and approved for water trading. Collected in pipes 800/900 metres above sea level and used in hydroelectric power station. Chloride contents less than 2 ppm. Annual delivery capacity 50 million m^3. Sheltered anchorage berth for tankers up to about 350,000 dwt. Long diversions from main tanker routes: 140 km steaming up the Hardangerfjord from the sea.

Matre. Surface water at same qualities as above. Annual delivery capacity 30 million m^3. Loading delivery rate 6-8,000 m^3/hr. Sheltered berth for tankers up to 350,000 dwt. Easy access from the sea. Some diversion from main tanker routes.

Vaksdal. Surface water of excellent quality. Annual delivery capacity 15 million m^3. Sheltered berth for tankers up to 350,000 tons. Some diversion from main tanker routes.

2. Netherlands

Rotterdam. Fresh surface water from Brielse Meer of good quality with an average chloride content of 240 ppm. It is used for irrigation. Water availability 30 million m^3 annually, but more can be made available for tankers. Minimum loading rate 2,000 m^3/hr. Situated close to Europe's largest seaport and the oil terminals. Planned fresh water loading facilities to accommodate tankers up to 300,000 dwt, maximum draft 68 feet.

3. Ireland

Bantry Bay. Fresh surface water from rivers and lakes of good quality. Availability of substantial volumes of water initially of the order of 15 million m^3/yr, which can be increased to 30 million m^3. The chloride content in the water is about 20 ppm. Sheltered oil terminal. Can accommodate tankers up to 120,000 dwt at present. A damaged berth can be restructured to take tankers up to 326,000 dwt. Short deviation from main tanker routes.

Shannon Estuary. River water suitable for irrigation at the source. Water availability about 20 million m^3/yr. Average chloride content in the water is 20 ppm. Oil terminal has berthing facilities for 250,000 dwt tankers. Short deviation from main tanker route.

Table 14 (continued)

4. United Kingdom of Great Britain and Northern Ireland (Power, 1984)

Milford Haven (Wales). Good quality water available, up to 10,000 m^3/hr loading rate; can handle tankers up to 300,000 dwt for backhaul water service. Located on main tanker routes.

Northumberland (north-east England). Potable quality water up to 45,000 m^3/d available, with larger quantities of lower-quality water if required. Supplied by Kielder reservoir through Tyne-Tees-Wear distribution system.

5. North-west Spain

La Coruña-Cape Finesterre. Potable water from local water works. About 4 million m^3/yr are available from present facilities. Can be increased to 9 million m^3. Average chloride content in the water is 13 ppm. Sheltered berthing facilities for tankers up to 80,000 dwt, which will be increased to 200,000 dwt. Close to main tanker routes.

Corcubion. Raw surface water from River Xallas; 30 million m^3/yr available as surplus water from hydroelectric power station. The average chloride content in the water is 13 ppm. Partly sheltered harbour with easy access from the sea and close to passing oil tankers returning from northern Europe. Loading from a connecting line by buoy mooring system. Can accommodate any size tankers.

Muros. Surface water from rivers and lakes of good quality; 30 million m^3/yr available as surplus water from hydroelectric power station. Average chloride content in the water is 20 ppm. Sheltered harbour with easy access from the sea and close to passing oil tankers returning from northern Europe. Loading from connecting line by buoy mooring system. Any size oil tanker can be accommodated.

6. Southern France

Marseilles/Fos/Lavéra. Surface water of good quality from Canal de Provence. In 1983, Lavéra delivered water by tanker to Tarragona, Spain (100,000 dwt tanker carrying 83,000 m^3 of water on six-day round-trip shuttle run; it returned empty); 10 million m^3/yr available. Port of Lavéra has terminals suitable for small to medium tankers up to 100,000 dwt. Fos, the largest oil port in the Mediterranean, can handle any size tankers, but fresh water piping for loading water has to be constructed (Meyer, 1983 and World Water, October 1983).

7. Italy

Trieste. More than 25 million m^3/yr of river surface water of acceptable quality could be made available for export. Principal port of Italy; the oil terminal can handle four 160,000 dwt tankers simultaneously; 30 million tons oil discharged annually.

Table 14 (continued)

8. Réunion (France)

Island in Mozambique Channel. Lake and river surface water can be made available. "Riviere de l'Est" is the nearest power station to the sea where water which has passed turbines can be made available for export. Potential water supplies can be 50 million m^3/yr. Water submarine supply line to an offshore mooring buoy has to be provided. This may accommodate any size oil tanker. Some deviation from main tanker route.

9. Japan

Yakushima Island. Raw surface water from rivers of high quality. Abundant water resources available: 20-50 million m^3/yr. Quantity can be increased; island receives 8,000 mm precipitation yearly. Chloride contents about 3 ppm. Offshore mooring buoy facilities connected to source via submarine piping. Tankers up to 350,000 dwt can be accommodated. Close to main tanker route.

10. Eastern Caribbean

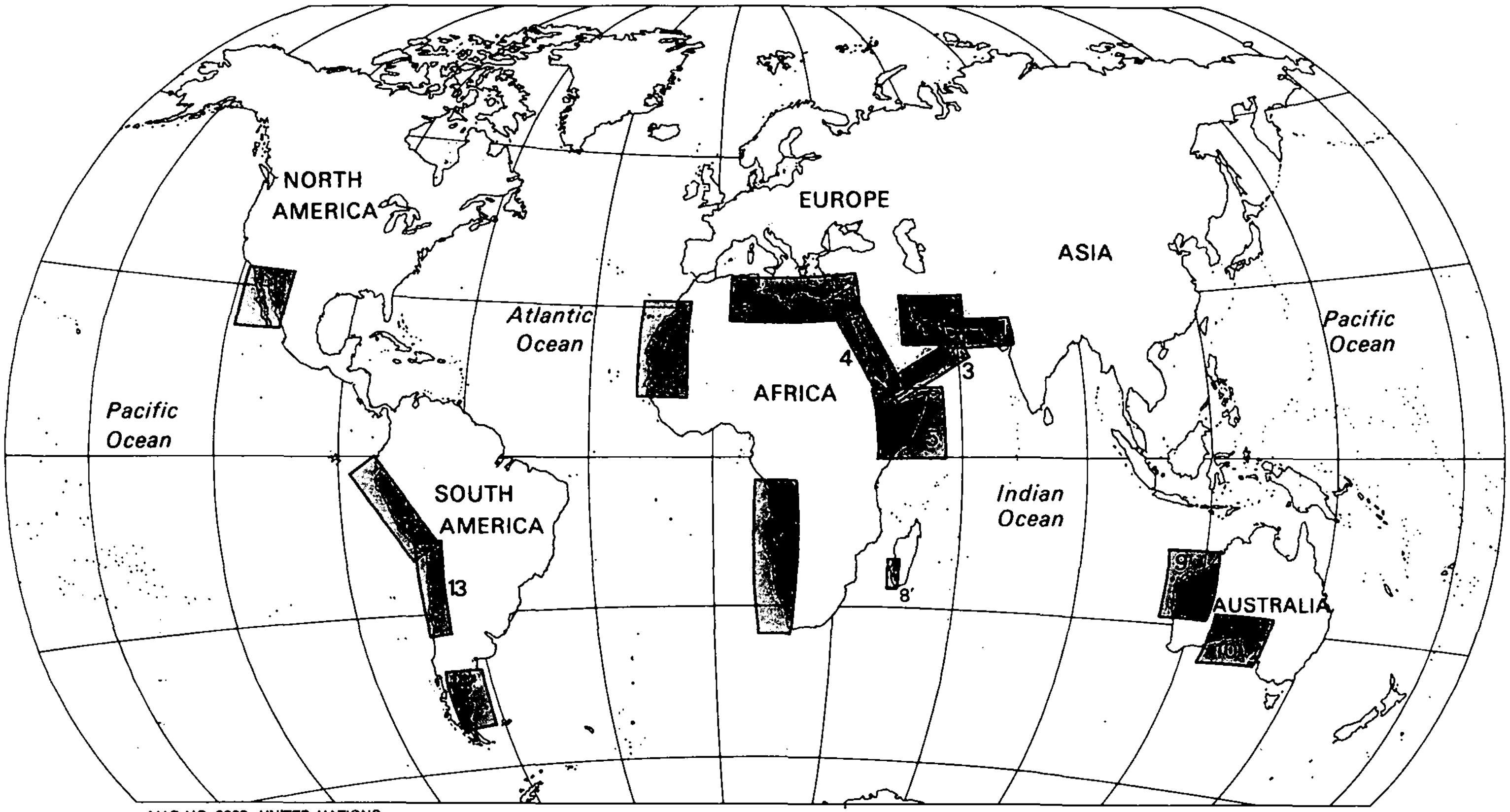
Dominica. Abundant raw surface water of excellent quality from the Layou River. The chloride contents average 10-19 ppm; 50 million m^3/yr, which can be increased substantially. Offshore buoy mooring facilities with submarine pipelines to shore water reservoir, with current capacity to pump 3,800 m^3/day without disrupting local water supplies. Close to main tanker routes.

11. Pakistan

Indus River. Unclean raw surface river water. The run-off to sea can supply water to one or more fresh water tanker terminals; 50-100 million m^3/yr or more may be made available. The water may contain silt which will settle and build up as sediments in the cargo tanks. Offshore buoy mooring systems connected to submarine piping at a length of about 10 km to upstream fresh water pumping station. Arrangement could be made to load tankers up to 350,000 dwt on shuttle runs to the Arabian Gulf. Weather conditions during the monsoon season, mid-June to mid-December, place constraints on regular supplies.

Source: Information on all locations, except those otherwise indicated, adapted from Trygve A. Meyer, "Freshwater ballasting as a means for the conservation of energy and natural resources", in Proceedings of the International Seminar on Fresh Water Tanker Ballasting, Tripoli, 31 May to 1 June 1983 (London, International Maritime Organization, 1983).

Map 1. Desert and very arid coastal areas of the world



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Source : Adapted from maps contained in Peveril Meigs, *Geography of Coastal deserts* (Paris, UNESCO,1966).

Many of the identified sources of good quality water are located in the industrialized countries. In northern Europe, water supplies are available from locations in Norway, the United Kingdom of Great Britain and Northern Ireland, Ireland, the Netherlands and the Federal Republic of Germany. In addition, supplies are available from some European Mediterranean ports such as Lavéra in southern France. The province of Galecia in northern Spain also has large quantities of water available for shipment (Meyer, 1983). In Asia, Yakushima Island (Japan) has vast quantities of water which could be transported by oil tankers returning to the Persian Gulf area (Akiyama, 1983). In the western hemisphere water supplies are available for shipment from areas along the east and west coasts of Canada, as well as from some river estuaries in the United States.

Plans have been developed for tanker water supplies in several of these developed countries. The potential of water ports to supply water can be adapted to demand and transport capabilities. Generally speaking, for short distances water shuttle operations using small- to medium-sized tankers have been found to be economical. For example, a 100,000 dwt tanker (which carried 83,000 m^3 of water) was leased in 1983 to shuttle water between the Mediterranean ports of Lavéra in southern France and Tarragona in eastern Spain. The contract was signed in mid-1983 for a one-year period or as long as the drought lasted in that part of Spain (World Water, October 1983). Operations were suspended in mid-November 1983 when the drought ended, after 1.3 million m^3 had been shipped over a three-month period in tankers which completed the round-trip voyage in six days. Costs of water to the Spanish buyers amounted to approximately $\$2.50/m^3$: \$0.50 for water and \$2.00 for transportation and other fees. French authorities at the Société du Canal de Provence and Port autonome de Marseille were looking for new markets in early 1983 for shuttle service within a range of 4,625 km (2,500 nautical miles) which they considered a realistic shuttle target (Power, 1984). Among markets they were considering were Cyprus, Malta and Mauritania.

The Port Authority of Rotterdam in the Netherlands has also granted export rights to a private firm for transport of water from Brielse Meer to Mediterranean and Red Sea ports as well as to the Persian Gulf (Holman, 1983). In Norway, high-quality mountain water in quantities of about 6,000 to 12,000 m^3/hr can be made available for loading in VLCCs and ULCCs at short notice (Meyer, 1983).

However, as distances become greater and vessels become larger, backhaul ballasting seems to be more economical than shuttle service. The Port Authority at Milford Haven (Wales) has indicated that it has available up to 10,000 m^3/hr of water for backhaul transport in ships of up to 300,000 dwt. Similarly, quantities of up to 45,000 m^3/d of potable water are available for export from the Northumberland Water Authority (north-eastern England), with larger quantities of lower-quality water which could be used for agriculture or industry. This water is supplied by the vast Kielder reservoir and its system of tunnels serving the Tyne-Tees-Wear river valleys (Power, 1984). Backhaul fresh water could be loaded into clean ballast tanks for up to 30 per cent of the carrier's capacity, which would enable medium-sized tankers to return through the Suez Canal.

In Japan, fresh water could be loaded either at oil unloading ports such as Yokohama or Kiire or at Yakushima Island, which lies along the main tanker routes. A fresh water backhaul system would be the only economical method, because of Japan's great distance from the Persian Gulf (Akiyama, 1983).

Ports in developing countries have not so far been widely adapted for water loading. The Governments of Dominica in the eastern Caribbean and the Philippines have both extended water exporting rights to private firms. Dominica is located close to tanker routes and has made its prodigious supply of good quality water available for shipment. Offshore buoy mooring facilities are available in deep water with submarine pipelines to onshore water reservoirs. Abundant water of good quality from the Layou River can be made available at quantities exceeding 50 million m^3/yr for shipment to Caribbean or Middle Eastern ports. In early 1984 exports of water were being shipped from Dominica to Aruba (Netherlands Antilles). In the Philippines, the Government extended the right to export water from that country in 1982. A major underground aquifer located adjacent to Batangas Bay on the island of Luzon has been identified as the likely initial export source. VLCCs could be loaded at the existing Caltex wharf and the trip would entail only a modest diversion from the major Japan/Persian Gulf tanker routes (Holman, 1983).

Moreover, significant quantities of water could be made available annually from the island of Réunion in the Mozambique Channel. This would require a submarine water supply line to an offshore marine buoy. Any size of tanker could be accommodated, but some deviation from the main tanker routes would be necessary.

Perhaps additional potential for fresh water sources in developing countries would be the mouths of the world's major rivers. For example, the Amazon, Orinoco and Plate Rivers in South America could supply almost unlimited quantities of fresh water. In most cases, offshore mooring would be required and, in some cases, underwater pipelines. However, fresh water from the Amazon extends more than 200 km from the coast. In this case, it may be possible for a tanker to pump water directly. Of course, much of this water will require extensive treatment if it is to be used for drinking. Also, some deviation from the main Europe/North America to Persian Gulf routes will be necessary.

Under major rivers in Africa, such as the Congo and Zambezi, and in Asia, such as the Indus, Brahmaputra, Irrawaddy, Mekong and Ganges, have huge surplus supplies, particularly in the monsoon seasons. This water could easily be harnessed for transportation to water-short areas. For example, in utilizing water from the Indus River (Pakistan), arrangements could be made to load tankers up to 350,000 dwt on shuttle runs to the Persian Gulf. Offshore buoy mooring systems are already connected to submarine piping at a distance of 10 km to a fresh water pumping station upstream. From 50 to 100 million m^3 could be made available annually from this source alone. The main problem with almost all the major rivers is the heavy sediment load that would require treatment to remove suspended materials.

(c) Advantages of transporting water by tanker

Transporting water to a water-short area by large tankers offers a number of advantages, some of which are listed below.

(i) Availability

Tanker operations are being conducted in free market conditions and at present tankers are generally available, not only for charter but also for purchase. If the water-short area is located along the international tanker routes, then arranging for backhaul capacity is quite possible.

(ii) Bartering

If an oil importer can supply fresh water for the tanker's return voyage to a water-short oil-exporting country, then a possible swap arrangement or discount on the oil price might be arranged, which would be advantageous to both countries.

Some institutional arrangements are needed between oil suppliers/receivers, ship operators and other private and governmental interests to accommodate the overseas oil transportation, combined with fresh water movements by tankers. Within the existing framework of oil-chartering régimes (single or consecutive voyage charters, contracts of affreightments and time charters), it is feasible to adapt chartering provisions to meet the needs of regular fresh water supplies. Contractual arrangements can be negotiated once there is a market need.

(iii) Environmental protection

If the carriage of fresh water ballast is implemented on a regular basis, it would be beneficial from an environmental point of view, because the undesirable practice of discharging dirty (sea water) ballast into the sea at oil-loading terminals in oil-exporting countries could be significantly reduced. Energy may be conserved by less tank cleaning and recovery of oil from discharged ballast water.

(iv) Potential tanker surplus

With the implementation of MARPOL 73/78 in October 1983, about one third of the world's fleet will be rendered out of class for the carriage of oil. Many ship operators will find it highly uneconomic to invest money for technical upgrading of tankers for compliance with new IMO requirements. Thus, some 100 million dwt tanker tonnage might be rendered redundant in the coming years. One alternative is to employ such tankers for water transportation.

Technology exists to adjust and adapt vessels to carry fresh water with a minor degree of modification. This will benefit water-donating and water-recipient countries and tanker operators. Moreover, it may contribute to the conservation of energy, ecology and marine environment, create more employment and stimulate economic growth to the benefit of the consumers.

International financial institutions that have substantial interests in more productive use of currently laid-up tankers might join with Governments of both developed and developing countries to investigate various modalities for viable water transportation schemes. The United Nations system of organizations could conceivably act as a catalyst in this endeavour by identifying routes and initiating projects for water supply to water-short developing countries.

(d) Disadvantages of transporting water by tankers

Although the transport of water by tankers offers some unique opportunities for some water-short areas, there are also potential disadvantages, some of which are discussed below.

(i) Dependence

The use of long-distance transport of water places the importer in a situation where he is dependent on many circumstances beyond his control. These include: the weather and economic situation in and political relations with the water exporter; the physical and financial condition of the shipping companies and their vessels; the world petroleum and tanker markets; and the weather and political conditions along the tanker routes. That is why most schemes currently being proposed emphasize that the transported water would be a complementary source to existing supplies, to be used for agriculture or artificial recharge. Tanker supply as one of two or several sources might be an attractive option for some countries experiencing short- or longer-term shortages (Power, 1984).

(ii) Port and terminal facilities

The VLCC and ULCC tankers are large vessels, which require good port facilities for safely manoeuvring and docking. Channels with depths of more than 25 m are needed to allow fully loaded tankers to approach the unloading facilities. In addition, large pumps and storage facilities are needed so that the tankers can be rapidly unloaded to minimize turn-round time (and expense) in port. Treatment facilities may also be needed to treat any water requiring it.

All of this could mean that substantial capital investments must be made to permit tankers to be used for water transport to a country. It might be that those facilities could not be effectively utilized for other cargo to the extent necessary to distribute the cost. In locations that have small demands relative to the capacity of the tankers, large storage facilities must be constructed. Storage facilities will also be necessary to hold sufficient water for supply during an emergency situation. Those situations could occur if a tanker is diverted or damaged. The excess storage involves considerable expense.

(iii) Foreign exchange

Since the transport of water will almost always involve purchasing the water and shipping services from outside countries and companies, it will require a continual need for and expenditure of foreign exchange. The nature of the transaction makes it very easy for the exporter and shipper to cease operation if payments are not made when desired.

For oil-exporting countries, foreign exchange may not be a serious problem as either the monies are available or bartering arrangements can be made, but for some developing countries obtaining foreign exchange may be difficult.

5. Economic considerations

The unit costs incurred in a water transportation scheme will depend on the type of transport system and the scale of operations required. The latter will depend on the total annual demand for water, taking into account seasonal variations, and the distance from place of origin to destination.

The total transportation capacity requirements will depend on the residual demand for water after available sources are used. Scheduling of transportation vessels (tankers or tugs and barges) in a given scheme will be based on demands, capacities of vessels and the optimal use of marine infrastructure facilities at loading and discharging terminals.

For budgetary purposes, the unit costs of transport for water carried in marine vessels is assessed on an annual basis. The cost per unit is arrived at by dividing the total annual operating costs (amortization of capital on vessels, port charges, transport costs etc.) by the total amount of water transported. The costs of a number of water transportation schemes, both for dedicated water carriers and backhauling operations, are reviewed below and summarized in table 15. Those costs, however, have not taken into account the costs of water at source and the costs of storage at destination.

(a) <u>Oceanic inter-island water schemes</u>

In 1980, a case was selected for a study involving a small-scale water transportation scheme between oceanic islands 67 km apart from each other. The quantity requiring transportation was estimated at about 13,600 m^3/d of water. Because of the loading port draft constraints, a small tanker of about 5,000 m^3 carrying capacity was selected for the study. In addition, a one tug and two barge system of total carrying capacity of about 10,000 m^3 was also studied. The unit costs of water transported were estimted at:

(a) $1.00/$m^3$ ($3.78/1,000 gal) for tug and barge shuttle operations;

(b) $0.95/$m^3$ ($3.60/1,000 gal) for tanker shuttle operation (Bradanovic, 1980).

The estimated annual operating costs for the tug and barge shuttle operation and the tanker shuttle system were based on 1980 costs for the following:

(a) Fixed operating costs. Crew, stores and supplies, maintenance and repairs, insurance charges, and amortization of capital at 10 per cent (economic life of 12 years for tug, 8 years for tanker, 12 and 20 years for barge);

(b) Variable costs. Port charges, fuel and lubrication;

(c) Commercial costs. Commissions, claims, management fees.

Table 15. Summary of transportation costs of water transported by tankers, tugs and barges

Water transport scheme	Type of vessels	Approximate cost ($/m3)	Remarks
Small-scale oceanic inter-island shuttle service	Tug and two barges a/ (capacity 10,000 dwt)	1.00 b/	135 km round trip
	5,000 dwt tanker a/	0.95 b/	135 km round trip
	Tug and barges (capacity 10,000 dwt) c/	4.25	200 km round trip
	Tanker (40,000 dwt) d/	2.00-3.00	2,000 km round trip
	Small tankers e/	1.00-1.50	
Large-scale fresh water shuttle service a/	VLCC: 100,000 dwt a/	2.25	Round trip > 1,850 km
		3.00	> 3,700 km
		5.50	> 11,100 km
	ULCC: 300,000 dwt a/	1.20	> 1,850 km
		1.80	> 5,550 km
		3.00	> 11,110 km
Large-scale fresh water backhaul transportation	VLCC/ULCC: 250,000 to 350,000 dwt a/	1.10	Yakushima-PG at WS 30
		1.50	Dominica-PG at WS 60
		1.60	Rotterdam-PG at WS 50
		1.60	Dominica-PG at WS 70
		1.85	Yakushima-PG at WS 70
		2.00	Rotterdam-PG at WS 70

Notes:

PG = Persian Gulf

WS = World scale. World scale is the world-wide nominal freight rate scale widely used as a reference with the chartering of tankers. It is a set of standard values, revised twice yearly, which is quoted per ton of oil. The world scale base rate is 100 per cent and, depending on origin and destination, type of vessel, speed, tonnage, bunker consumption, and fixed hire rate, charters are fixed as a percentage of the world scale figure. Thus, a quotation of "world scale 100" would imply transporting the cargo at the full world scale price; "world scale 60" at 60 per cent of the full price: and "world scale 130" at 30 per cent above.

a/ Estimates based on studies referred to in section 5.

b/ Costs based on operating cost of fleet in 1980, amortization and operating costs of terminals.

c/ Actual costs, 1980-1981: Puerto Rico to St. Thomas, United States Virgin Islands.

d/ Estimated costs of tanker transport of water from Dominica to Aruba, early 1984.

e/ Costs of water transport from mainland Greece to small islands offshore such as Hydra and Spetses provided by A. A. Delyannis (1984).

However, caution needs to be exercised in using costs estimated from studies. The costs for the operation of barges and tankers between Puerto Rico and St. Thomas in the United States Virgin Islands are reasonably well-documented for the final years of operation from 1980 to 1981 and are considerably more expensive than those indicated above. For the Puerto Rico-St. Thomas operation about 40,000 m^3/mo (10.5 million gallons/mo) of water was being transported. The transport distance was about 100 km (60 mi) and it took about one day to unload a barge at St. Thomas. The water was purchased for about $0.40/$m^3$ ($1.50/1,000 gal) in Puerto Rico, delivered by small tankers and barges with capacities of 3,800 to 11,500 m^3 (1 to 3 million gallons) for a cost of about $4.00/$m^3$ ($15.15/1,000 gal). The dockage and pilot fees amounted to an additional $0.25/$m^3$ ($1.05/1,000 gal). Those costs were incurred under long-term contracts with a private commercial water hauler. The total cost of $4.65/$m^3$ ($17.70/1,000 gal) exceeded the local cost of desalted sea water, which was about $2.80/$m^3$ ($10.50/1,000 gal) during that period, but additional desalination facilities to produce the needed water were not completed until 1981.

In 1981, the Government of Dominica, which has ample sources of fresh water, entered into a long-term agreement with a private shipping firm to sell them rights to collect and ship water to other areas of the Caribbean. The agreement called for payments to the Government of $0.50/$m^3$ ($1.90/1,000 gal) of water, rising during a 15-year period to $2.00/$m^3$ ($7.60/1,000 gal). The firm would be financially responsible for the construction and operation of all necessary infrastructure involved in collecting and transferring of the water to the tankers. By early 1984 this operation had not yet begun. However, the Government of Dominica was selling fresh water in early 1984 for a price of about $1.40/$m^3$ ($5.30/1,000 gal) for delivery to Aruba. The water is being transported to Aruba in a small tanker of approximately 40,000 dwt. The cost of transport is roughly estimated to be about $2 to $3/$m^3$ ($7.50 to $11.90/1,000 gal). Studies were also being conducted on the economic feasibility of selling water to be transported to the Middle East as ballast on the return voyage of oil tankers delivering oil to refineries in the Caribbean.

(b) Large-scale fresh water shuttle service

The costs of large-scale fresh water shuttle service have been evaluated by Meyer (1983). The use of tankers in a shuttle between the water loading and discharging terminals has been found to be a relatively high cost operation compared with the low commodity value of the water.

The most significant parameter influencing the transportation costs of a shuttle service operation are the ship's size and the distance of the round-trip voyage. The larger the vessel and shorter the round-trip voyage distance, the lower the transportation cost will be. Figure VI indicates the transportation cost per cubic metre by tankers of 100,000 and 300,000 dwt carrying capacities over the respective round-trip voyage (distance in nautical miles). Representative costs are given in table 15 above.

The opinion of the French Port Authorities in Lavéra and Fos has been that barging water in medium-sized tankers to water-short customers within a 4,625 km (2,500 nautical mile) arc would be a realistic shuttle target. They are convinced that within this range tanker water costs can compare favourably with conventional desalination, and, with half the world's tanker fleet lying idle, there is no shortage of ships (Power, 1984).

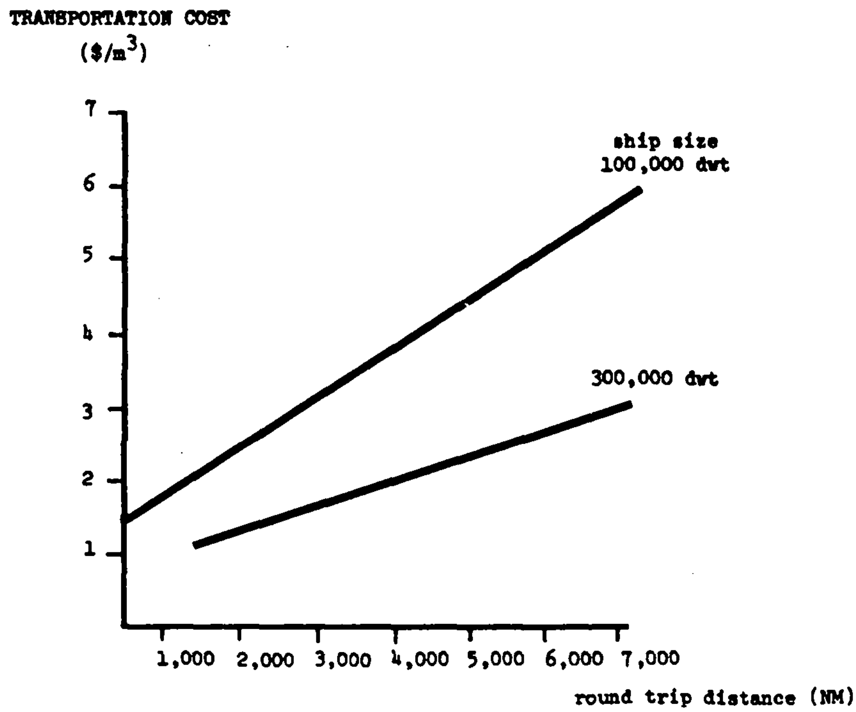

Figure VI. Shuttle service transportation costs, by ship size and round trip distance.

Source: T.A. Meyer, "Freshwater ballasting as a means for the conservation of energy and natural resources". In Proceedings of the International Seminar on Fresh Water Tanker Ballasting, Tripoli, Libya, 21 May-1 June 1983 (London, International Maritime Organization, 1983) p. 12.

(c) Large-scale fresh water backhaul transporation

Under this transportation arrangement, there are essentially three alternatives: use of segregated ballast tanks, use of clean ballast tanks, or backhauling of water on the tanker's return voyage.

The segregated and clean ballast tank systems, as discussed in section 3 above, are very promising, provided that the tanks are thoroughly cleaned, inspected and certified for the transportation of fresh water. Considering that up to 30 per cent of the tanker's carrying capacity may be reserved for fresh water ballast, VLCCs and ULCCs could make a substantial contribution to the water supply of arid coastal or island communities. Those vessels could transport from 25,000 to 80,000 m^3 of fresh water on their return voyages, depending on the size of the tanker.

The cost of transport for a backhaul scheme will have to take into consideration any cost for deviation from the normal route and the loss of time in loading and discharging. Holman (1983) presents an example of the costs which would be incurred from a deviation from the Yokohama-Ras Tanura tanker route. It is assumed that a 280,000 dwt tanker agrees to take on a fresh water cargo of 150,000 m^3 at the Philippines for discharge at Bahrain. This would mean some of the ballast would be carried in clean ballast tanks and some in tanks used for oil. The vessel averages 12 knots on 100 long tons of fuel per day. It takes 5.9 extra days for the deviation to Batangas Bay, loading, extra time at sea, discharge and allowing half a day for contingencies. The extra fuel consumed is 490 tons.

Holman estimates that the daily cost of such a vessel is $4,000 per day, equal to world scale 24-25.* This is the rate that Holman and his associates believe will permit tanker owners to avoid lay-up in a surplus market. Using a fuel cost of $180/ton, the total incremental cost would be $112,000. For 150,000 m^3, this would mean a unit cost of $0.75/$m^3$. Of course, this does not include the cost of water at its source. Actual circumstances differ, but this type of estimation forms the basis for negotiations between tanker owners, importers and exporters (Holman 1983). Depending on the size of the tanker involved and the voyage distance, the unit cost of delivering fresh water probably ranges from $0.75 to $2.00/$m^3$.

The transportation costs for backhauling of fresh water as a full ballast cargo on the return voyage are directly related to the crude oil tanker market. The ship operator evaluates the economics of transporting water in terms of costs and revenues. Revenues arising in the currently depressed tanker market are hardly covering the costs. Therefore, almost any economic contribution that exceeds the incremental costs connected with a deviation involving alternative work is of interest. In a good tanker market, the revenue from water transport deviation would have to be compared with the alternative income from oil transportation.

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* See note to table 15.

The buyer of fresh water, who will have to assume the extra costs for fresh water ballasting, will need to compare delivered fresh water costs with other available water supply alternatives. Fresh water backhauling involves a set of deviations varying with the location of the water port, quantity of water and the extra time required. It is quite possible that oil exporters would offer incentives for any vessels arriving with fresh water cargoes.

If suitable fresh water supply and reception facilities are available in the oil discharging and loading ports, respectively, there will be no extra cost incurred for the time lost to transport a quantity of fresh water corresponding to the normal ballast requirement. Although the additional transportation costs are virtually nil, this alternative may not be the most attractive for large-scale fresh water transportation schemes for several reasons. In addition to the problem of water availability, considerable investment would have to be made at the oil loading and discharging ports to handle the water and provide tank cleaning and water treatment.

There are a number of backhaul transportation alternatives that will give different transportation cost figures. In the following estimates, however, it is assumed that 100 per cent of the carrying capacity of the tankers is utilized for water cargoes and that the maximum tolerable oil concentration in the water at the receiving end is 15 ppm. Three common trade routes have been evaluated for tankers in the range of 250,000 dwt to 350,000 dwt.

These routes are:

(a) Rotterdam (Netherlands) - Persian Gulf (Cape route);

(b) Dominica (Caribbean) - Persian Gulf (Cape route);

(c) Yakushima (Japan) - Persian Gulf.

The economic evaluation, as seen in figure VII, has been based on a reasonable range of the tanker market conditions, that is, from world scale 30 to 60.

If the VLCC tankers (100,000 dwt and up) are used to backhaul water using 100 per cent of their carrying capacity, then their routes would be restricted because of their excessive draft. Currently, fully loaded VLCCs cannot negotiate the Suez Canal. Thus, their backhaul with a full load of fresh water from a European port to a gulf port would need to be via the Cape of Good Hope, which would add considerably to the normal round-trip distance. In order to use the Suez Canal, only a partial cargo of fresh water could be transported, which would reduce the distance, but decrease the payload.

The estimated costs for backhaul transport of fresh water appear to be considerably less expensive than for a dedicated large-scale fresh water shuttle service, when costs for equivalent distances are compared.

Table 15 at the beginning of this section summarizes the estimated costs discussed above. Those costs do not include the initial cost of the water nor, except as noted, do they include the cost involved in amortizing the port facilities and terminals.

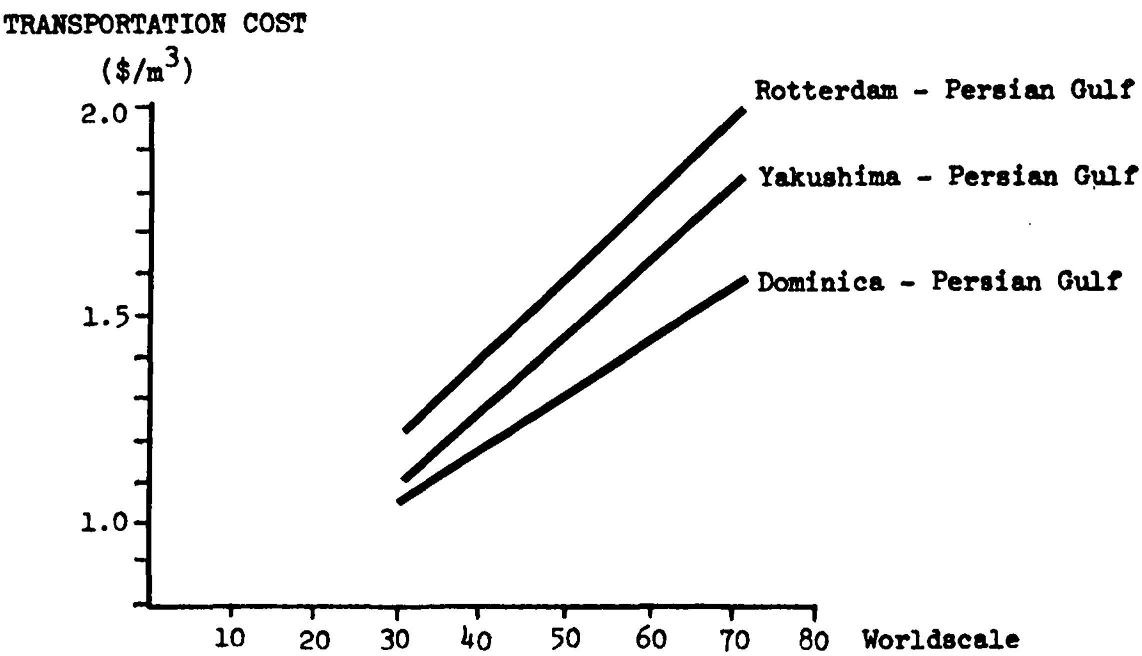


Figure VII. Fresh water backhaul transportation costs for 250,000 to 350,000 dwt tankers

Source: Adapted from T.A. Meyer, "Freshwater ballasting as a means for the conservation of energy and natural resources", in Proceedings of the International Seminar on Fresh Water Tanker Ballasting, Tripoli, Libya, 31 May-1 June 1983 (London, International Maritime Organization, 1983), p. 11.

(d) Tanker costs

The current overcapacity in tanker tonnage has resulted from overbuilding on easy credit in the 1960s and 1970s and the decline in average yearly growth of oil exports since 1974. Crude oil shipments reached a peak of 1,538 million tons in 1979, falling steadily to 1,045 million tons in 1982. From 1975 to 1981 the average volume of tanker demolition had been 10.3 million dwt per year. However, in 1982 over 20 million dwt of tanker capacity were scrapped. A total of 242 tankers were removed, of which 61 were VLCCs. In 1983 it was expected that VLCCs would account for 15 million dwt out of 23 million in tanker tonnage sent for scrapping, according to London's Drewry Shipping Consultants (Economist, 10 December 1983). The decline in oil shipments resulted from lower oil exports as well as the more widespread use of pipelines.

Second-hand prices for VLCCs have therefore fallen just above scrap levels, and a newly ordered VLCC might cost 10 times as much as a second-hand tanker (less than seven years old). For example, the value of a VLCC of approximately 226,000 dwt fell from about $45 million in 1973 to $5 million in mid-1982. A newly built VLCC ordered from Japan in mid-1982 would have cost approximately $55 million, but no new orders were being made. In late 1983 a 330,000 dwt tanker built in 1976 was sold to a Norwegian tanker operation for $6 million (Economist, 10 December 1983).

The tonnage surplus situation therefore offers a unique opportunity to acquire tankers at low second-hand prices for fresh water shuttle services. The laid-up tankers represent an unused resource which could be productively employed in various water transportation schemes at low initial capital costs. Current bargains for tankers will not last indefinitely, however, especially if demolition trends continue and the world economic situation improves.

C. Icebergs

1. Historical background

Although the potability of iceberg water was recorded by Captain Cook in 1773, the economic feasibility of transporting icebergs or iceberg-derived water to drought-stricken regions of the world has not yet been proved by demonstration. There were a few instances between 1980 and 1900 of small icebergs having been deliberately towed from Laguna San Rafael, Chile, to Valparaiso, the port of Santiago, and from Antarctica to Callao, Peru (12° S), the latter a distance of nearly 4,000 km (Rosenberg, 1978). Moreover, a considerable amount of research has been carried out on the behaviour and structure of icebergs. Following the sinking of the Titanic in the North Atlantic in 1912, the United States Coast Guard took over operation of the International Ice Patrol in 1914. It was recognized that surveillance had to be maintained off the costs of Newfoundland and Greenland because during the spring of each year hundreds of icebergs drift into North Atlantic shipping lanes. Since 1968 more extensive surveys have been carried out using aerial photographic documentation, shore visits and measurements of the position of icebergs. The scientific and operational reports of the International Ice Patrol go back almost 70 years and form the backbone of peresent day iceberg technology (Kollmeyer, 1978).

In the Second World War military forces from North America and the United Kingdom of Great Britiain and Northern Ireland considered the use of tabular icebergs as aircraft carriers in the North Atlantic. Although this idea was abandoned, icebergs have been used as landing and experiment stations (Galal, 1978). Icebergs calving from the ice fields of northern Canada have been used for many years as floating platforms in suport of numerous scientific experiments; they even provide their own source of fresh water for the scientific stations. A large "ice island" (6 by 14 kms, 58 m thick) was occupied by the United States from 1952 through 1961, as the first sizeable United States drifting station. The island completed a circular route in the Beaufort Sea in 10 years (Kelley, 1978).

In the early 1950s the first scientifically based proposal for transporting an iceberg for potable use had been articulated by John Isaacs of Scripps Institution of Oceanography at La Jolla, California. He proposed that an iceberg might be transported from Antarctica to supply the fresh water needs of southern California. The results of his research were not published until 1961, however. He based his proposal partly on the fact that a few times in recorded history an Antarctic iceberg had turned up on the shore of Peru, brought there by the Humboldt current. Moreover, during the 1950s there had been an example of the commercial transport of Alaskan ice and later glacial ice to San Francisco when water was in short supply. Since that time, larger-scale use of glaciers for water had been suggested many times (Kelley, 1978).

The idea of towing icebergs to Chile was also being discussed in the mid-1950s at the Snow, Ice and Permafrost Research Establishment (SIPRE), United States Army Corps of Engineers. The original idea was relatively simple: to sail south from Valparaiso, Chile, with a few tugboats, find a good iceberg, attach cables to it, tow it into the Humboldt current and keep it on course until it floated up along the Chilean cost. Then it would be pushed into a cove, and a fabric curtain would be strung across the mouth of the cove. The promoters would install pumps and pipelines and establish a prosperous farming community. This was to be the seed for development of irrigated agriculture on some 50,000 km^2 of very fertile volcanic soil along 2,500 km of arid coasts of Peru and Chile, where the cold water is deep right up to the coastline (Bader, 1978).

The first serious research on the feasilbility of iceberg transport was published by Weeks and Campbell in 1969 and 1973. They had expanded the original idea by looking at western Australia and the Namib desert in south-west Africa as possible destinations. Those areas have shallow coastlines, however, and the iceberg would have to be anchored 10 to 20 km off the coast. Thus, the operation had become much more complicated (Bader, 1978). Weeks and Campbell did contribute significantly to the debate, however. They reported some statistics on the numbers and sizes of naturally occurring icebergs in the Antarctic and estimated towing power requirements and expected melting rates. They concentrated on terminals in the southern hemisphere because of the melting problem (Weeks and Campbell, 1973).

The idea was carried further by Hult and Ostrander (1973), who developed a model for transporting an iceberg from the Ross Sea in Antarctica to southern California. Available environmental data on currents, winds and temperature were included in the model. Although the data were relatively crude and limited, their preliminary feasibility model showed that it was a feasible operation, but it would require insulation of the icebergs for acceptable survival to the northern hemisphere.

Engineering experiments on the towing of Arctic icebergs off eastern Canada were undertaken in the early 1970s by Memorial University of Newfoundland. Seven icebergs were towed, ranging from 77,000 to 265,000 tons. The towing experiments utilized different types of towing slings attached to a regular 2,500 ton cargo vessel. Iceberg towing has now become a fairly frequent practice when oil rigs or platforms are threatened in the Labrador Sea and western Greenland (Bruneau and others, 1978).

By the mid-1970s the idea of harnessing icebergs for the vast amounts of fresh water and energy stored in them had captured the imagination of many scientists and laymen. However, none of the Governments were willing to put a major effort into researching the feasibility of such a venture until Saudi Arabia hired engineers to look into the feasibility of delivering icebergs to the coast of Saudi Arabia.

The expanded interest stimulated by the Saudi initiative led to the holding of the First International Conference and Workshops on Iceberg Utilization for Fresh Water Production, Weather Modification and Other Applications at Iowa State University, Ames, Iowa, from 2 to 6 October 1977. A wealth of information on icebergs was brought together at that conference (Husseiny, 1978). However, interest waned following 1977, perhaps because the economic feasibility of iceberg utilization looked questionable. The need for fresh water may not yet be great enough to justify the towing of icebergs to fill that need. Other non-coventional sources, such as desalination, transport by tanker and waste-water reuse, currently seem more realistic and less expensive. However, the glaciers are an enormous source of unexploited water, which eventually may become usable.

2. Technical considerations

Approximately 80 per cent of the earth's supply of Fresh water is imprisoned in glacier ice, the equivalent of about 60 years' precipitation over the entire globe. Even in North America the volume of water stored in snow and ice exceeds that of all rivers, lakes and reservoirs. Although there is not now an apparent economic way to utilize them, small icebergs entering the Atlantic Ocean shipping lanes number in the tens of thousands. Ice is a vast resource barely tapped. Water is now in storage for mankind to use when he desperately needs it (Kelley, 1978).

Hult estimates a total continuous annual yield from Antarctic icebergs of 1,200,000 million m^3 of high-quality water, which could be harvested beneficially and without depletion or environmental damage in Antarctica. If it were possible to deliver 10 per cent of the annual yield, it would satisfy the water demands of an urban population of 500-600 million, with an annual usage of 200-300 m^3 per capita (Kelley, 1978; Hult, 1978a).

(a) Source of icebergs

The large tabular icebergs of the Antarctic appear to be the most suitable for transport by towing. Major iceberg production sites in Antarctica are the Ross and the Amery Ice Shelves. The Ross Ice Shelf is the largest (530,000 km^2) and most accessible in the area and constitutes abut one third of the Antarctic ice shelf. The flow of ice in the Ross Shelf tends to move in rigid blocks; the average discharge velocity of ice at the front edge of the shelf amounts to about 700 metres per year. The icebergs calve or break off the seaward edge of the Ross

Ice Shelf in January to March and should produce a sufficient supply of usable tabular icebergs for transportation to the west coast of South America and northward (Hult, 1973).

The second largest shelf, the Filcher (400,000 km^2) is considered by Weeks and Campbell (1973) as the best source of icebergs for transport to the Namib desert on the south-west coast of Africa. The Amery Ice Shelf, although smaller, is considered to be the best supplier of icebergs for Australia. This is an extremely productive shelf and the most important of the smaller ice shelves. Icebergs in the Antarctic have been found floating as far north as 50° S.

There are also tabular icebergs in the North Atlantic, but they are neither common nor large when compared to those of the Antarctic. The main source of tabular icebergs in the Arctic is the Ward Hunt Ice Shelf. Unfortunately, iceberg producion there is not consistent and the icebergs do not normally exit from the Arctic Ocean into the Greenland Sea where they could be transported by towing (Kelley, 1978). On the other hand, Kollmeyer (1978) has speculated on the possibility of using Greenland icebergs as a source of water for countries bordering the Mediterranean in North Africa or the Middle East.

(i) Size and shape

The most suitable shape for an iceberg which is to be transported is tabular, roughly rectangular in cross-section, to avoid rolling or calving during towing. The tabular shape of Antarctic icebergs makes them attractive for towing. The best shape is one with a large length to width ratio to reduce drag and width to thickness ratio greater than unity, so that the iceberg does not turn over. Weeks and Campbell chose a length to width ratio of 4.0 for their experiments because that is the largest frequently found. A width to thickness ratio of at least 1.5 was considered necessary to ensure stability.

A limited survey of icebergs in the east Antarctic has indicated that the icebergs have a mean length of greater than 1.0 km and a mean height above water of about 50 m (Hult, 1973). Approximately one sixth of the iceberg's total height appears above the surface. Lengths of up to 21 km do not appear to be uncommon (Kelley, 1978).

Weeks and Mellor (1978) noted that icebergs with horizontal dimensions more than 2 km may well be prone to mechanical break-up by long wavelength swells. They stated that a suitable iceberg should not be longer than 2 km and should be 0.5 to 2 km wide, depending on what length/width ratio is considered most advantageous. Those dimensions correspond to up to $1.0 \times 19^9 m^3$ of ice or up to roughly $0.5 \times 10^9 m^3$ of ice delivered off the coast of Australia. Such a scheme was deemed viable only if the water were intended for industrial or municipal use. However, it does make a case for the small iceberg (Weeks and Mellor, 1978).

Other researchers, particularly Hult, consider that only much larger sizes of iceberg could be transported economically. He proposed that long trains of more than 20 km be formed of insulated icebergs for transport to North America.

The sea ice forms in March-April and locks up an increasing area, including its icebergs, until October. The daylight season thaws the shallow (1-2 m) sea ice and most of the icebergs of interest become unlocked by January to March for easiest collection into iceberg trains (Hult, 1973).

(ii) Quality

Antarctic icebergs have been found to be remarkably free of impurities (about 4 ppm mineral content), because they are formed from precipitation in a relatively pollution-free atmosphere. The large tabular icebergs are practically all carried to sea from the ice shelves, where most of the bottom-rafted debris is melted and dropped off. One reason that the idea of harnessing the icebergs has been taken seriously is that pure ice is potentially a very valuable resource and could help solve problems caused by a shortage of high-quality water throughout the world.

(b) Melting rates

There has been considerable speculation on melting rates of icebergs, and several models have been simulated. The overall viability of any such scheme depends on the portion of the iceberg remaining when it reaches its destination.

In Hult's model, the melting rates of unprotected icebergs were dependent on local heat-transfer coefficients and water and ice temperatures. Thus, the rate varied along the length of the iceberg and with depth changes in ocean water temperature. Actual melting rates were determined only crudely. However, Hult found that more than 1,000 m depth of ice would melt from an unprotected water-exposed ice surface in transit to the northern hemisphere at any reasonable transit speed. Hult concluded that it would be necessary to insulate icebergs travelling to the northern hemisphere, and that insulation by the quilt network method would limit melting to less than 10 per cent in one year's transit (Hult, 1973).

Weeks and Campbell, in their appraisal of icebergs as a source of fresh water, concluded that large Antarctic icebergs could be transported without insulation to destinations in the southern hemisphere with less than half the ice melting in transit (Davis, 1978)

J. G. Job (1978b) did a simulation of towing unprotected icebergs from the Antarctic (66° S) to latitude 38° S. His nominal findings were that icebergs could be delivered with about 50 per cent yield to latitude 38° S, but that the rate of deterioration in warm waters indicated that protection would be required for longer journeys. Therefore, his conclusions agree essentially with Weeks and Campbell. He noted, moreover, that the task of moving an iceberg through the temperate waters of the southern hemisphere was a relatively simple operation compared to the idea of transporting one from Antarctica to Saudi Arabia (Job, 1978b).

In 1976 United States Coast Guard scientists tracked a large tabular iceberg off the coast of Newfoundland, and their findings were much less optimistic than the above simulations. Although the surface water temperature at the time (May/June) was between 2° and 4° C, the iceberg diminished in surface area from 19 to 11 hectares in 25 days and then disintegrated (Bader, 1978).

(c) Weather modification

It is likely that towing an iceberg to a warmer climate would result in altered weather patterns. An iceberg is a solid mass, somewhat like a small island, and a heat sink. Thus, it will influence wind and ocean currents to some degree. The actual effects of iceberg transport are uncertain because it has not yet been done, and private interests trying to develop the technology have kept much of the data to themselves. Uncertainty may lead to uneasiness on the part of some countries: an iceberg off the coast of one country may influence the weather in a neighbouring country. Such an iceberg project is bound to cause some subtle change in weather, so the argument becomes one of degree. A huge environmental change can result from a change of only one or two degrees Celsius. Therefore, it would be desirable to have some form of international supervision, and an environmental evaluation should accompany all efforts at iceberg utilization. Among the items to be monitoried are: (a) the iceberg's impact on wind currents, precipitation and evaporation patterns; (b) its impact on ocean currents, heat transport and upwelling and (c) the impact of removing the iceberg on the total polar ice mass (Ponte, 1978).

Weeks and Campbell expected that the in-transit effects would be minimal, but that the icebergs would definitely cause a drop in the sea temperature near the delivery site. In addition, there would be a decrease in the salinity of the sea water as a result of the mixing of escaped fresh water during the melting process. There would also be the possibility of changes in the local climate in the vicinity of the moored icebergs; for instance, the increased occurrence of fog and rain (Rosenberg, 1978).

Hult (1973) seemed to think that the main impact of a large iceberg would be limited to an area a few kilmoteres in length from the ice itself. An iceberg train of tens of kilometres in length tethered on the ocean bottom 5 to 10 km from the California shore would serve as a huge breakwater to tame the inland sea. Hult assumed that the local waters would be cooled slightly since the ice would have a cooling effect on hot thermal pollution. He noted that this would have local effects on marine life, and the migrations and types of marine life would likely be modified as would be expected from a small change in latitude. Those effects would have to be studied (Hult, 1973).

Scientists generally agree that even a heavily insulated iceberg brought to lands such as Saudi Arabia or southern California, where such ice is alien, would cause more condensation of water vapour from the air than it would give off in evaporation. Simpson calculates that in the region of the Red Sea an iceberg could produce significant amounts of fog. She speculates that, if anchored off the east coast of Florida, an iceberg might reduce evaporative energy available to hurricanes passing nearby (Ponte, 1978). While that could potentially weaken hurricanes, it might also slightly weaken the heat transport of the Gulf Stream, however. Were the Gulf Stream blocked, currents to northern Europe would be much cooler. Any such effect on ocean currents could influence many countries and involve the iceberg purchaser in controversy if those nations saw a hazard in any small modification of currents (Ponte, 1978).

The promoters in Saudi Arabia, on the other hand, would welcome some weather modification on their coast. They hope that an iceberg might lead to a change in vegetation and climate in some coastal areas. The cooling effects of the large cold iceberg surface might bring about rainfall over the arid and potentially irrigable land in the province of Asir, south of Jeddah. In the hot summer, when the humdity is over 90 per cent, the floating berg would cause condensation of atmospheric water, which might add up to 25 per cent to the yield of fresh water produced from the melting ice (Abdul-Fattah, 1978).

3. Recent technological advances

The transport of a large iceberg from Antarctica to an arid region is a major undertaking beset with uncertainties. Identifying an iceberg, insulating it, harnessing it, providing the power to transport it perhaps 8,000 km through the open seas and across the tropics, mooring it at the destination and extracting the water from it are all challenging engineering problems for which solutions are without precedent.

Perhaps the most challenging and complex problem is that of actual transport. The magnitude of forces required, the possibility of fractures and fragmentation developing to cause the icebergs to roll in transit, the losses en route through melting, and possible insulation are all aspects on which considerable study and experiments must be carried out before answers can be obtained. One approach to solutions is to study the behaviour of small-scale models under given conditions in which the significant parameters may be varied to optimize the solutions and identify critical conditions. Hult suggested (1978b), that a pilot project be carried out, which would involve towing two small insulated icebergs to California. No Government or research institute has yet come up with the funds for such an experiment, so ideas for such a scheme are still within the realm of speculation. Some of the technologies that have been developed or proposed are discussed briefly below.

(a) Remote sensing

The problem of iceberg selection has been simplified by satellite imagery of high resolution. Improvements in very high resolution satellite techniques coupled with real time transmission of data and remote sensing by aircraft should greatly improve, if not be essential to, the success of economical large-scale use of the continuous Antarctic iceberg yield.

Tracking of icebergs also adds to limited knowledge of ocean currents around Antarctica. Long-term tracking and surveillance will be relevant to the selection and harvesting of icebergs for use in a particular region. A variety of remote sensing and enhancement techniques are available and can be used not only to track, but to learn more about the dynamics of the environment through which icebergs must move (Kelley, 1978).

Satellite imagery has demonstrated an abundance of Antarctic icebergs of suitable size and shape, according to Hult (1978b). The imagery should be adequate for selecting the area east of the Ross Ice Shelf from which pilot icebergs can be chosen and identified. Specific alternative icebergs of between 300 and 500 metres thick could be chosen for the pilot project.

Sea ice, because of its high reflectance, can be identified in all the multi-spectral scanner (MSS) spectral bands of Landsat satellites, although bands in the visible range are the most useful for mapping ice edges and detecting thin ice. Because of high contrast between water and ice, linear surfaces as narrow as 70 cm can be observed. Therefore, Landsat data are ideal for studies of patterns and floe size distributions. Also, the different classes of thin ice can be noted and distinguished from thicker ice.

Thermal infra-red imagery and measurements from the infra-red scanners on Nimbus satellites and the scanners on satellites of the National Oceanic and

Atmospheric Administration (NOAA) are being used increasingly in operational and research applications for sea ice surveillance. Those investigations have shown that infra-red band and microwave imagery provide a means of mapping gross ice boundaries during periods of polar darkness.

The limitation on satellite sensing of sea ice and icebergs at visible and infra-red wavelengths is cloud cover. Emission from ice surfaces at microwave wavelengths is attenuated only slightly by clouds typical of polar regions. Large brightness temperature contrasts - owing to emissivity rather than physical temperature differences - found at ice-water boundaries can be observed readily through clouds.

(b) Transport methods

There have been several attempts over many years to demonstrate that moving icebergs was feasible. Three United States icebreakers demonstrated that an elongated tabular iceberg could be moved 4 km in 12 hours. It was found that the total drag of the iceberg could be considerably lowered if it had a large length to width ration. Slow steady speeds of about one knot were found to be most effective. At this rate, transport times to the southern hemisphere would range from 120 to 160 days. Weeks and Campbell (1973) found that, in spite of inherent engineering problems and evaporative and melting losses, it would still be worth the effort (Kelly, 1978).

Hult emphasized that the cost of delivering icebergs would depend on the design of transport operations and configurations of the iceberg "trains". Narrow trains of 300 to 600 m width would be desirable because they are estimated to reduce the net Coriolis effect on the icebergs. Trains more than 20 km long would increase the mass, transport resistance and insulation costs proportionally.

Hult suggested that the transport operation could utilize shrouded propellers driven by electric motors strapped to the sides of the iceberg train. Power could be supplied from a diesel fuel power plant on an escort ship.

(i) Tugs

The most commonly suggested method of transporting an iceberg is by means of very powerful tugboats. Weeks and Mellor (1978) noted that the power requirements for towing large icebergs through the heavy sea ice were tremendous. For example, taking a representative thickness of Antarctic sea ice as 1 m, and estimating the power required to move a 1 km wide icebreaking ship through such ice at a velocity of 1 knot, they obtained a value of 3.3×10^5 kW (449,000 shaft horse power (shp)). It would take 17 of the largest tugs currently available to provide that amount of power. In fact, the actual power requirements through the sea ice would be greater since a blunt-edged iceberg is hardly as efficient an icebreaking system as a specially designed ship.

Large icebergs require a bollard pull of 100 to 10,000 kilo Newtons (kN). The size and power of individual tugs has increased significantly since the late 1960s. At that time the largest tug had a power limit of 9,000 hp. By the late 1970s tugs had been constructed by the South African Marine Corporation with 26,200 hp. The largest United States Navy ocean-going tugs have a bollard pull of 500 kN, while commercial tugs are available with a bollard force of up to 1,200 kN. As noted above, several tugs would be required to tow one large iceberg.

The towing force of a tug is determined by the shaft horsepower and the propeller characteristics, and it is calculable when those things are known. Weeks and Mellor plotted values of rated bollard pull for existing tugs as a function of installed power, based on data from an industry survey conducted in 1977. Most of the data lie in a band representing pulls of 0.10 to 0.18 Newtons/Watt.

A diesel tug with direct or geared drive might have a fuel consumption of about 1.8 tons of fuel per hour for each 10,000 shp. At this rate a tug utilizing 20,000 shp would burn about 15,900 tons of fuel on a six-month tow or 23,800 tons on a nine-month tow.

Hult estimated that for his proposed pilot project, approximately 4,000 kN of towing force would be required to tow two small icebergs over a one-year period to California. He estimated that this could be provided with 40,000 hp, utilizing perhaps two tugs and a tanker, consuming 80,000 tons of fuel.

(ii) Other transport methods

Researchers have proposed a number of systems for transport, some of which have been tried on a scale-size model. Some are listed below.

(a) A thermodynamic cycle similar to ocean thermal energy conversion could provide the needed power. Energy is available from the iceberg in two forms: salinity gradients and temperature gradients. The energy available from the difference in temperature between the ice and the sea water could be used to turn a large (say, 23 m diameter) propeller. In transit from Antarctica to Los Angeles, 1.6 per cent of the iceberg would be converted to water as a result of power extraction (Fuhs and others, 1978).

(b) Paddle wheels attached along both sides of the iceberg would be capable of running under water. They would be powered by power generation units located on top of the iceberg or on ships accompanying the iceberg. By varying the speed of rotation of the paddle wheels on one side, it would be possible to keep the iceberg on the correct route (Al-Faisal and Ismail, 1978).

(c) Another alternative uses a parachute system similar to a floating anchor, and is said to produce an effective thrust with an efficiency five times greater than a conventional propeller. This parachute would be placed in the water on a line of supporting floats ahead of the iceberg, which would be towed towards it by a suitable reeling method. When the iceberg approaches the parachute, a support ship redeploys it out ahead (Job, 1978a).

(d) Another proposed system would utilize a form of solar power, specifically the difference in osmotic pressure between sea water and the melt water from icebergs. The melt water would be converted to an osmotic propulsion system, propelling the iceberg with the assistance of a support ship (Davis, 1978).

None of those systems has yet been attempted. Only tugs, cargo ships and icebreakers have been used to move icebergs drifting in the path of drilling platforms.

(c) Slings and harnesses

Under the sponsorship of the East Coast Petroleum Operators Association, Bruneau and Dempster carried out iceberg-towing experiments in the early 1970s with Arctic icebergs off eastern Canada. The largest iceberg towed was 90 m wide, 115 m long, 23 m above water at its highest point, and weighed 265,000 tons.

The ship was a regular cargo vessel of 2,500 tons and 84 m long, with engines producing a total of 2,500 shp. Two types of towing sling were used - the first was a double wire sling 220 m long fabricated from two 2.5 cm steel wires; the wires were connected by 8 mm chains 9 m in length. The whole thing was supported by floats on 12 m chains.

The second type was a single wire of 220 m length made of 20 cm polypropylene, connected to a 220 m towing hawser attached to the towing bridle on the ship. The second type was much less cumbersome and better for handling tabular bergs, since the single sling makes one groove in the iceberg at the water surface. The double sling gets a better grip on non-tabular bergs, but it is more expensive and more complicated to handle.

The techniques originally demonstrated by Bruneau and Dempster in 1972 have now been adopted as a routine feature of exploration activities along the Labrador coast. Benedict reported that the towing method used involves attaching a positively buoyant 10 cm polypropylene rope around the waterline and applying between 45 and 310 kilo Newton force at that point to direct the iceberg away from the drilling platform. The system must be quickly deployed and recovered. Because of the relative size of the iceberg to the tender vessel, this means circumnavigating the iceberg while deploying more than 600 m of necessarily bulky equipment as fast as possible.

An improved system was suggested by Benedict because the existing configuration sometimes failed for smaller, unstable or dome-shaped icebergs. He added one elastic and one submerged member to the floating member, the three held together by a shackle and swivel assembly. This configuration was said to overcome the problem of adaptability common to all systems that use two or more parallel load-bearing members at the same time. Furthermore, it is said to be easy to handle and compatible with existing systems (Benedict, 1978).

In Hult's proposed pilot project for transporting two small icebergs to California he suggested experimentation with various harnessing techniques along the route. A cable network should be designed to apply thrust to the iceberg throughout its life including at the time of acquisition in the Antarctic, export to its destination and mooring while being converted for fresh water and cooling. Proprietary harnessing techniques would be compared which would maintain the harness in its proper location under proper tension and with the appropriate distribution of stresses on the ice near the corners of high stress. Connecting points for towing and mooring cables would be available at each corner (Hult, 1978b).

(d) Insulation

As previously mentioned, Hult determined that it would be essential to insulate icebergs if they were to be brought to the northern hemisphere. He suggested wrapping the iceberg with overlapping bands of tough plastic fabric about

3 m wide along its width. Each lap should require no more than one roll of plastic. He assumed that only the sides and bottom of the iceberg would have to be covered for insulation. The top side could be used to cinch the loop and sink the cinch edges of the film into the ice to anchor it against downstream skin friction pull.

Underwater preparation would involve passing a weighted cable under the iceberg between two tugs. The cable would be tied in an endless loop around the iceberg and, with appropriate top-side winches, the cable would pull a tracking, ice-grooving and film-unrolling remote control vehicle around the bottom of the iceberg.

The rolls of plastic might consist of two layers of thin film with the layer next to the ice interlaced with a waffle network of tension cords (at, say 0.2 m spacing) and with the two layers of film laminated together at the edges with the major cinching cords. As the tension cords sink into the ice they would trap melt water in the waffle quilt pattern to form pockets of still water under the stretched film, between the iceberg and the flowing sea water (Hult, 1973). Hult felt that this system would limit melting to less than 5 per cent per year for most icebergs.

Bader (1978) was less optimistic, believing that the insulation would easily get stripped off. If even a small section of insulation were to break away at the waterline during a storm, the break would quickly deepen by undercutting and meltback, leading to the widespread stripping away of more skin.

Researchers involved with testing the possibility of transporting icebergs to Saudi Arabia suggested that thermal insulation was more promising (Basmaci and Jamjoom, 1978; Frisch and Kresta, 1978; Hussain, 1978). Extensive analyses were carried out on various types of foam. Foam was considered superior to plastic wraps because of its ease in application, better insulating properties and better stability in transit. Polyurethane foam was selected as the best since it has the lowest thermal conductivity of all known insulating materials. Hussain found that polyurethane foam could be sprayed on the surface of the iceberg by specially built equipment which could operate underwater by remote control. The underwater remote control vehicle would supply foam for the bottom of the iceberg through an insulated pipe using a frothing system. For the sides, insulation would be covered by a reinforced plastic sheet or foam panels could be bound together using a tongue and groove system.

Hussain estimated costs for this insulation system to cover an iceberg measuring 1,200 m x 300 m x 260 m at $8.1 million (1977 prices). This would have amounted to approximately $\$0.09/m^3$ of ice. Taking inflation into account, the figure would reach about $\$0.15/m^3$, which still seems very low for the type of complex operation suggested.

4. Application in developing countries

From historical evidence, as well as from more recent simulations, it seems that the most feasible route for transporting icebergs would be along the Humboldt current going north from Antarctica along the west coast of South America. The countries with arid areas along this route are Chile, Peru and possibly Mexico. Chile and Peru have the advantages of very deep and cold water along their coasts.

Thus, those two developing countries could most easily benefit from a scheme for transporting uncovered icebergs from Antarctica. Oceanographers are counting on major forces of nature to aid in reducing costs. Once the tug enters the Humboldt current off the coast of South America, most of the iceberg's northward movement would be made by ocean flows, and the vessel's main task along the route would be to get and keep the iceberg in the current flows. Nevertheless, the expenses are great and other alternatives would certainly be chosen by the South American countries before they would venture an iceberg scheme. In regions further north along that route, such as Mexico or California, insulation would be necessary and the cost would probably be prohibitive for the time being.

On the other hand, in the late 1970s, Hult still believed that the best prospects for large-scale use of Antarctic icebergs would be in the south-western United States and north-west Mexico, where most of the required resources for such use might be made available. Most other demands would most likely be on a smaller scale at many locations throughout the world. However, if a cash demand were developed for food to supply the world population with an adequate diet, Hult believed that the coastal areas of North Africa, the Middle East and Australia could be developed for the large-scale use of Antarctic icebergs (Hult, 1978a).

Saudi Arabia has indicated the most serious interest in transporting icebergs in recent years, but the Antarctic-Indian Ocean route represents perhaps the most difficult case. Most of the Indian Ocean along the proposed tow route is covered by water of greater than 20°C temperatures. During the months of January and February (the north-east monsoon), the waters of the Arabian Sea reach temperatures of 25° to 28°C. From July to August, during the south-west monsoon, surface temperatures are above 28°C. The high sea surface and air temperatures would cause substantial melting, and severe storms are likely to plague the tow. This scheme seems impossible to implement unless thermal insulation and protection can be provided for the iceberg or unless a method can be devised for collecting melt water along the route (Denner, 1978).

Weeks and Mellor (1978) felt that transport of icebergs might be feasible for south Australia. The resulting operation would provide the experience necessary to assess realistically the chances of successful delivery of icebergs to more distant sites and time to contemplate ways of solving the formidable problems of decreasing in-transit melting losses by insulating icebergs from the surrounding sea. However, the coasts around Australia do not provide the depth necessary to moor an iceberg close by. Moreover, limits on demand are imposed by increasing costs of pumping water further inland and higher up.

Another serious problem that has not been adequately addressed is what to do with the iceberg on arrival. The questions of how to moor the iceberg, dispose of it, collect the water before it mixes with the surrounding sea water, and store huge quantities of water at the terminal must be answered before such a scheme could be considered feasible.

In the short term, perhaps it would be feasible to use the water from an iceberg without transporting the whole iceberg. The iceberg could be quarried by blasting and the resulting blocks of ice could be loaded onto an ore transport ship. This method would supply as much water as could be loaded onto the ship (that is up to 200,000 m^3), would eliminate melting and towing problems, and would deliver the water much faster than an iceberg-towing operation.

Despite the considerable research and speculation that has gone into trying to prove the feasibility of an iceberg transport operation, the technology has not yet been developed, nor has growing demand justified the necessary expenditure. This water will continue to be stored for future use at a time when mankind becomes desperate enough to require its harnessing.

5. Economic considerations

During the Iceberg Utilization Conference held at Ames, Iowa, in 1977, many of the researchers estimated costs for various aspects of iceberg transport: fuel, tugboat and tanker operation, insulation, and others. All of those costs were measured in huge orders of magnitude. Even for Hult's pilot project, which would tow two small icebergs from Antarctica to California, the costs were estimated at $30 million ($48 million at 1984 prices).

The magnitude of initial expenditures for an iceberg project for Saudi Arabia was estimated at anywhere from $10 billion to $50 billion in the multivariate planning model developed by Ahmed, Cho and Abdul-Fattah (1978). Allowing for inflation, that project would cost somewhere in the region of $16 billion to $80 billion. According to the researchers, this expenditure would in the long term result in relatively low costs of water (from $0.02 to $0.85/m^3 ($0.08 to $3.20/1,000 gal) at today's prices), because of the massive amounts of water transported. However, the initial investment for facilities, dredging and port modification would be so great that there are few nations which could even contemplate such an expenditure. Such a project will probably remain within the realm of speculation for some time to come.

III. WATER REUSE

A. Introduction

Water is used for a variety of applications, such as drinking, cooking, cleaning, sanitary flushing, agricultural irrigation and industrial processing. In many industrialized countries, water is so plentiful that the same grade of water is used for all of those purposes. In water-short areas, where the cost of potable grade water is very high, it may be prudent to consider the use of water of lesser quality for some of those applications.

In the overall use of water for domestic purposes in urban areas, very little water is actually consumed. It is used mostly as a convenient method of transporting wastes in the form of dissolved or suspended material away from home or work to a place where it can be discharged. Even in the strongest domestic waste waters, the waste materials seldom amount to more than one tenth of 1 per cent of the waste-water stream. Where water is abundant, then it is usually easier to use new water rather than clean up the used water (or sewage). However, as new water becomes scarce and expensive, it becomes more cost-effective to remove some of the waste materials and reuse the water than to develop new sources. The greater the percentage of waste materials (contaminants) that are removed, the more difficult and expensive the treatment process becomes. A solution that is generally used is to remove only a portion of the contaminants and then to reuse the water in an application that will tolerate the presence of those materials. Common applications for reclaimed water are for agricultural and landscape irrigation, sanitary flushing water and industrial cooling. In each of those cases, the use of reclaimed water will substitute for higher-grade water, thus reducing the overall demand for new water in an area.

If a community collects its waste water in a sewerage system, then it has an opportunity to treat and reuse it for some beneficial purpose. The extent of treatment needed is governed by the way in which the reclaimed waste water will be used. Those uses can range from cooling water to agricultural irrigation to potable water. The reclamation of waste water for the deliberate direct use as potable water has only occurred rarely and, to be viable on a long-term basis, it would involve rather complex and sophisticated treatment. However, for certain industrial and agriciultural purposes, treatment can be much simpler and can often be accomplished using low-energy systems such as lagoons and wetlands.

B. Waste-water reclamation

Waste water is a potentially valuable water resource that can be reclaimed and reused either to reduce the demand for or augment available potable water sources. A technique to reduce the demand for or the usage of potable water is the substitution of an available, lower-quality, less expensive water for those purposes that do not require high-quality water. In some localities, waste water or sewage from municipal or industrial sources can be treated and reused (reclaimed) for some beneficial purpose. This can have a double benefit as it can reduce the impact of waste-water discharges while reducing the demand for potable water.

In discussing waste-water reuse there is occasionally some conflict in the exact meaning of the terminology used. The definitions used for terms in the present chapter (adapted from Kasperson and Kasperson, 1977) are contained at the end of the present section.

The following sections discuss the use of reclaimed municipal and industrial waste water for domestic, industrial and agricultural applications. A diagram illustrating the reuse potential for waste water is shown in figure VIII.

Some of the common applications for reclaimed waste water that have helped to reduce demand on available water supplies have been for agricultural irrigation and industrial cooling. Applications that involve augmentation of available supplies include ground water recharge and direct reuse (after appropriate treatment) for potable purposes.

1. Historical background

The past 100 years has seen a tremendous increase in the use of water for the transport of domestic and industrial waste products, the processing of agricultural and industrial goods and industrial cooling. The water has generally been derived from lakes, streams or ground water and once used has been discharged back into lakes, streams or ground water for disposal. This sequence of use, discharge, use, discharge etc. has produced a certain amount of reuse of previously used water (waste water) in many areas. This is especially true in the industrialized countries where industrialized countries where industries and population centres are often concentrated along major rivers. This inadvertent reuse occurs routinely along river systems such as the Rhine or the Mississippi.

The natural cleansing ability of lakes, rivers and soils, along with the treatment both of waste-water discharges by users and raw water supplies by the consumer, have helped to minimize potential water quality problems associated with unplanned reuse. Deliberate reuse of waste water has been conducted in a much more controlled fashion. Municipal waste water and sludge have been used for agricultural irrigation using varying degrees of treatment in countries such as Australia, the Federal Republic of Germany, Mexico, South Africa and the United States of America for a considerable time. Mexico City, for instance, has used a portion of its waste water for agricultural irrigation since 1886. Often reuse in various countries has been more for treatment of the waste water than for demand reduction or water supply augmentation.

The planned direct reuse of waste water for potable purposes has been explored with increasing interest by several of the developing countries during the past 30 years. A severe drought in the mid-1950s in the central United States, provided the impetus for a small city, Chanute, Kansas, to utilize temporarily a portion of its waste-water plant effluent as a direct source for its water treatment plan in order to provide a continuing supply of potable water (Metzler and others, 1958). In the late 1960s the city of Windhoek, Namibia, constructed an advanced waste-water treatment plant and began to utilize a portion of its treated waste water to supply up to about 30 per cent of its potable supply.

During the 1970s, considerable research was directed in many of the industrialized countries to the potentials and hazards of direct potable reuse. Although this has resulted in considerably more information being generated on the subject, it has not resulted in any widespread application of direct reuse of waste water for potable purposes. Instead, any current applications are small in scale and generally of a research nature.

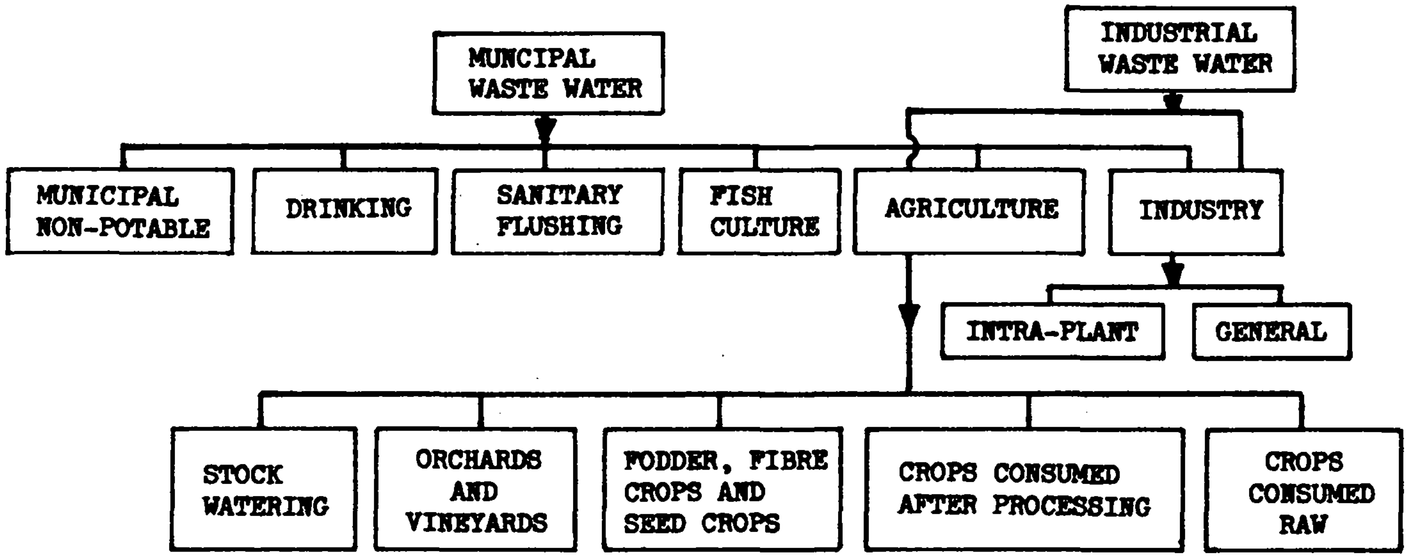


Figure VIII. Intentional reuse of waste water

<u>Source</u>: Adapted from F.M. Middleton, "Advanced wastewater treatment technology in water reuse", in H.I. Shuval, ed. <u>Water renovation and reuse</u> (New York, Academic Press, 1977), p. 6.

Reuse of waste water for non-potable purposes such as agricultural irrigation, ground water recharge and in-plant recycling have, however, significantly increased in use during the past 20 years. This has generally been in the industrialized countries, where considerations of pollution control often entered into the decisions to reuse waste water.

2. Technical considerations

Waste water can be divided into two general classes, domestic and industrial waste water. Domestic waste water consists mainly of a mixture of water and waste products from non-industrial (household, restaurants, schools) activities. Those wastes generally include dissolved and suspended material made up of human and animal wastes, soaps, oils, greases, vegetable and animal residues, household chemicals, soil, bacteria and viruses.

Tables 16 and 17 illustrate the general composition and characteristics of domestic waste waters. The medium-strength waste water is typical of the type of waste water found in an industrialized country such as the United States or Canada, where an abundant supply of water is available. In areas where water is used more sparingly, owing to scarcity or cost, a stronger waste water can be anticipated. Weak waste water generally occurs where the waste-water collection system (sewers) also collects significant amounts of ground and/or storm water due to leakage or inlets.

Industrial waste water is characterized by its variability in flow, composition and temperature, depending on the applications for the water in the particular industrial process. Those applications can vary from dissolving and/or flushing away substances such as chemicals and food wastes, to acting as cooling water for power-generating stations or metal-finishing plants. Each different use will alter the characteristics of the water that is discharged from that industry.

Table 16. Typical composition of domestic waste water

	Composition in mg/l		
	Mineral	Organic	Total
Suspended solids	65	170	235
Dissolved solids	210	210	420
Total solids	275	380	655

Source: G. M. Fair and J. C. Geyer, Elements of Water Supply and Waste Water Disposal (New York, John Wiley and Sons, 1958).

Table 17. Physical and chemical characteristics of domestic waste waters

Major constituents	Concentration (in mg/l) Strong	Medium	Weak
Total solids	1 200	700	350
Dissolved solids	850	500	250
Suspended solids	350	200	100
Nitrogen (as N)	85	40	20
Phosphorus (as P)	20	10	6
Chlorides a/	100	50	30
Alkalinity (as $CaCO_3$)	200	100	50
Grease	150	100	50
BOD b/	300	200	100

Source: This data adapted from Metcalf and Eddy, Inc., *Wastewater Engineering; Treatment, Disposal, Reuse*, 1st ed. (New York, McGraw Hill Book Company, 1972), p. 231.

a/ This amount should be increased by the concentration of these constituents in the carriage water. The table shows major constituents only.

b/ BOD is the five-day biological oxygen demand measured at 20° C. It is a measure of the biodegradable organic content of waste water.

Except for very strong industrial wastes, waste water, either municipal or industrial, is almost pure water with only a small amount of contaminants contained in it. In domestic waste water, this usually consists of less than 1,000 ppm of the total mixture. Unfortunately, this small concentration is usually difficult to remove totally and its presence can severely limit the potential reuse of the water.

The major concern in the reuse of domestic waste water is the existence of potentially pathogenic substances such as bacteria, viruses and other micro-organisms that can cause disease. With the use of industrial waste, the major concern is generally the existence of potentially toxic or other substances that could be detrimental to public health. As more chemical substances are developed and utilized in home and industry, the likelihood of problems increases. Reuse of waste water is complicated by the fact that most waste water collected by municipalities is derived from a combination of industrial and domestic sources.

The key consideration in the successful reuse of waste water is to remove from the waste water economically those substances that will be detrimental to the use proposed for the reclaimed waste water. The limitation on the reuse of water is that the cost of reliably removing those potentially harmful substances often exceeds the cost of obtaining water from another source.

(a) Domestic reuse

Domestic reuse refers to the reuse of waste water for domestic purposes. Two specific examples of this are the use of reclaimed waste water for flushing and potable consumption purposes. The use of filtered or unfiltered secondary effluent for toilet flushing is a common practice in many of the hotel and apartment complexes in water-short areas of the Caribbean, as well as in Singapore, and in some hotels, office buildings and industrial complexes in Japan.

The quality of the water must be sufficiently good to avoid any public health problems, if short-term contact occurs, and must be aesthetically acceptable. The crucial element in this type of reuse is to have control of the activities in an area, so as to eliminate the potential for cross connections between the potable and non-potable systems.

Potable reuse can be divided into two classifications, direct and indirect reuse. In direct reuse the waste water is treated and then used directly for potable purposes. With indirect reuse the waste water is treated, then discharged into naturally occurring water where it is mixed and then recovered for future use. A prime example of indirect reuse is the recharge of ground water with treated effluent.

In either direct or indirect reuse, care must be taken to protect the public health, since waste water, by its very nature, is a potential health hazard. For domestic reuse, waste water from domestic sources is generally preferable to industrial wastes, as domestic sewage is generally more amenable to treatment and the chance for the existence of toxic chemicals is much less.

(i) Direct potable reuse

The processing of waste water to the extent that it can be safely reused for potable purposes is generally considered the highest level of reclamation. It definitely requires the most care and caution, as the long-term health risks associated with potable reuse of waste water treated by different processes have not been fully determined. To minimize risks, only localities with high levels of technological support for the construction, operation and monitoring of advanced waste-water treatment systems should consider direct waste-water reuse for potable purposes (United Nations, 1974).

Although direct potable reuse has been extensively discussed for the past 20 years, there is practically no intentional direct reuse taking place at present. Several countries or areas have embarked on establishing policy goals and/or experiments with the objective of possibly utilizing reclaimed water for potable purposes. Among these have been Hong Kong, Namibia and the United States.

During 1979-1980, the Government of Hong Kong constructed a pilot plant facility and investigated various waste-water sources and reclamation processes to ascertain which ones would be most appropriate to utilize as a potential potable water source. Although the experiments indicated that physical-chemical methods of treatment showed promise, the incentive for continuing and expanding the project was minimized when the Governments of Hong Kong and China came to an agreement on a long-term supply of surface water for Hong Kong from China (Everest, 1981).

In Namibia, the city of Windhoek began to recycle directly a portion of its treated municipal waste water in 1969. The treatment process was modified during the period 1974 to 1976 to include solids contact using lime, ammonia stripping, recarbonation, filtration, carbon adsorption and disinfection by chlorination. The amount of reclaimed water in the potable water system has varied depending on demand, ground water availability and plant operation. During a period in 1977-1978, the percentage of reclaimed water in the distribution system varied between 20 and 50 per cent (Van Vuuren and others, 1980).

An early occurrence of deliberate direct reuse took place in the United States in 1956 and 1957 when a drought forced city officials to take emergency action and use a portion of their waste-water effluent as feed water into their water treatment plant. The waste water was treated by trickling filters and after discharge into a holding pond (with a 17-day average residence time) the effluent was treated at a water plant by a solids contact softening unit using alum, lime, and soda ash, followed by recarbonation, sedimentation, filtration and disinfection (Metzler and others, 1958).

In a more controlled and planned fashion, a 3,800 m^3/d (1 mgd) waste-water reclamation facility began operation in Denver, Colorado, in late 1983. This facility is part of a $29 million project of the Denver Water Board to demonstrate the feasibility of processing secondary waste-water effluent reliably into potable quality water. The current intention is to prove the plant's reliability over a five- to seven-year period. If it proves successful, then the Water Board will consider building a full-scale plant capable of processing up to 380,000 m^3/d (100 mgd).

Although the product water from the reclamation plant will not be used now as potable water in the city's water system, the reclaimed water will be used to conduct extensive health effects research and monitoring. The facility, which processes secondary effluent, has a sophisticated treatment train. A diagram of the process is illustrated in figure IX and includes chemical coagulation, filtration, ion exchange, carbon adsorption, ozonation, reverse osmosis and final disinfection by chlorine dioxide. The progress and data obtained from this facility over the next five years will be of tremendous importance in evaluating the potential for safe direct potable reuse (Armstrong, 1983).

(ii) <u>Indirect potable reuse</u>

This type of reuse is characterized by the treated waste water being discharged to naturally occurring water where it is mixed before being recovered for subsequent reuse. The most common example of this is the discharge of treated (or untreated) waste water into a river or stream after which it is diluted, naturally aerated and then withdrawn downstream for use in a water supply. This type of inadvertent indirect reuse is fairly universal and is generally unplanned.

A more planned form of indirect reuse is the recharge of ground water with treated effluent. This can be for augmentation of existing ground water and/or the control of sea-water intrusion; both can result in subsequent human consumption of a portion of the reclaimed waste water.

Spreading (or rapid infiltration) basins have been used to recharge ground water successfully. The waste water is first treated to some degree and then conveyed to the basins in areas having permeable soils and receiving aquifers. As

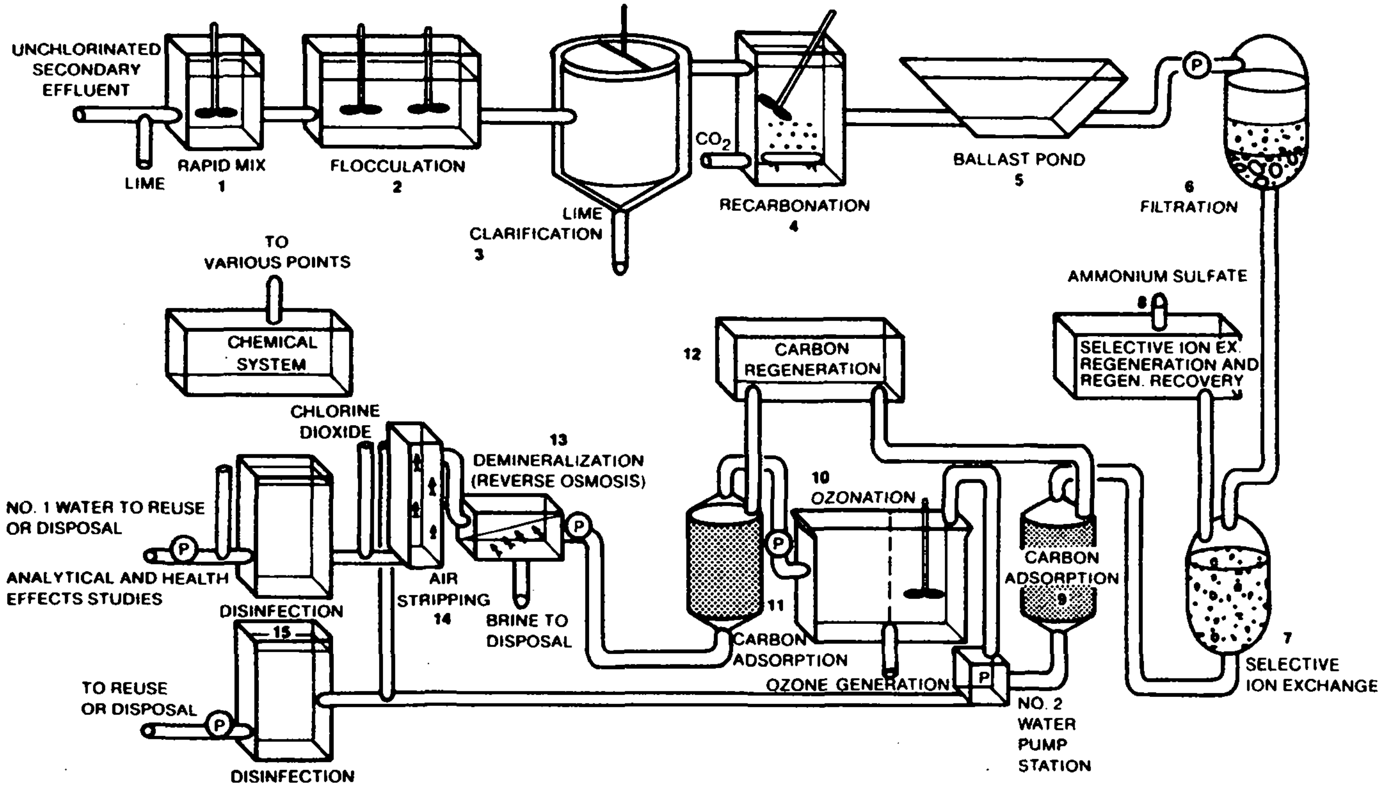


Figure IX. Denver's Water reuse treatment process

Source: A. Armstrong, "Technological magic demonstrated in Denver", in CH2M Hill Reports 21:4 (Denver, CH2M Hill International corporation, 1983).

the water infiltrates through the soil surface and percolates down through the soil profile, biological, physical and chemical reactions provide additional treatment and eliminate most contamination. A high die-off of pathogens and viruses occurs if the travel time is sufficiently long. As shown in table 18, the quality of the ground water extracted can compete with the advanced waste-water treatment system. It is, moreover, a natural system, less likely to fail with inexpert operation, and simple to operate and construct. One of the common operational problems that occurs is the clogging of the soil under the basins. This can be minimized by adequate pre-treatment and using wet-dry cycles for the basins.

Table 18. Expected quality of water recovered after rapid infiltration in a spreading basin (mg/l)

Constituent	Average a/	Upper range a/
BOD	5	< 10
Suspended solids	2	< 5
NH_3 as N	0.5	< 2
Total nigtrogen as N	10	< 20
Total phosphorus as P	1	< 5
Fecal coliform No/100 mL	10	< 200

Source: Adapted from United States Environmental Protection Agency and others, Process Design Manual: Land Application of Municipal Wastewater (Cincinnati, Ohio, USEPA, 1981).

a/ Based on using pre-treated waste water with a minimum of primary sedimentation and percolation through 4.5 m (15 ft) of unsaturated soil.

Despite the fact that infiltration systems yield renovated water of high quality, the recharged water may not be as good as the natural ground water, especially as regards salinity levels. Where it is important to protect the natural ground water, the movement of renovated water can be controlled and removed from the aquifer for reuse. This can be done by draining the recharged water into a natural water body with underground tile drains, or with a series of wells, if the water table is deep.

In special circumstances, where the aquifers are confined or suitable land for infiltration basins is not available, injection well techniques can be used. This type of aquifer recharge has two main disadvantages. One is that the waste water must undergo significant pre-treatment before injection so as to minimize the clogging of the geologic formations adjacent to the well. The second is that this type of placement does not provide as much natural treatment as takes place with surface spreading basins.

Recharge by injection wells is generally used with facilities designed to control sea-water intrusion by building up a fresh water barrier in the coastal aquifer. The use of rapid infiltration basins and ground water recharge as part of an integrated waste-water reuse programme has occurred in many parts of the world.

Since about 1956 water resource planners in Israel have recognized the need and potential for the reclamation of waste water for use as an alternative water source. By 1981, Israel was reusing about 30 per cent of its available waste water for a variety of purposes, but mostly for agricultural irrigation. In the late 1960s, the Dan Region project, which involved the reclamation and reuse of waste water on a large scale, was proposed and implementation was begun. The project was to collect waste water from the Tel Aviv area, treat it biologically, and use the effluent to recharge the ground water using spreading basins. The resultant new ground water was to be recovered, mixed with potable water being transported from the north of the country to about 50 small communities to the south of Tel Aviv for potable and agricultural usage (Shuval, 1980). However, in the mid-to-late-1970s, considerations of the potential health effects led the Government to modify the plan so that the usage of the recovered water would be limited to agricultural and industrial applications.

The recharge operations have been taking place since the mid-1970s and between 1977 and 1982 about 77 million m^3 (20 billion gal) were treated and recharged as part of this project. Treatment includes oxidation ponds followed by chemical coagulation and clarification using the lime ($Ca(OH)_2$) and magnesium ($Mg Cl_2$) process. The high pH effluent is then detained in a series of polishing ponds to permit free ammonia stripping and natural recarbonation before being recharged into the regional ground water aquifer using spreading basins. Ground water in the vicinity of the recharge area is being pumped by a series of recovery wells.

By the end of 1982 about 70 million m^3 (18 billion gal) of ground water were pumped by the recovery wells. This water was still mainly native ground water, as the recharged ground water had not yet reached the recovery wells. This ground water, which contains very little of the recharged waste water, is being pumped into the central water transmission main which transports and distributes water to the south of the country. When the recovery wells begin to pump higher proportions of water derived from the recharged waste water, then the recovered water will not be added to the central transmission main but will be distributed in a separate network to be used for non-potable purposes. This purpose is expected to be unrestricted irrigation (Idelovitch and others, 1983).

In the early 1970s, a United States Government-sponsored recharge project was conducted on the island of St. Croix for a period of three to four years. Domestic waste water was treated in a secondary (activated sludge) plant with alum addition, filtration and chlorination. The effluent was transported to spreading basins which recharged ground water upgradient from municipal well fields. The operations were interrupted owing to the occasional existence of saline water in the waste water from the use of sea water for sanitary flushing in one portion of the island. The programme was discontinued in the late 1970s as a result of saline intrusion and problems with the collection system (Buros, 1981).

A successful example of the use of reclaimed waste water as a salinity barrier is in Orange County, California. In that area the coastal aquifers had been overdrawn in the past and reclaimed waste water had been injected into the aquifers to minimize any sea-water intrusion. Although a portion of the injected water flows seaward, another portion is mixed with the naturally occurring ground water and is extracted by the wells in the area. To protect the public health and the aquifers, the local water district built a 57,000 m^3/d (15 mgd) treatment facility referred to as Water Factory 21. This water reclamation facility has been treating secondary effluent from an adjacent plant since 1978. The facility is designed to provide advanced treatment (including nutrient and salt reduction) before the reclaimed water is injected into the aquifers. The treatment used since 1979 has consisted of oxidation (activated sludge), chemical precipitation with lime, air stripping, carbon adsorption and demineralization with reverse osmosis. The long-term operation of the plant has provided an opportunity for valuable experimentation on various aspects of the treatment train such as the reliability of the pollutant removal and the optimal use of the reverse osmosis components (McCarty and others, 1981; Argo, 1981).

(b) Agricultural reuse

The use of reclaimed waste water for irrigation and other agricultural purposes can have important benefits in many countries. Agriculture is almost always a major user of water in every country. In Asia and Africa more than 90 per cent of the total water demand is for irrigation and in Latin America it is about 80 per cent. Even in the industrialized United States, agricultural usage amounts to about 40 per cent of the total fresh water used, which is more than four times the quantity used by municipalities.

Reuse of waste water in agriculture is mainly for irrigation of crops or landscape, although it has been used to a lesser degree for aquaculture and livestock watering. One advantage in using reclaimed waste water for irrigation and aquaculture is that the nutrients (generally phosphorus and nitrogen) in the waste water can act as a plant stimulant, rather than a potential pollutant as it could if discharged to a stream or lake. Because of its nutrient content, waste-water irrigation can lower fertilizer requirements and increase crop yields. For example, in India non-edible crops have been cultivated with a 30 to 40 per cent higher yield using municipal waste water for irrigation rather than plain water (Arceivala, 1977). The use of treated waste water for agriculture can not only aid agriculture, but can also provide additional treatment for the sewage before it eventually reaches a water course. This additional treatment is often critical in developing countries where many people in the rural areas obtain their water supply directly from rivers (Diament, 1981).

Waste-water irrigation has been practised for some time in a number of countries on a variety of crops. The cities of Melbourne, Australia, and Johannesburg, South Africa, have been using treated waste water for irrigation purposes since 1892 and 1914, respectively, on pasture and silage crops. In India, municipal waste water has been used in some areas for irrigation of crops since the nineteenth century. In Mexico, crops including alfalfa, corn, wheat, tomatoes and chili have been grown successfully with Mexico City waste water, despite the sometimes unusual physical and waste-water chemical characteristics of the effluent (Aguirre, 1977 and Mendoza, 1981). Favourable experiences have been noted with the use of treated waste water to irrigate sugar cane on the islands of Puerto Rico and Hawaii, as well as enhancing the yield of cotton in the south-western United States (Hrudey, 1982).

Owing to stringent pollution control through legislation implemented in the late 1970s, many municipalities in the United States have made use of land application methods, generally irrigation, as part of their waste-water treatment process. Although land application has been used by those localities as a method of reducing pollution in receiving waters, the effect has been to provide many areas in the United States with experience in the reuse of waste water for agricultural purposes under a wide variety of conditions.

Although irrigation with treated waste water can provide benefits, there are also some potential problems or cautions that are associated with its use. Careful consideration must be given to the health hazards that may arise from the reuse of waste water in irrigation. Some of the localities using waste-water irrigation in the past have experienced problems with increased incidence of diseases among workers and consumers of produce when proper precautions were not taken. The hazards can be reduced by proper training of personnel and matching the type of crop to the level of treatment provided. Often this will mean restricting irrigation to certain non-edible crops used for fodder or industrial purposes and by limiting access to the irrigation areas to trained workers (Mara, 1976).

Overall careful planning must be carried out if irrigation projects are to be successful. The crops selected must be suitable for the soils, climate, drainage, irrigation techniques, and market conditions of the area. Generally, a large storage capacity or alternate method of disposal must be provided to allow the cessation of irrigation during periods of excess rainfall, harvesting and/or inclement weather. Suitable drainage must be provided. Drainage can be crucial even in arid areas where there may be soils such as clays or hard pans which restrict vertical permeability.

Other operational problems are the potential for moderate to high concentrations of dissolved salts in the irrigation water which may require that additional irrigation water be used to flush out the soil and maintain the salinity in the root zone within acceptable limits. Some specific constituents such as boron and cadmium in the waste water could also be detrimental to crop yields. Table 19 outlines some of the guidelines to be considered in evaluating the potential for agricultural problems based on the concentration of various constituents in the waste water.

A major consideration must be the positive acceptance by both the farmer and the consumer of the agricultural products produced using reclaimed waste water for irrigation purposes. If the use of reclaimed water means a diminished value for the produce, then it could create economic difficulties for the programme.

(c) Industrial reuse

The overall demand for water for industrial purposes is directly linked to some measure of the economy of any country. In a heavily industrialized country such as the United States, industrial use of water amounts to about 50 per cent of the fresh water used and most of this is for cooling water. Water usage by industries in developing countries generally accounts for less than 10 per cent of the total use, but a rapid increase in demand is expected owing to the priorities given to economic growth and industrialization in those countries. The main new industrial activities in developing countries are often those which process primary products, agro-industrial operations, and heavy industries such as metallurgical, petro-chemical and mineral complexes. Many of them require an abundant water supply and are based in or near large cities. Where urban areas could be or are sewered, this offers the potential for reuse for an industry that is located close to a supply of the collected waste water.

Internal reuse within a manufacturing complex is an increasingly common practice in industrialized countries because the cost of buying and treating fresh water for use and processing the effluent for disposal is often higher than treating and recycling waste water for reuse. Table 20 shows some examples of reductions in water consumption by industries which were achieved by internal recycling in South Africa.

Many applications in industry, especially cooling, which accounts for a large proportion of the water used, have water quality requirements that can be met by treated waste water. The water quality requirements vary widely between industries, different plants in the same industry, and between various processes within a single plant. Table 21 summarizes some of the major potential industrial applications for reclaimed waste water and the general level of treatment required.

Cooling water alone accounts for 50 to 60 per cent of all water used by industries; this water can often be of relatively poor quality. However, potential problems from residual contaminants in the water could include scaling, fouling, corrosion and biological growth.

Three industrial groupings have considerable waste-water reuse potential: electricity generation, manufacturing industries and mineral industries. Electricity generation by steam power requires water primarily for the condenser-cooling tower cycle. Since sea water is already used for cooling in coastal plants in the United States, highly saline water is acceptable for once-through cooling purposes. With pre-treatment to control scale deposition, corrosion, slime formation and delignification of the cooling towers, reclaimed waste water offers the potential for cooling for several cycles.

Treated waste water has been used as cooling water in a number of electricity-generating plants around the world. Some of these include plants at Oldham, Stoke-on-Trent and Croydon in the United Kingdom; a plant in the Veal River Triangle in South Africa; and, in the United States, plants at Palo Verde, Arizona, and Los Angeles, California. Some of the major concerns in using reclaimed waste water for cooling water in electricity-generating stations are foaming, corrosion, slime and scale formation, and potential health hazards (Goldstein and Casana, 1982).

Recycling has been carried even further in power plants where pollution control regulations prevent the discharge of brine blowdown from the cooling towers. In two cases of this sort in the United States (Gainesville, Florida, and Colorado Springs, Colorado) the blowdown is recycled in the towers for a few cycles, treated by standard chemical coagulation to remove some dissolved and suspended solids, and then concentrated by reverse osmosis before the dissolved salts are separated in a special vapour compression desalination unit. The product water from those various processes is used for make-up water in the cooling towers and boilers.

Table 19. Guidelines for interpretation of water quality for irrigation

Problems and quality parameters	No problems	Increasing problems	Severe problems
Salinity effects on crop yield:			
Total dissolved solids concentration (mg/l)	< 480	480-1 920	> 1 920
Deflocculation of clay and reduction in infiltration rate:			
Total dissolved solids concentration (mg/l)	> 380	< 320	< 128
Adjusted sodium adsorption ratio (SAR)	< 6	6-9	> 9
Specific ion toxicity:			
Boron (mg/l)	< 0.5	0.5-2	2-10
Sodium (as adjusted SAR) if water is absorbed by roots only	< 3	3-9	> 9
Sodium (mg/l) if water is also absorbed by leaves	< 69	> 69	
Chloride (mg/l) if water is absorbed by roots only	< 142	142-355	> 355
Chloride (mg/l) if water is also absorbed by leaves)	< 106	> 106	
Quality effects:			
Nitrogen in mg/l (excess N may delay harvest time and adversely affect yield or quality of sugar beets, grapes, citrus, avocados, apricots, etc.)	< 5	5-30	> 30
Bicarbonate as HCO_3 in mg/l (when water is applied with sprinklers, bicarbonate may cause white carbonate deposits on fruits and leaves)	< 90	90-250	> 520

Source: H. Bouwer, "Waste water reuse in arid areas", in E. J. Middlebrooks, *Water Reuse* (Ann Arbor, Michigan, Ann Arbor Science Publishers, 1982), p. 145.

Table 20. Water savings effected by planned reclamation of process waters for internal reuse

Industry	Water requirements in m^3/ton: Without reclamation and reuse m^3/ton	With reclamation and reuse m^3/ton
Fruit and vegetable canning	11.2	5.4
Kraft paper pulp	201	4.0-11.2
Newsprint	116	27
Hardboard	67	33.5
Soap, oils and fats	54	10.7
Steel	246	5.3-6.7
Glass containers	1.8	0.7

Source: Adapted from O. O. Hart and L. R. J. van Vuuren, "Water reuse in South Africa", in H. I. Shuval, ed., Water Renovation and Reuse (New York, Academic Press, 1977).

Table 21. Suggested treatment required for domestic waste water before industrial reuse

Industrial usage	Possible treatment required
Power plant and industrial cooling	
Once through	Secondary treatment
Recirculation	Secondary plus nitrogen and/or phosphorus reduction
Industrial boiler make-up water	
Low pressure	Secondary plus nitrogen and phosphorus reduction
Intermediate pressure	Advanced waste water treatment (AWT)
Industrial water supply	
Primary metals	Secondary treatment
Petroleum and coal products	Secondary plus nitrogen reduction or Secondary plus filtration

Source: Data adapted from Culp/Wesner/Culp, Water Reuse and Recycling, Volume 2: Evaluation of Treatment Technology (Washington, D.C., United States Department of the Interior, Office of Water Research and Technology, 1979), report OWRT/RV-79/2.

Reductions in water consumption and discharge in various manufacturing industries have been achieved by recycling and reusing plant waste water (after in-plant treatment). Among those industries are textiles, food processing, metal plating, paper processing, chemicals and petroleum refining (Hrudey, 1981 and Hrudey and Smith, 1983).

As an example of waste-water reuse in industry, Bombay has experimented with its industrial water supply by treating 5,000 m^3/d (1.3 mgd) of municipal waste water, taking it from a point not heavily contaminated with industrial waste. The raw sewage inflow can be reclaimed at 15 per cent of the cost of obtaining additional fresh municipal water and can be used for cooling or other industrial purposes. According to a survey of industries conducted by the city, considerable savings could be realized mainly in the chemical, paper, petrochemical and textile industries through renovation and reuse, providing water suitable for most needs at a fraction of the cost of municipal water. One reuse scheme for a textile plant was able to reduce fresh water demands by more than 50 per cent in an industry that already used only about one third of the designated water requirements of textile mills in industrialized countries (Arceivala, 1977).

In some cases, industrial waste water should be considered for irrigation, as some of the specific chemical compounds in the waste water can be beneficial. For example, in Pakistan, waste water from a tannery proved useful in improving the physical and chemical properties of a highly saline and sodic soil during irrigation application (Hrudey, 1982).

Some of the key manufacturing industries which have potential for reuse include primary metals, chemicals, paper and allied products, petroleum and coal products, transportation equipment, textiles and food processing. Water use in manufacturing industries is primarily for cooling, boiler feed and processing. Industrial use for cooling represents the greatest potential for waste-water reuse and recycling. Boiler feed and process waters must be of high quality, generally limiting the reuse potential, because reclamation costs are high.

The mineral industries include metal, fuel and non-metal mining. Most of the water needed is utilized for coal or sand washing, sub-surface injection and ore extraction. The water quality requirements for those applications are minimal; the potential for use of reclaimed waste water is, therefore, large.

Make-up water requirements for an ore-processing plant in Arizona were reduced by 30 per cent simply by increasing the thickness solids content of the tailings slurry prior to disposal. At Ontario Mills, tailings decant water was capable of supplying 67 to 75 per cent of the mill concentrator water demand (Hrudey and Smith, 1983).

3. Recent technological advances

During the past 20 years, the major technological advances have come in the monitoring and detection of biological and chemical substances in water. Along with a general world-wide concern over carcinogens, investigators dealing with waste-water reuse have become cautious over uses of reclaimed water associated directly or indirectly with ingestion by people. The caution is warranted in that there is still insufficient data available to evaluate fully the long-term health effects of some of the reuse practices.

The area that has not kept up with the increased ability to detect trace amounts of substances, especially organic chemicals, is the establishment of scientifically based threshold concentrations which would be acceptable for the wide range of exotic materials found in waste water. Those values must be set wherever possible so as to provide guidance for planners and policy-makers in making decisions on the costs, risks and opportunity associated with reuse in the future.

The treatment processes used in renovating waste water for reuse are almost all standard unit processes (such as biological oxidation, coagulation and sedimentation) used in water and waste-water treatment plants. Those unit processes have not changed much over the past 20 years although experience has been gained with using them in various combinations with a variety of waste waters. The one unit process that has really developed in the past 20 years is the use of semi-permeable membranes for separation. Reverse osmosis membranes are used to demineralize saline water and microfilters to separate large molecular substances from water. Both applications have been used only in a very few of the waste-water reuse facilities.

A major state-of-the-art project recently initiated is the 3,800 m^3/d (1 mgd) potable reuse demonstration plant which began operation in Denver, Colorado, in 1983. Its operations over the next five to seven years should provide valuable practical information and costs on the potential for reliably converting waste water into potable water.

4. Application in developing countries

A primary problem in reusing waste water in developing countries is the lack of collected waste water. The technical solutions proposed by industrially developed countries begin with the disposal of collected waste water as the basic problem, and are therefore of very limited value for developing countries where excreta disposal with little or no water is the first priority (Pacey, 1978). In large metropolitan areas where a system of sewers is used to collect waste water, there is often difficulty in building and maintaining sewage treatment systems.

Many problems, such as mosquito breeding, inadequate maintenance, heavy rainfall and excessive amounts of organic matter in effluents, have been reported from more than 20 countries in Africa, Asia and Latin America, using conventional waste-water treatment systems (Reid 1982). In Kenya, for example, none of the existing sewage works surveyed outside Nairobi was working satisfactorily, the most common problem being lack of skill in operation and maintenance (Hrudey and Smith, 1983). A survey of 10 treatment plants in India showed that eight of them were improperly operated (Reid, 1982).

General problems with existing plants include: difficulties in obtaining treatment chemicals of the required quality, delays resulting from the unavailability of spare parts and the climatic conditions which speed up reactions, increase sedimentation and reduce the oxygenation capacity. As a result, in one survey in Asia 70 per cent of the observed plants did not operate properly because of lack of training and insufficient after-sales service (Osenga, 1980).

Conventional methods, including water-borne sewerage and subsequent treatment by activated sludge plants or trickling filters, often cannot be directly transposed to developing countries. The conventional methods require levels of water use that far exceed those of a community with standpipe service which is a delivery system recommended where water has to be distributed to a large number of people at minimum cost (World Bank, 1980). Therefore, the sanitation options for developing countries may not lead to conventional sewerage systems as found in industrialized countries, because of the high cost of equipment and operations and the requirements of skilled labour.

(a) Characteristics of treatment methods

The ideal system for waste-water treatment (management) would satisfy all of the criteria listed below (Mara, 1976):

(a) Health requirements. The treatment should yield a product free of health-endangering material and assure removal of a high degree of pathogenic bacteria and virus;

(b) Reuse. The process should allow a beneficial and safe reuse of the products;

(c) Ecological criteria. When waste cannot be reused, the discharge of effluent should not exceed the self-purification of the recipient water;

(d) Absence of nuisance. The degree of odour release must be below the threshold, and no part of the system may become aesthetically offensive;

(e) Cultural compatibility. The methods chosen for collection, treatment and reuse should not interfere with local habits and social or religious practice;

(f) Reliable operation. The skills for the routine operation and maintenance of the system components must be available locally or easily acquired with minimum training;

(g) Affordability and costs. Capital and running costs must not exceed the community's ability to pay. The financial return from reuse schemes should contribute to operation and maintenance expenses.

Since it is difficult for a system to satisfy all the above demands, compromises must be made but it is desirable to minimize any disadvantages arising from the chosen system.

(b) Appropriate applications in developing countries

Where adequate collection and treatment systems are possible, then the most appropriate waste-water reuse techniques appear to be: agricultural irrigation, ground water recharge, livestock watering and various industrial uses. Owing to limited resources available, the treatment and reuse of waste water for potable purposes is not recommended. A hindrance to the appropriate reuse of waste water in any area is a government subsidy for source development, treatment and transmission of potable water. Such subsidies keep the price of potable water unrealistically low, reducing the incentive for reuse.

In a reuse scheme the use of low-energy low-maintenance pond or wetland systems to provide secondary treatment is recommended. These mimic natural systems for providing treatment. Design parameters for various types of waste-water treatment ponds are shown in table 22.

Their major disadvantage is the large land area requirement, but in many developing countries, sufficient land is normally available at relatively low cost, and land can easily be reclaimed if needed for another purpose at a future date. Maintenance needs are minimal but essential for safe operations without odour problems. They involve such activities as cutting peripheral vegetation to control insects and removing floating scum to avoid sunshading.

Table 22. Design parameters for typical ponds

Paramater	Aerobic (high-rate) pond	Aerobic pond a/	Aerobic (maturation) pond	Aerated lagoons	Aerobic-anaerobic (facultative) pond	Aerobic-anaerobic (facultative) pond	Anaerobic pond
Common name	High-rate aerobic pond	Low-rate aerobic pond	Maturation or tertiary pond		Facultative pond	Facultative pond with mechanical surface aeration	Anaerobic lagoon anaerobic pre-treatment ponds
Identifying characteristic	Designed to optimize the production of algae cell tissue and achieve high yields of harvestable protein.	Designed to maintain aerobic conditions throughout the liquid depth.	Similar to low-rate aerobic ponds but very lightly loaded.		Deeper than a high-rate pond. Photosynthesis and surface reaeration provide oxygen for aerobic stabilization in upper layers. Lower layers are facultative. Bottom layer of solids undergoes anaerobic digestion.	Same but small mechanical aerators used to provide oxygen for aerobic stabilization.	Anaerobic conditions prevail throughout, usually followed by aerobic or facultative ponds.
Application	Treatment of soluble organic wastes and secondary effluents	Nutrient removal treatment of soluble organic wastes, conversion of wastes	Used for polishing (upgrading) effluents from conventional secondary treatment processes such as trickling filter or activated sludge		Treatment of untreated screened or primary settled waste water and industrial wastes	Treatment of untreated screened or primary settled waste water and industrial wastes	Treatment of domestic and industrial wastes
Flow régime	Intermittently mixed	Intermittently mixed	Intermittently mixed	Completely mixed	....	Mixed surface layer	....
Pond size, ha	0.25-1	<4 multiples	1-4	1-4 multiples	1-4 multiples	1-4 multiples	0.2-1 multiples
Operation, b/	Series	Series or parallel	Series or parallel	Series or parallel	Series or parallel	Series or parallel	Series
Detention time,d b/	4-6	10-40	5-20	3-10	7-30	7-20	20-50
Depth, m	0.30-0.45	1-1.5	1-1.5	2-6	1-2	1-2.5	2.5-5
pH	6.5-10.5	6.5-10.5	6.5-10.5	6.5-8.0	6.5-9.0	6.5-8.5	6.8-7.2
Temperature range, °C	5-30	0-30	0-30	0-30	0-50	0-50	6-50
Optimum temperature, °C	20	20	20	20	20	20	30
BOD_5 loading, kg/ha/d c/	80-160	40-120	$\leq$15	20-450	15-80	50-200	200-500
BOD_5 conversion	80-95	80-95	60-80	80-95	80-95	80-95	50-85
Principal conversion products	Algae, CO_2, bacterial cell tissue	Algae, CO_2, bacterial cell tissue	Algae, CO_2, bacterial cell tissue NO_2	CO_2, bacterial cell tissue	Algae, CO_2, CH_4, bacterial cell tissue	Algae, CO_2, CH_4, bacterial cell tissue	CO_2, CH_4, bacterial cell tissue
Algae concentration, mg/l	100-260	40-100	5-10		20-80	5-20	0-5
Effluent suspended solids, mg/l d/	150-300	80-140	10-30	80-250	40-100	40-60	80-160

(Source and footnotes on following page)

(Source and footnotes to table 22)

Source: Adapted from Metcalf and Eddy, Inc., Waste Water Engineering; Treatment, Disposal, Reuse, 2nd ed. (New York, McGraw Hill Book Company, 1978), pp. 551-553.

a/ Conventional aerobic ponds designed to maximize the amount of oxygen produced rather than the amount of algae produced.

b/ Depends on climatic conditions.

c/ Typical values (much higher values have been applied at various locations). Loading values are often specified by state control agencies.

d/ Includes algae, micro-organisms and residual influent suspended solids. Values are based on an influent soluble BOD of 200 mg/l and, with the exception of the aerobic ponds, an influent suspended-solids concentration of 200 mg/l.

Note: ha x 2.4711 = acre
m x 3.2808 = ft
kg/ha/d x 0.8922 = lb/acre/d

Because of their advantages, ponds are used for sewage treatment, fish production and land irrigation throughout Asia, Africa and Latin America (Reid, 1982). Some design and performance details are given in table 23.

Pond systems are used extensively on farm communities in Israel to treat the waste water of both the community and urbanized areas nearby. In many cases the effluent from the ponds is used for irrigation purposes and for raising fish. During the recent upgrading of the sewage system in Alexandria, Egypt, consideration was given to treating the waste water by use of ponds and reusing the effluent for agricultural irrigation. Unfortunately, the lack of suitable space for the ponds and the cost of long-distance pumping has prevented that reuse scheme from being implemented at this time.

Wetlands are another low energy and maintenance type of treatment system. These can be existing or constructed wetlands. They use natural systems to treat waste water. They are especially well suited to warm climates and low population densities. Some design criteria for artificial wetlands systems are summarized in table 24.

Effluent from wetlands could be used for irrigation, ground water recharge, pisciculture or various industrial processes.

5. Economic considerations

It is very difficult to estimate costs of treatment for reuse in general because they vary according to a multitude of factors. These include: the degree of treatment desired; costs and availability of land; labour and equipment; and transportation costs, depending on the proximity of the reuser.

Table 25 summarizes the costs of different treatment systems used in various reuse applications. Those costs have been generated by using standardized energy curves and cost data. The costs represent typical values in the United States. Capital costs have been amortized and added to the operation and maintenance costs based on labour, materials, chemicals and primary energy requirements to arrive at the total annual unit treatment costs (Culp/Wesner/Culp, 1979).

Costs of ground water recharge depend on the degree of pre-treatment and the recharge method. For surface spreading and recharge by rapid infiltration, the pre-treatment is usually primary or secondary, as achieved by ponds or aerated lagoons.

Industrial reuse can include cooling water, boiler feed and process water. The lowest treatment requirements and greatest volume needs are usually for cooling water, and this is the industrial reuse application with the highest potential. At three different industries with reuse facilities in the United States, the costs of reusing industrial water for cooling averaged $0.10/m^3 or $0.38/1,000 gal (Crites, 1981). Costs of waste-water reuse can be kept low by reducing pre-treatment or through the use of alternative treatment processes such as replacing conventional activated sludge sytems with more land-intensive facultative ponds.

Table 23. Design and performance data for ponds in developing countries

Location	Loading (Lb. BOD_5/acre/day)	Depth (feet)	BOD removal (percentage)	Coliform removal (percentage)	No. of lagoons	Remarks
Latin America						
Canas, Costa Rica	213	3-5	93	97	2	Facultative, parallel
Lima, Peru	254	2.3-40	70	...	1	Facultative
Lima, Peru	241	5.5 a/	...	...	21	Facultative, series
Mexicali, Mexico	1 062	15 a/-4.6 b/	...	...	...	Anaerobic-facultative, series
Brasilia, Brazil	536 a/-80 b/	6.5 a/-3.3 b/	86	90	2	Anaerobic-facultative, series
Canal Zone, Panama	150	6 a/-4 b/	75	99 (+)	3	Anaerobic-facultative, series
Palmira, Colombia	150	3-5	93	99 (+)	3	Facultative, series and parallel
Asia						
Madras, India	180	2.75 a/-5 b/	67-87	93-99	5	Anaerobic, facultative, series
Ahmedabad, India	200-250	3-4	80	...	2	Facultative, series
Ahmedabad, India	325	4	73	...	1	Facultative
Nagpur, India	185 a/	3.5 a/	88	...	2	Facultative, series
Nagpur, India	417 a/-394 b/	5 a/, b/	74-79	...	2	Facultative, parallel
Bangkok, Thailand	5 000	3	...	...	...	Anaerobic
Bangkok, Thailand	200-400	8-15	83-95	...	24	High rate, parallel
Danang, Viet Nam	220	...	...	...	2	Facultative, series
Africa						
Mandarellas, Zimbabwe	166 a/	4 a/-3 b/	74-88	...	6	Facultative, series
Nairobi, Kenya	91.5 a/-57 b/	5.7 a/, b/	...	...	2	Facultative, series

Source: Adapted from L. W. Canter and others, "Waste water disposal and treatment", in G. W. Reid, ed., *Appropriate Methods in Treating Water and Wastewater in Developing Countries* (Ann Arbor, Michigan, Ann Arbor Science Publishers, 1982), p. 207.

a/ Primary ponds.

b/ Secondary ponds.

Table 24. Design parameters for planning artificial wetland waste-water treatment systems a/

Type of system	Flow régime b/	Detention time, days: Range	Detention time, days: Typical	Depth of flow, m (ft): Range	Depth of flow, m (ft): Typical	Loading rate, cm/d (g/ft⁻/d): Range	Loading rate, cm/d (g/ft⁻/d): Typical
Trench (with reeds or rushes)	PF	6-15	10	0.3-0.5 (1.0-1.5)	0.4 (1.3)	3.25-8.0 (0.8-2.0)	4.0 (1.0)
Marsh (reeds, rushes, others)	AF	8-20	10	0.15-0.6 (0.5-2.0)	0.25 (0.75)	0.8-8.0 (0.2-2.0)	2.5 (0.6)
Marsh-pond							
1. Marsh	AF	4-12	6	0.15-0.6 (0.5-2.0)	0.25 (0.75)	0.8-15.5 (0.3-3.8)	4.0 (1.0)
2. Pond	AF	6-12	8	0.5-1.0 (1.5-3.0)	0.6 (2.0)	4.2-18.0 (0.9-2.0)	7.5 (1.8)
Lined trench	PF	4-20 (hr.)	6 (hr.)	-	-	20-60 (5-15)	50 (12)

Source: United States Environmental Protection Agency, Aquaculture Systems for Waste Water Treatment; an Engineering Assessment (Washington, D.C., EPA, 1980), Report MCD-68 430/9-80-007, p. 27.

a/ Based on the application of primary or secondary effluent.

b/ PF = plug flow; AF = arbitrary flow.

Table 25. Estimated unit costs for various waste-water treatment processes a/

(In 1983 United States dollars)

Description of treatment process	Plant capacity 3,800 m^3/d 1 mgd		Plant capacity 38,000 m^3/d 10 mgd	
	\$/m^3	\$/1,000 gal	\$/m^3	\$/1,000 gal
Aerated lagoons plus spreading basins (high-rate infiltration system)	0.19	0.54	0.07	0.28
Aerated lagoons plus irrigation (low-rate infiltration system)	0.30	1.14	0.23	0.88
Biological treatment by extended aeration (oxidation process)	0.16	0.61	0.11	0.40
Secondary treatment b/	0.39	1.48	0.21	0.78
Secondary treatment plus nitrification	0.51	1.94	0.30	1.12
Secondary treatment plus nitrogen reduction	0.64	2.41	0.31	1.15
Secondary treatment plus phosphorus reduction	0.66	2.49	0.29	1.09
Secondary treatment plus nitrogen and phosphorus reduction	0.83	3.14	0.36	1.36
Secondary treatment plus filtration and carbon adsorption	0.66	2.51	0.27	1.04
Advanced waste-water treatment (AWT) c/	1.08	4.09	0.48	1.80
AWT plus reverse osmosis	1.80	6.83	0.80	3.05
Physical-chemical d/	0.95	3.59	0.41	1.55

a/ This table and costs are adapted from a discussion and cost tables in Culp/Wesner/Culp, Inc., Water Reuse and Recycling, vol. 2 (Washington, D.C., Department of the Interior, 1979), OWRT/RU-79/2. Some of the treatment processes have been combined for clarity, and the original costs in 1977 United States dollars were converted to 1983 prices by assuming an annual average increase of 6 per cent. Costs include operation and maintenance and amortizing the capital cost at 7 per cent per annum for 20 years. Labour, energy, chemicals and equipment are estimated under conditions in the United States.

b/ Secondary treatment is biological oxidation by activated sludge, trickling filters or rotating biological contactors with the appropriate pre-treatment and clarifiers. This cost is an average of the three.

c/ AWT is secondary treatment plus nitrogen and phosphorus reduction, filtration and carbon adsorption.

d/ Physical-chemical treatment consists of precipitation with lime, stripping towers (ammonia removal), filtration, carbon adsorption and disinfection or precipitation with ferric chloride, filtration, carbon adsorption, selective ion exchange and disinfection.

Agricultural reuse is normally one of the least expensive forms of reuse because the pre-treatment can be limited to primary or pond treatment and because of the potential revenue of the crops. The total capital cost of a waste-water irrigation system includes several components, such as pre-treatment level, amount of storage, type of distribution system, land costs and drainage requirements. Since waste-water irrigation, or slow rate land treatment, is relatively land-intensive, land represents the largest portion of the capital cost.

The feasibility of any water reuse scheme ultimately depends on the costs of alternative supplies and public acceptance.

Definition of terms

Planned reuse involves the collection of waste water and purposeful provision for its subsequent use. Water reclamation (treatment) may or may not have taken place. Intention and planning are the important considerations.

Inadvertent reuse occurs when waste water produced by one party is returned to a water source (usually discharged to a lake, river or aquifer) without the specific intent or plan for its use by the first or other parties; nevertheless, it is so used.

Direct reuse involves the transmission of waste water, either treated or untreated, directly to some specific intended use.

Indirect reuse involves returning the waste water to the natural hydrologic cycle, thereby permitting natural buffering systems such as rivers, lakes and aquifers to aid in upgrading the water quality by natural purification and dilution.

Reclamation refers to the upgrading of the quality of waste water to make it usable for some purpose.

Domestic reuse refers to the reuse of reclaimed waste water for some domestic purpose such as potable or sanitary (toilet flushing) water.

Municipal waste water refers to the spent, or used, water of a community. It consists of waste water from domestic and industrial sources plus whatever surface or ground water that enters the collection system.

Source: Adapted from R. E. Kasperson and J. X. Kasperson, eds., Water Reuse and the Cities (Hanover, New Hampshire, University Press of New England, 1977), p. 11.

IV. ENHANCEMENT OF EXISTING SUPPLIES OR SOURCES

A. Introduction

One positive way to increase the water resources in an area is to enhance the supplies or sources that are already available. A key way to increase water resources is to increase the rainfall through weather modification. Although weather modification has a variety of meanings, in the context of the present volume, it will be limited to precipitation enhancement (cloud seeding). Work in this field has concentrated on converting water vapour contained in clouds into rain. Obviously, the prime ingredient necessary is clouds of the appropriate type and in a suitable location to produce beneficial rainfall. Once suitable clouds are available, which must happen naturally, they are seeded with materials in an attempt to promote rainfall.

The seeding of clouds to modify the weather pattern is not an exact science. The clouds must be suitable and the proper amount of chemicals (not always known) must be applied. It appears to work better in some places than in others, although ascertaining whether rain was actually caused by seeding or would have occurred anyway is another complex matter. Moreover, it cannot be predicted with certainty that seeding will work for any given event.

Despite the fact that today's techniques aimed at precipitation enhancement rest upon sound physical principles, the progress made in this field, though quite significant, has been fairly slow. Carefully controlled application of such principles, however sound, is made difficult by the overwhelming complexity of atmospheric phenomena. The unpredictability and variability of atmospheric phenomena in time and space make the science of weather modification a difficult one.

Pseudo-scientific rain-making experiments of the past have given way in recent times to a concentrated scientific effort, resting on accepted principles of cloud physics. Over the past 35 years, some progress in this field indicates that artificial precipitation may be an economically beneficial method of producing rain (Gagin and Neumann, 1981). Efforts have been made to modify the weather in such countries as Australia, India, Israel, Spain and the United States. The most successful experiments so far seem to have been in Israel, where it is postulated that the right kinds of clouds are common.

To be effective, the rainfall produced must have a beneficial method on the water resources of the region where it falls. Thus, crops should be irrigated and ground water and/or surface water should be increased and the increase used. This means that careful regional planning and investment are probably needed before weather modification is attempted and a back-up plan formulated, in case it fails.

The second method of enhancing existing supplies explored in the present chapter is the reduction or suppression of evaporation from open reservoirs. This can be extremely important where runoff from wetter uplands is collected and stored in reservoirs located in arid lower reaches of river basins. Annual surface evaporation of 2,000 to 3,000 mm (80 to 120 inches) is not uncommon in arid areas. This can mean a water loss of 20,000 to 30,000 m^3/hectare of reservoir surface area if not counter-balanced by rainfall.

The major effort to reduce this evaporation has concentrated on covering the water surface with some type of inexpensive material. Plastic sheets, foam plastic pellets and liquid chemical films are among the materials that have been tried. There is a fine balance between economic considerations and effectiveness. With the large surface areas involved, it is difficult to provide an effective yet economical cover.

The United States, with large reservoirs in its arid western region, has devoted considerable efforts to developing and testing evaporation suppression methods. However, those efforts were essentially abandoned in the late 1970s when none proved to be effective.

B. Weather modification

1. Historical background

Throughout recorded history, man has speculated on the relationships between clouds and rain and why some clouds produce rain while others do not. The mechanisms by which clouds are formed, grow and dissipate have long been the subject of both popular mythology and scientific inquiry.

Cloud seeding dates back to 1946, when Vincent Schaefer discovered that small pellets of dry ice could convert a supercooled water cloud into an ice cloud - at least in the laboratory. The concept of supercooling is central to the theory of cloud seeding. Water may be cooled to a temperature below its freezing point and still not crystallize. However, if a nucleus is present around which the ice can grow, then crystallization will proceed in the normal manner. After his laboratory work, Schaefer experimented in the real atmosphere, using solidified carbon dioxide (dry ice) to convert supercooled fogs and stratus clouds (Simpson, 1971).

A year later Bernard Vonnegut discovered that silver iodide (AgI) was nearly as good a cloud nucleator as dry ice, primarily because of its similar crystalline structure. Seeding clouds with silver iodide has been the standard experimental methods since 1947.

Following Schaefer's experiments, officers of the Division of Radiophysics of Australia's Commonwealth Scientific and Industrial Research Organization (CSIRO) carried out seeding trials on cumulus clouds inland from Sydney in February 1947. Rain was observed to fall from the seeded clouds, while similar nearby untreated clouds did not produce any precipitation. Those trials were among the first documented cases in which rainfall was artificially stimulated by man. Since that time CSIRO has played a leading role in the development of the science of cloud seeding (King, 1982).

During the period 1950 to 1960, the Division of Radiophysics of CSIRO conducted four experiments in the following areas: the Snowy Mountains, the Yorke Peninsula of south Australia, the New England District of New South Wales, and the Warragamba catchment area west of Sydney. Of those four, only the one conducted in the Snowy Mountains produced statistically significant evidence for rainfall increases over the entire duration of the experiment: a 19 per cent increase at the 5 per cent significance level (King, 1982).

Similar experiments were being carried out in the 1950s in the United States. Project Whitetop was a five-year programme for seeding summer cumulus clouds over Missouri, under the direction of Roscoe R. Braham. Statistical controls were applied in both space and time. However, the results of Project Whitetop were disappointing: the seeding apparently decreased rainfall by about 21 per cent over an area of 260,000 km^2. Moreover, Braham found that many rather warm, but still supercooled, cumulus clouds had a great deal of natural ice in them already. In fact, he often found about one ice particle per litre in unseeded clouds. Since that was exactly the amount supposed to be introduced by seeding, there should have been precipitation. If the theory were correct, there would be no point in introducing much larger injections of ice nuclei, since this would only result in "overseeding" (Simpson, 1971).

Those early experiments were based on what Joanne Simpson calls the "static" hypothesis. According to that theory (developed by Vincent Schaefer and Irving Langmuir), one way to achieve rain artificially might be to introduce 1 to 10 artificial freezing nuclei per million supercooled droplets, oı about one nucleus for each 1 to 10 litres of cloudy air. This would require only a few grams of silver iodide per cloud. The ice was to fall as rain when it melted at a lower altitude. The static theory ignored the motion structure of the cloud and possible cloud changes.

Simpson and her colleagues at the National Oceanic and Atmospheric Administration deliberately chose to "overseed" in the early 1960s. They intended to release th heat of freezing (fusion) rapidly in the supercooled water, thereby increasing cloud buoyancy and enhancing the cloud's updraft and vertical growth. She calls this the "dynamic" theory of precipitation growth. The technical means for a real-life experiment first appeared in 1963 when massive seeding techniques first became available. Invented at the Naval Ordnance Test Station in California, the innovation consisted of generating silver iodide smoke by pyrotechnics or fireworks.

In August 1963, the NOAA group conducted a preliminary pyrotechnic seeding experiment in the Caribbean area. Six clouds were seeded with about 20 kg of silver iodide per cloud - about one nucleus per cloud drop instead of a few per million, as the static theory required. Four of the seeded clouds showed a spectacular or explosive growth following seeding. However, those results were viewed with some skepticism by the meteorological community. The group then applied statistical control and randomization to check their results. In 1965, an extensive randomized seeding experiment was undertaken in the Caribbean. That experiment established definitively that massive silver iodide-seeding could increase cloud growth, but only under certain conditions (Simpson, 1971).

Meanwhile, additional extensive experiments were being carried out in Israel and Australia. In Israel, a series of small-scale cloud-seeding experiments had been carried out throughout the 1950s, using both aircraft and ground-based burners. In 1961, a major experimental programme was launched to gain a better understanding of the physical phenomena causing cloud precipitation and to gain experience in weather modification techniques. The programme tested the hypothesis that seeding could increase precipitation. Another programme begun in 1967 tested the more specific hypothesis that yields could be increased by cloud seeding in the catchment basin of Lake Galilee, Israel's principal reservoir. Both experimental programmes indicated that, as a result of cloud seeding, precipitation was augmented over the whole of the target area by about 15 per cent. There was also evidence that the effects could be extended over larger geographical areas, that is, that precipitating efficiency could be increased in large areas downwind of the seeding (Gagin and Neumann, 1976).

In Australia, a well-designed area experiment was begun at Tasmania in 1964. The experiment was carried out in alternating years until 1971, and the results suggested that rainfall increases of as high as 30 per cent were achieved in autumn, at a significance level of 3 per cent. The results were not as conclusive for the other seasons, but those for autumn and winter were sufficiently encouraging to continue the experiments to test the possibility of using cloud seeding as a water resources management tool (King, 1982).

In May 1968, the United States NOAA group conducted its first overland experiment in south Florida. The results were very successful: 13 out of 14 seeded clouds grew explosively following seeding. It was confirmed that increased cloud-growth upward resulted in lateral growth as well as increased mounts of rainfall. A graph was developed relating the predicted differences between maximum top height of a seeded cloud and that of an unseeded cloud to rainfall change caused by seeding. Thus, the model was ready to be used to predict the seeded rainfall amount in advance of the experiment.

Project Skywater, which was authorized in 1961, has been one of the leading ongoing precipitation management research programmes in the United States. It is based on systematic approach integrating field projects in various geographical areas, laboratory research and theoretical studies. The objective of Project Skywater is to learn how to alter clouds, by various seeding methods, to produce or increase rain and snowfall. The programme's research deals not only with cloud physics but also with the social and economic implications of cloud seeding and its environmental impact.

One of the major projects carried out under Skywater is the Colorado River Basin Pilot Project, which tested experimental cloud seeding during winter seasons from 1970 to 1975. Winter cloud systems over the San Juan Mountains were seeded to determine if snowfall, and the resultant runoff, could be increased. Extensive analysis of the pilot project revealed that precipitation could probably be increased by 10 per cent, producing substantial increases in the quantity of water in the San Juan River. Those experiments prompted planning for additional research in the basin, and a more advanced research programme was scheduled for the 1980s (United States Department of Interior, 1979a).

Much of the controvery and confusion that followed the early cloud-seeding experiments could have been resolved if those experiments had been adequately designed and sufficiently followed through to become instructive and contribute to this branch of atmospheric sciences. It has been found by several groups that, if properly conducted, the seeding by silver iodide of cooler stratiform and cumulus clouds could increase rainfall. The increases in precipitation recorded by some of the Australian, American and Israeli experiments during the 1960s varied between 10 and 25 per cent. However, it was found that improper or overseeding could cause a decrease in rainfall. Moreover, seeding during conditions either too warm or too cold might lead to negative results. The main reason that some cooler clouds respond so well to seeding is that, while they have a high water content, they lack an ice crystal multiplication process, a deficiency which the addition of solid precipitation particles effectively overcomes. The Israeli scientists have found that seeding can be effective for quite a number of days per year. It can either cause precipitation in clouds that otherwise would not have precipitated, or make the already existing precipitation processes more efficient (Gagin and Neumann, 1976).

Experiments in the United States during the 1970s continued to test the hypotheses developed earlier. Detailed testing and data gathering continued on the Colorado River Basin Pilot Project under Project Skywater (United States Department of the Inteior, 1979a) and in Florida under the Florida Area Cumulus Experiment (Woodley and Sax, 1976). Other weather modification experiments continued into the 1980s under the Sierra Co-operative Pilot Project (SCPP), the Co-operative Convective Precipitation Experiment (CCOPE) and the High Plains Co-operative Programme (HIPLEX). Those programmes were still in existence in the early 1980s, but had been considerably reduced by budget cut-backs. During the 1970s, Israel and Australia continued their weather modification programmes with quite different results: Israel concluded that weather modification provided a positive addition to its water supply, while Australia abandoned its programme, because of inadequate results. Apart from that of Israel, the major weather modification programme currently being undertaken is the Precipitation Enhancement Project, which was launched by the World Meteorological Organization in the late 1970s. It is hoped that this scientific effort will lead to a better understanding of weather modification techniques.

2. Technical considerations

Weather modification is the purposeful attempt to change natural phenomena such as clouds, rain, snow, hail, lightning, thunderstorms, tornadoes, fog and hurricanes so they are more beneficial or less destructive. Precipitation management is specifically concerned with understanding cloud processes and how they may be altered to help mankind.

All the atmospheric water that does not fall as natural rain or snow may be one of the world's major sources of water. Approximately 10 per cent of the moisture in the sky is estimated to fall daily as precipitation. That leaves a vast reservoir - estimated at more than $1.2 \times 10^{18} m^3$ - of fresh water enclosing the earth.

Precipitation is neither regular nor dependable. Weather scientists in many countries are learning how to manage precipitation - to pump some of the fresh water out of the sky's reservoir. They hope to provide the knowledge upon which cloud-seeding decisions can be made.

(a) Cloud physics

If the scientific knowledge of precipitation processes were complete, the likely effectiveness of weather modification techniques could be predicted without the need for experimentation. Even if existing knowledge had been available to past experimenters, many of the contradictory results obtained could possibly have been avoided. However, there are still many areas of uncertainty in cloud physics which must be resolved before weather modification can be considered a viable source of previously unavailable water resources.

Much of the early research on cloud physics was carried out by the Experimental Meteorology Laboratory of the United States National Oceanic and

Atmospheric Administration, under the direction of Joanne Simpson. The group, located at Coral Gables, Florida, was studying cumulus cloud behaviour with an eye towards developing techniques of managing weather on a regional scale. Cumulus clouds not only produce more than three fourths of the rain that reaches earth, but also generate hurricanes, thunderstorms, tornadoes, hailstorms and all other severe storms. From years of study, Simpson and her colleagues had learned that the life cycle of a cumulus cloud is a fierce struggle for existence, with the forces of growth and destruction in near balance. Because it is very difficult to study a nearly balanced natural phenomenon by measurement, they wanted to upset the balance. Their dynamic theory postulated that massive seeding could release enough fusion heating to increase the cloud buoyancy, and hence, under favourable circumstances, could produce a much larger, longer-lived cloud.

The main growth force in a cumulus cloud is buoyancy. The air of the cloud has a lower density than the surrounding air. Gaseous water condenses into the liquid droplets that make up the cloud; in the process, heat is released. Thus, the average tropical cumulus is warmer than its environment by about 0.5° to 1.0° C. Freezing its liquid water content of one to two grams per m^3 can about double this excess and thereby double its buoyancy, if the freezing is done suddenly in the cloud's ascending region (Simpson, 1971).

A cumulus is composed of a group of swirling particles and air currents that can be physically measured and described in the language of the cloud physicist. Simpson developed a series of cloud models, which consisted of sets of differential equations describing the evolution of in-cloud and ambient temperatures, humidity, density, pressure and the internal motions of a simplified cumulus under specific environmental conditions. By feeding those numerical relationships and assumptions into a computer, scientists at the Experimental Metereology Laboratory could express the theoretical balance of forces within a theoretical cloud on paper and approximate its behaviour. Although at the beginning the group had not been directly concerned with increasing rainfall, it soon became clear that increased rainfall was a likely by-product of the invigorated cloud dynamics.

Simpson has pioneered the development of models that can predict what should happen for both seeded clouds and their unseeded control clouds concerning: maximum growth upward, whether the top will cut off and drift away from the base, the amount of precipitation formed in and falling from the rising part of the cloud (the tower), the rise rate of the tower, and tower temperature compared to surrounding air temperature. Predicted rainfall was related to both cloud growth and predicted seedability. The main results of the statistical analysis of data collected in 1968 and 1970 showed that the dynamic seeding effect on rainfall was large, positive and significant. The seeded clouds rained more than three times as much as did the controls after the seeding run (Simpson, 1971).

A. Gagin and his colleagues at the Department of Atmospheric Sciences, Hebrew University, emphasized the cloud physics research component in the experiments carried out in Israel, which was expected to provide the necessary plausibility to the statistical data and results. The transferability of knowledge, results and techniques could only be accomplished on the basis of factual information obtained through extensive measurements of cloud and cloud system properties.

The rain-producing cloud systems in Israel are predominantly those associated with cold, winter, low-pressure cumulus cloud systems affecting the eastern Mediterranean. Air masses have been found to be of a continental character, originating predominantly in either Central or Eastern Europe or Western Asia. It has been found that the continental air masses moving to Israel over North Africa are charged with cloud condensation nucleus (CCN) particles, which may be liquid or solid particles. However, the size of droplets measured at various elevations above the bases of the prevailing clouds have been found to be fairly narrow, with larger drops being almost totally absent (Gagin, 1981). This type of cloud system depends on the "cold" process for precipitation, in which precipitation particles result from the initial formation of ice crystals followed by a combined growth process from the vapour and riming (freezing of supercooled water droplets). The cold continental clouds are particularly amenable to cloud seeding with AgI smoke, because the latter provides the ice crystals necessary to increase the precipitation efficiency of those clouds.

Gagin has identified another natural precipitation mechanism that generally functions in maritime or warm continental clouds. This he calls the "all-water" or "condensation-collision-coalescence" mechanism. In the all-water process, the precipitation particles are formed by a rapid process of condensation of cloud drops that subsequently collide and coalesce to form larger drops. While those clouds have a relatively high likelihood of precipitation because of their larger droplets and "colloidal instability", they possess relatively few cloud condensation nuclei. Such clouds present a limited opportunity for artificial intervention, as their natural precipitation mechanisms are quite efficient and seeding might inhibit those natural processes.

Thus, clouds that form in different atmospheric or geographic conditions may have basically different microstructures and hence different precipitation mechanisms. Efficient precipitation in clouds depends on the existence of large drops and a minimum vertical thickness to provide the proper conditions for rain formation. While continental clouds experience little variation of the droplet size with height, maritime clouds exhibit significant broadening of the size with height. The rapid formation of the much larger drops in maritime clouds has been shown to result from an efficient condensation-collision-coalescence process. Because of the initially wider droplet size distribution of maritime clouds, the drops are capable of producing, quite rapidly, even larger drops, which would in turn accelerate the process of collisions to form raindrops. Conversely, continental clouds are far less efficient in promoting growth through this process because their droplets and collision efficiencies are much smaller at all levels of the cloud.

Maritime clouds also require less depth in order to precipitate - about 1,500 m compared to 4,500 m for continental clouds - and precipitation likelihood is quite high even for shallow clouds. In tropical areas, maritime clouds will not form ice crystals, and the artificial introduction of ice crystals may even reduce their precipitation efficiency. Such clouds, which are colloidally unstable, rely almost entirely on the coalescence mechanism for rain formation.

The warm summer continental convective clouds are also colloidally unstable, because their warmer cloud bases may create conditions that promote the formation by condensation-collision and coalescence of large drops that will either increase the rate of ice formation or generate precipitation particles rather efficiently.

Colder continental clouds, on the other hand, have been described as "colloidally stable entities", because they generally lack large droplets and are limited in the formation of ice crystals. The likelihood of natural precipitation in those clouds is low compared to maritime clouds. However, they are more amenable to seeding than the colloidally unstable types.

An increase in precipitation efficiency can be realized in two ways. The first is that by which nucleation rates are increased (static seeding), which subsequently make use of the naturally available conditions for more efficient growth rates of the nucleated particles. The cold continental clouds would be more amenable to static seeding than the all-season maritime clouds or summer continental cumuli. The second is by enhancing the growth of the clouds (dynamic seeding), which leads to an increase in their dimensions and hence an increase in their moisture release rates. The latter effect would then be a result also of the increases in nucleation rates and growth of particles for a prolonged period of time. The convective clouds seeded in Florida and South Dakota often grew "explosively" and released considerable rain. However, some cloud towers were seen to be cut off from their bases following the same type of seeding (Gagin, 1978a).

Thus, the apparently contradictory results of early seeding experiments can be explained partly by the observation that clouds, which are supercooled to the same extent but which have different microstructures and ice budgets, may respond in a different manner to a given seeding technique. The high colloidal stability, for example, of the winter stratiform clouds of Tasmania or the winter orographic (pertaining to mountains) clouds of the central United States (in the Climax experiments), and the winter continental cumuli of Israel, seem to render those clouds more favourable to seeding for microphysical effects than the maritime cumuli of Australia or the summer cumuli in the "Whitetop" (United States) experiment. The latter clouds have been shown to produce naturally high ice particle concentrations that probably made the addition of ice nucleants in those cases unnecessary or even detrimental. Seeding seems to produce positive results in those cases when the processes of ice nucleation and particle growth are slower than the rate at which moisture is released in the clouds by the seeding (Gagin, 1978b).

<u>Temperature</u>

The formation of ice in clouds has long been known to depend on cloud temperature. In the absence of an alternative rain-forming process, normal ice crystal formation and its subsequent growth have been found to produce precipitation-sized particles only in convective clouds that have top temperatures colder than -10° to -12° C (equivalent to a cloud 3.25 km deep). The size and concentration of precipitation elements in the various clouds are proportional to the depth of the clouds and their top temperatures. Colder clouds with greater depths will produce more and larger raindrops.

Clouds having top temperatures warmer than -10° to -12° C are unlikely to be affected by seeding with silver iodide particles having a threshold activation temperature of -5° C.

Convective clouds having top temperatures in the range of -12° to -20° C seem to be most favourable for seeding. On a typical rainy day in Israel, a substantial proportion of the daily cloud population is within that temperature range. Seeding seems to be exceptionally positive when top temperatures are in the range of -15° to -21° C. Clouds with colder summit temperatures -25° C will produce natural concentrations of ice crystals which make seeding pointless or even detrimental. Concentrating on clouds in this temperature range, the overall effect of experimental seeding was 24 per cent, significant at the 0.5 per cent level. The mean daily rainfall on the experimental days having rainfall less than or equal to 15 mm was 8.8 mm. The heavier rainfall days associated with the colder cloud tops contributed much less to the end result (Gagin, 1981).

There are still many questions that have not been answered in the field of cloud physics. First, most cloud-seeding experiments have been based on the premises that natural mechanisms are not fully efficient in converting to precipitation the inflow of moisture into a cloud or cloud system and that seeding can increase the efficiency. However, there is very little information on precipitation efficiency, and it could be that in many cases the assumption of low natural precipitation efficiency is unwarranted.

There has also been much discussion whether precipitation enhancement in one region will be at the expense of precipitation elsewhere. This is not necessarily so, but more detailed data on the actual area affected must be collected and analysed.

To a large degree it is now possible to define cloud conditions suitable for the successful implementation of known seeding strategies. However, it is not clear what the optimum ice crystal concentration is for producing maximum precipitation. The optimum seeding rate may depend on that part of the life cycle of the cloud or cloud system at which the seeding material is injected. Better knowledge of the results of stimulation of the ice phase in a cloud as a function of the time of its life cycle when it is seeded may help predict when adverse effects (reductions in natural precipitation) might occur. From this point of view, there are still problems in pre-determining the seedability of clouds (Gagin and Warner, 1978).

(b) <u>Weather modification technology</u>

The technological aspects of weather modification contribute to both the uncertainties and the understanding of cloud processes. A proper seeding technology can be applied only on the basis of the availability of well-calibrated seeding generators, reliable estimates of the spatial distribution of the seeding agents following their release into the atmosphere, an adequate delivery system that will satisfy the requirements of accurate timing and controllable "dosages", and finally of an equally suitable surveillance system that will ensure the co-ordination and comprehensive monitoring of such a complicated effort.

A major problem is that nucleation theory cannot at present specify in sufficient detail the relative importance of the various modes of ice nucleation, nor can the environmental and cloud conditions that are conducive to those processes be specified. Hence, laboratory calibration is largely carried out in ignorance of the way in which the seeding material will act when eventually released into target clouds.

There are still difficulties in planning a sound seeding strategy. For example, with present knowledge it is not possible to calculate the concentration of the seeding agent as it disperses (for example, by turbulent diffusion) throughout the target area. Some of the uncertainty can be removed by direct measurement of the concentration of the seeding material within the area, and such measurements will be carried out during the Precipitation Enhancement Project of WMO (Gagin and Warner, 1978).

Only some clouds, in fact very few, have the proper set of conditions that can be influenced by cloud seeding to promote rain or snowfall. In all methods, the "seeding agent" is used to start the precipitation process, which then continues on its own. Some cloud-seeding methods use aircraft to deliver the seeding agent directly to the clouds, while others use ground-based equipment that releases the seeding agent into the air where it is carried to the clouds by updrafts.

(i) Cloud seeding techniques

Most all of the experiments to augment precipitation to date have involved seeding of clouds with particles, with the objective of affecting the clouds in one of the following ways:

(a) By enhancing the condensation-collision-coalescence (all-water) process;

(b) By initiating or increasing the growth of ice precipitation particles;

(c) By changing the dynamic properties of the clouds.

The first technique has very limited applicability because of its large material need and the severe requirements for suitable specific conditions. It can be carried out either by water spray or by the use of hygroscopic materials (such as salt). Both materials create a severe logistics problem owing to the need for large quantities to produce a large-scale effect. Furthermore, this technique requires conditions in a cloud, such as a maritime or warm continental cloud, which themselves render natural precipitation mechanisms quite efficient.

The second technique involves adding the correct amount of seed agent (usually AgI) at the right time in suitable clouds. This can be expected to produce additional precipitation by either initiating precipitation in clouds that otherwise would not have precipitated owing to a lack of ice crystals, or by increasing the precipitation efficiency in already precipitating clouds, mainly by the introduction of ice nuclei in "warmer" parts of the cloud where they would not naturally form. The magnitude of this effect depends mainly on the microstructure and external dimensions of the clouds. It should be noted that, if done incorrectly, this technique can decrease precipitation.

The third technique is rainfall augmentation by massive seeding aimed at affecting the dynamic properties of cumulus clouds. Cloud dynamics - strength, size and duration of vertical air currents - have a major effect on cumulus precipitation. Generally, the larger the cloud the greater the chance that one of the mechanisms will progress to the stage where the cloud precipitates. Techniques aimed at "explosion" and merger of clouds have successfully augmented precipitation (Gagin and Neumann, 1976).

(ii) Seeding agents

The common seeding agents for ice crystal production are dry ice and silver iodide. When dry ice, with a temperature of about -62° C, is used, it is released as small pellets from an airplane. It chills the air to temperatures at which ice crystals form naturally. Once the crystals are present they begin to draw moisture from the cloud, growing into snowflakes, the largest of which are heavy enough to fall. Dry ice was and is used on single clouds, but for logistical reasons it may be difficult for large-scale experiments. However, it is absolutely non-toxic and lacks residual effects.

The natural ice crystal enhancing mechanism operates most efficiently at -5° C, the threshold temperature of AgI, the most commonly used seeding agent. AgI has been found to be most suitable because of many properties - high maximum temperature of activity, high output of active particles per gram of the substance, slight solubility in water, low toxicity and transportability. Twenty years of research has cleared AgI of earlier environmental suspicions. AgI smoke can be produced by CSIRO-type burner-generators or pyrotechnics.

(iii) Pyrotechnics

In 1963, the massive seeding techniques developed by the Naval Ordinance Test Station in California became available. The innovation consisted of generating silver iodide smoke by pyrotechnics. The development of pyrotechnic devices for generating ice-forming nuclei was a major technological advance. The Navy pyrotechnic generators, known as Alectos, each released 1.2 kg of AgI, which could be dropped by aircraft from above directly into the centre of the cloud.

Silver iodide is powdered and mixed with oxidizer and fuel in a pyrotechnic flare. When the material burns, it vapourizes the silver iodide. The tiny AgI particles that form on recondensation are generally very effective as ice-forming nuclei. Some hundreds of grams are packed into a cardboard cylinder inside an aluminum cartridge about 15 cm long. Those cartridges are then placed in a rack mounted under each wing of the seeder plane. The flares can be ignited electrically and discharged downward to diffuse AgI smoke into the supercooled water near the top of the cloud. The Experimental Meteorology Laboratory in its experiments was using about 20 flares or 1 kg of AgI to seed each cloud, but the optimum amount of AgI for use in seeding is still debatable (United States Department of Commerce, 1972).

Flare ejection can be initiated manually with the release button operated by the flight meteorologist or automatically by establishing a firing programme with other control panel settings, selecting the number of flares per burst and initiating the firing programme through the release button. Available options may permit the selection of from one to three flares per burst and from 2- to 20-second firing intervals.

(iv) Delivery techniques

There are three basic methods of delivering the agent to be used for cloud testing. First, ground-based generators are used mainly for orographic cloud seeding. The technique is particularly effective in mountain ranges. Generators located on the upwind slopes of mountains are switched on before the cloud system reaches the target. The generators are ignited internally and throw a mist of AgI particles into the sky. In order to deliver AgI to the cloud, complex calculations and modelling experiments must be carried out and suitable control systems, which take account of wind velocity and direction, must be utilized.

Large-scale seeding at the level of the cloud base (1,500-2,000 m) can be used for seeding convective cloud systems of frontal origin. The seeding is carried out from aircraft along the upwind flight paths separated from the target by 10 to 15 km. Seeding can be performed by AgI-acetone burner-generators mounted on the aircraft.

Direct aircraft injection of dry ice or AgI into the supercooled cloud has been found to be effective in seeding cumulus clouds. For example, in the Florida Area Cumulus Experiments (FACE), when the model predicted good seedability or potential growth, a monitoring aircraft or aircrafts would fly through the test clouds (tops in the 6,000-8,000 m range) about three minutes prior to seeding to measure temperature, wind speed, humidity, amount of precipitable moisture and particle habit. A shorter-range seeder plane would pass once through the cloud top, and then pass again at right angles to the first, approximately three minutes later. The pilot would drop 10 AgI flares at about 100 m intervals on each pass. Following the seeding run, the monitoring aircraft would fly through again and gauge changes in the cloud characteristics measured earlier. All aircraft were co-ordinated via radar and a flight controller (Simpson and others, 1970). In Israeli experiments, aircraft fly back and forth along a pre-determined path and continuously spray a fine mist of AgI particles into the clouds.

(v) Radar and remote sensing

Radar is used to gather cloud information and help estimate precipitation over large areas. Radar-rainfall calculations were carried out in 1969 and tested with a radar rain-gauge study by Woodley and Herndon. The rainfall at cloud base was evaluated by planimetering the areas with each contour, plotting area-time graphs and integrating over time (Simpson, 1970). Those techniques gave a more reliable indication of precipitation results. More recently, a combination of remote and direct measurements has been used on the ground, from aircraft and by satellite imagery. Data on precipitation, wind speed and direction, temperature, humidity and barometric pressure are quickly relayed by satellite from remote weather observation stations to central locations where researchers can evaluate them (United States Department of Interior, 1979b).

Radar measurements (from three-dimensional weather radar) can provide basic data regarding the way in which precipitation propagates both vertically and horizontally, and the information it can provide may be of major importance in the final analysis of results.

(c) The assessment of results

The lack of predictability of natural precipitation is a key factor that hinders evaluation of operational cloud-seeding projects. Operational projects are sufficiently complex to require a sizeable scientific and technical effort for a thorough assessment.

Statistical controls are essential in meteorological experiments to test and establish the soundness of the physical linkages in the models used. It is quite often possible to deduce entirely opposite outcomes from the same initial conditions, just by using different assumptions and parameters. In the early days of weather modification, carefully designed and randomized experiments based on the static hypothesis had puzzling results, which seemed to differ radically depending on the location, the synoptic situation and also on the method of seeding (Simpson, 1971).

Weather modification is dependent on statistical analysis for the quantitative evaluation of the results of an experiment. It is important that the basic statistical evaluation of a result be backed up by physical measurements which lend support to the hypothesis upon which the experiments are based. There are still uncertainties with respect to how the statistical tools available to experimenters should be applied and how to interpret the information those tools provide, as indicated below.

Randomization is a basic requirement of a weather modification experiment. However, when the number of experimental periods is limited by a relatively short total duration (that is, five years or so), it is difficult to ensure that truly random choice has led to equal weighting of meteorological events. Since the experimental periods may not all have been meteorologically identical, some bias will be given to the statistical result. Although attempts are made in all well-conducted experiments to reduce the possibility of natural bias, it is difficult to be certain that no bias exists, since not all the components of the seeding-precipitation process are fully understood.

Also important to the design of an experiment is the choice of appropriate control areas where rainfall is highly correlated with that in the target area but which are unaffected by the seeding. Lack of knowledge of the dispersion of the seeding agent introduces the possibility that the control area rainfall may be affected by the seeding.

Moreover, a statistical analysis merely gives the probability that the observed result was not a chance event. In order to carry out a given analysis, assumptions may have been made regarding the statistical distribution of rainfall. Different assumptions may lead to the prediction of different statistical significance levels, particularly for the comparatively small sample available. (Gagin and Warner, 1978).

The fundamental principle of any evaluation of seeding effects is that of comparisons - be they temporal, spatial or both. Factors relevant to an evaluation include choice of response variables, sampling unit, project type (rain, snow or hail), period used for data formation, target control design, sample size (seeded and unseeded), covariates, sizes of target and control areas, assumed seeding effect and statistical techniques employed.

Valid evaluations, which avoid obvious biases, may incorporate uniformly defined observations for seeded and non-seeded occasions, a uniform method for measuring response variables, selection of target control design and statistical technique a priori, adherence to a pre-ordained protocol, and complete documentation of the seeding operation, including seeding criteria used, methods of collecting and recording data, seeding agent amount and timing, instrumentation and seeding rate. It appears that, with such precautions, useful evaluations of operational projects can be made (Hsu and Changnon, 1983).

The harsh reality is that 35 years of scientific research on weather modification has not produced enough convincing evidence that scientists can successfully modify precipitation. Factors responsible for this lack of evidence include poor project design and administration, poor conduct of the projects, unsuccessful randomizations, inadequacies in data collection, poor leadership and most critically, insufficient funding at the national and local levels (Changnon, 1980).

In 1981, Australia's CSIRO decided to discontinue its active involvement in cloud-seeding experiments aimed at increasing rainfall in rural areas. Measurement programmes and active experiments had indicated that meteorological conditions in many areas of Australia were either not appropriate for the success of the available seeding techniques or were too variable in themselves to permit increases in rainfall to be directly attributable to the experiments. The Organization continues to maintain its expertise in the field of cloud physics and also continues to play an advisory role for potential users of the cloud-seeding technique (Wilson, 1982).

Results in Israel have been sufficiently convincing over the period of experiments to encourage that country to continue its experiments and expand into operational seeding programmes in order to establish the validity of the theory and technology. On the basis of experiments conducted in Israel from 1960 to 1975 by the Department of Atmospheric Sciences, Hebrew University, a decision was made to initiate an operational seeding project which fully applies the techniques developed in the previous experiments.

This operational effort is now being carried out in conjunction with a third experiment in the southern, more arid regions of Israel. It is anticipated that the latter effort will continue for at least 12 years, because of the highly variable nature of the rainfall régime in those areas. Israel's success seems to be mainly a result of the rather uniform cloud régime which consists predominantly of bands of cumuliform clouds with a high degree of colloidal stability having modal depths and temperatures that make those clouds particularly amenable to seeding (Gagin, 1981).

In the United States, the Sierra Co-operative Pilot Project, a winter cloud-seeding experiment under Project Skywater, has as an aim to learn more about increasing precipitation in the Sierra Nevada mountains, to supply more water to California's Central Valley. Planning, data acquisition and calibration were carried out from 1973 to the early 1980s. Cloud-seeding experiments were carried out using dry ice from January to March 1983. Analysis of the results is being carried out.

The other major projects currently being carried out in the United States are the High Plains Co-operative Programme, under Project Skywater, and the Co-operative Convective Precipitation Experiment. The purpose of HIPLEX is to develp a cloud-seeding technology to increase summer rainfall over the dry High Plains of the western United States. Three sites were selected and data gathering commenced in the mid-1970s. HIPLEX research and experimentation are planned to continue for several years. Understanding of both the technology and the costs and benefits will be refined (United States Department of Interior 1979a). CCOPE, centred in the Miles City, Montana, area, has similar objectives to HIPLEX and is the largest field experiment of its kind ever mounted.

Furthermore, the World Meteorological Organization initiated in the late 1970s a long-term Precipitation Enhancement Project. Among the project's objectives are to provide reliable information about the probabilities of successful artificial intervention in meteorological processes in order to increase the amount of precipitation over an area of the order of 10,000 km^2. The area of the project site in Spain is approximately 50,000 km^2, considered large enough for adequate evaluation of scientific feasibility and economic benefit, but small enough to permit adequate methods for seeding and observations. Extensive experiments are to be conducted over a five-year period of utilizing widespread systematic measurements in order to obtain well-documented scientific evidence that may lead to the optimization of the effects of seeding (World Meteorological Organization, 1978). One of the aims of PEP is to demonstrate at a satisfactory statistical significance level over a relatively short experimental period (five years), that any increse observed is not a chance event, but is associated with the seeding.

All of the key figures in the field of weather modification over the years in Australia, Israel, the Soviet Union and the United States are providing major inputs into PEP.

3. Recent technological advances

The techniques and equipment used to collect weather data, seed clouds and measure results are quite sophisticated, as indicated in section 2 above. Though some simple equipment, such as rain gauges attached to fence posts, is used to gather information for weather modification programmes, researchers also employ the latest in computers, satellites, radar systems and instrumented aircraft in their quest to understand the weather.

Aircraft with sophisticated instruments make direct in-cloud observations and deliver seeding agents during experiments. The data network stores and helps decipher vast quantities of information which enable scientists to better understand the atmosphere.

The best modern aircraft available for weather modification research have on-board computers and visual displays. It is possible for those aircraft to receive the signals from a sounding balloon and a ground network almost simultaneously. The on-board display of surface winds and, by objective analysis, their convergence fields, could guide the seeder to promising areas and keep him away from areas where he would be fighting nature.

In the area of cloud physics, in recent years a few new developments have taken place which open new possibilities for rainfall physics research. The detailed numerical models, encompassing many of the physical processes and interactions taking place in and around cloud systems may eventually be capable of reliably predicting cloud behaviour and may allow for a physical evaluation of the possible effects of cloud seeding for precipitation enhancement.

Important developments in cloud physics instrumentation have enabled the measurement of cloud microphysical parameters in real time and definitely with better accuracy.

Remote sensing techniques as related to clouds and cloud systems are becoming useful tools in weather modification research. Multi-Doppler radar systems can provide much of the information relevant to the dynamic structure of clouds in their associated weather systems. Some progress has been made with rain-gauge networks coupled with radar for area rainfall determinations (Gagin, 1978b).

Tri-Doppler radar displays are available which show the three-dimensional motion field inside a cloud system as it develops. In the Florida experiments, the potential for rain augmentation depended on a seeding window controlled by the motion field.

It is recognized that experiments involving sophisticated instrumented aircraft, Doppler radars, telemetering sounding and communications to computers are extremely expensive. To make those operations economic will require further distillation of the knowledge gained from research experiments into a set of readily measurable parameters introduced into readily solvable equations (Simpson, 1978).

In the PEP experiments, pre-processing and validation by mini-computer and storage are considered key requirements for responsible data quality control. Some data need to be directly available for decision-making (synoptic, radar and satellite). Other information, such as rain-gauge readings and recordings, radiosonde profiles and cloud physical parameters, has to be available for on-going research at the site.

Rawinsonde data appropriate for the site must be obtained on average at least four times per day throughout the season. Those observations are necessary for determining the atmospheric stability and humidity structure and possibly for use with cloud seedability models (Bollay, 1978).

There have also been some developments and experimentation with new seeding agents. Homogeneous nucleation of water vapour may be achieved by evaporation of liquid propane, introduction of liquid air or expansion of compressed air.

Moreover, heterogeneous nucleation by new aerosol particles possessing ice-forming properties has been tested on a limited scale. Materials such as cupric sulphide, lead iodide and organics such as 1.5-dihydroxynapthalene, metaldehyde, phloroglucinol, phenazine and copper acetyl-acetonate seem to be among the most promising (Sedunov and Voloshchuk, 1978). However, because of the greater experience with and knowledge of AgI and dry ice, those two agents will probably continue to be used in the medium term.

4. Application in developing countries

Most of the experimentation with weather modification, including cloud seeding for precipitation enhancement, hail suppression and fog dispersal, has been carried out by such industrialized countries as the United States, the Soviet Union, Australia and Israel. However, at one time or another operational cloud-seeding activities in precipitation enhancement have been carried out in most of the developing countries of Central and South America, Africa, Asia and the Middle East.

Many of those operations are carried out by private companies, which provide cloud-seeding services to nations throughout the world. For example, contractors have been hired in recent years to seed clouds under the sponsorship of several state Governments in India.

The interested parties inside countries vary widely from nation to nation. Sometimes private associations, such as farm co-operatives, hire the weather modifiers. In most cases, however, it is the government agencies that hire the operators or engage in their own operations. The variety of sponsors, operators, motivations and techniques, and the absence of a mandatory international reporting system, make it difficult to determine precisely what everyone is doing (United States Department of Commerce, 1978).

The overriding problem for operational cloud seeding is that, except in a few cases, the predictability of the results of seeding is not to the point where operations can be conducted with confidence. Nevertheless, many of the Governments of developing countries such as India, China and Thailand are carrying out their own research and operational programmes. In China, apart from the scientifically based weather modification research being conducted, the country has a system to mobilize whole communities to watch for hail and shoot at the clouds with rockets full of seeding agents to suppress the hail.

(a) Humid tropical areas

In the tropical or semitropical countries many of the potential rain-producing clouds are convective in nature and their tops do not exceed the height of the freezing level. Hence, the possibility of increasing rainfall from warm clouds by enhancing the efficiency of the collision-coalescence process has generated considerable interest in those regions.

The development of large droplets may be sufficiently slow in some warm clouds to delay the onset of significant growth by collision-coalescence until the cloud has passed its mature stage. In principle, it is possible to enhance precipitation from such clouds by seeding these with hygroscopic particles or water drops to hasten the growth process. However, only a limited number of experiments have been carried out to test the effectiveness of such techniques. One problem is that large masses of seeding material are required. In spite of the limitations, a few encouraging (but not conclusive) experiments have been carried out. None have the requisite combination of successful rainfall increases based on physical and statistical evidence (World Meteorological Organization, 1981). In some experiments (Puerto Rico, India) attempts to assess the statistical results of seeding with hygroscopic particles on the basis of physical plausibility could not be undertaken because of the lack or inadequacy of any substantiating cloud physics observations (Gagin, 1978b).

Similar experiments and operational cloud seeding have been carried out for over 15 years in Thailand under the patronage of His Majesty King Bhumipol Adulyadej. A high degree of success has been reported in cloud-seeding attempts using dry ice, chemicals or salt dropped from small agricultural aircraft. The hot humid conditions of Thailand may be generally conducive to this type of seeding, and farmers were frequently requesting the Government to assist them during periods of drought. However, while a high degree of success in making rain was recorded, the rain seldom fell in the targeted area which had requested seeding. Experiments continue at the Royal Rainmaking Research and Development Institute of Kasetsart Agricultural University on how better to predict cloud behaviour in that country.

The applicability of the single cloud experiments carried out in Florida to other areas has not been established, but seems hopeful for many tropical and subtropical regions. The extensive cumulonimbus anvils observed in the south Florida area are not uncommon in the tropics and, if artificially created over a wide area, could play a significant role in reducing storm damage by providing the warming required to transform a cold core tropical disturbance into a warm core (Simpson, 1970).

(b) Dryer areas

As for less humid areas, the Libyan Meteorological Service has claimed success in a cloud-seeding operation in November 1982 by inducing "heavy rainfalls" over large areas of the country. Such operations involve "bombing" rain-bearing clouds with AgI or dry ice crystals and have become regular practice in the Libyan Arab Jamahiriya, where water is seen increasingly as the critical factor in long-term development. Natural rainfall even over the hilly coastal area is extremely variable, while 90 per cent of the country is extremely arid or desert area (World Water, February 1983).

Moreover, Israeli meteorologists were requested to assist in bringing rain to a drought-stricken area of Peru in early 1983. Israeli reserachers feel their techniques would be particularly useful to other countries located in the Mediterranean which have similar cloud régimes to Israel (Ben Shaul, 1983).

The extension of existing theory to other climatic regions, especially to arid regions, would depend on the suitability of the clouds to such techniques. Both the nature of atmospheric instability and liquid water content of clouds play a major role in determining the suitability of this technique to clouds in other regions. For every cloud system, the kind of artificial stimulation technique that best suits the prevailing conditions must be adopted. The decision to apply a given technique in an area must always rest on a clear recognition of the cloud properties there in order to determine its feasibility. Beneficial effects are indeed feasible if they are applied in a judicial manner with a clear understanding of all processes which lead to precipitation formation (Gagin, 1978a).

(c) <u>Drought relief</u>

The problem is that when drought strikes, there is often a flurry of interest in cloud seeding as a means of relieving the effects of the drought. The hasty cloud-seeding projects that result from those emergencies are usually not carefully designed or operated. Evaluation of such projects is impossible.

Pressure for direct drought alleviation arises at times when clouds with the natural conditions conducive to enhancing precipitation are at a minimum. This is, of course, the least effective time to seed. A 10 per cent increase in rainfall that is 25 per cent of normal is 2.5 per cent, while a 10 per cent increase of normal rainfall is 10 per cent. One cannot expect to be relatively more efficient in enhancing rain or snow in dry or drought conditions. Therefore, it would be much better to adopt a longer-term plan of water management that assumes some periods of drought (United States Department of Commerce, 1978). During normal or slightly less than normal years, cloud seeding can be used to recharge ground water and fill reservoirs to carry the area through future droughts. Many countries do not have the capability to plan ahead for drought, however, and would only resort to seeding in relatively dry years. Humid countries would not want to risk flooding and erosion, and therefore would not generally turn to weather modification in normal or wet years.

It may be difficult or impossible to ameliorate drought conditions when they occur. In most droughts, clouds suitable for seeding are scarce. Replenishing aquifers with water or refilling reservoirs and augmenting snow packs is obviously easier, because timing of precipitation is not crucial. Thus, changes in agricultural practices, with conversion to storage and irrigation, may be needed.

Most of the past weather modification experiments are considered inconclusive by the scientific community. Careful evaluations involving both extensive physical measurements of the clouds and precipitation and statistical analysis of the measurements are now considered mandatory in arriving at sound judgements. At this time weather modification other than supercooled fog dispersal must be considered in the realm of research. While operational seeding projects may be successful on a small-scale basis, they are seldom conducted in a manner that allows scientific evaluation.

It is hoped, however, that the international effort going into the Precipitation Enhancement Project of WMO will be able to provide some answers that may be useful to future rain-making efforts in developing countries. At the site in Spain, a dense network of rain-gauges is being set up, many of them of the recording type, to measure the success of the seeding on the basis of rainfall on the ground. The measurement programme is designed to provide the basic understanding to assess the likelihood of transferability of results to other areas with similar meteorological conditions.

The transferability of PEP results to other parts of the globe is of enormous interest because it could significantly influence the design of operations elsewhere. However, procedures and conclusions can only be transferred through conceptual models constructed from extensive measurements in the areas of concern as well as in the PEP experimental site.

5. Economic considerations

Weather modification including experimental or operational projects, to enhance precipitation is conducted primarily for economic advantages. The advance evidence for such an advantage should therefore be as convincing as possible if the varied interests are to agree to proceed with the activity.

The design of the project should include provision for the measurement and subsequent evaluation of the complex economic factors to determine whether the project was actually beneficial. Few precipitation enhancement experiments to date have included a rigorous economic evaluation, nor was detailed economics formally included in the designs.

As is often the case in economic studies of benefits and costs, more information is available on costs than on benefits. When the site is selected and the seeding delivery mechanism and frequency are determined, it will be possible to estimate the direct seeding costs for a season or a year. Such costs may have been in the range of $1.00 per season per hectare in the late 1970s.

Far more difficult is the evaluation of benefits and disbenefits. The principal economic enterprises that may receive beneficial impacts from increased precipitation are agriculture, hydropower and water supply. The activities that may suffer from negative effects are construction and recreation (Ackerman, 1978).

One of the major difficulties in measuring the benefits from precipitation enhancement, if it is possible to determine how much additional water is available, is how to allocate the benefits among various sectors. Part of the water will benefit agriculture and part will benefit hydropower, ground water recharge and water supply. Certainly not the entire amount of additional rainfall will be put to beneficial use, as some is bound to be lost in runoff.

(a) Agriculture

Agriculture, which may lose some 15 per cent of its potential gross revenue from all weather-related losses, is generally the primary candidate for potential benefit to the extent that such losses are related to moisture deficiency or drought. Most crops will respond positively to increased precipitation in most years. Moreover, in the extensive arid or semi-arid regions of the world, additional precipitation might provide the opportunity of converting dry areas to fertile ones. Additional precipitation may also provide benefits to relatively low productivity areas and gardens and lawns in urban areas.

Indirect benefits may be widespread, depending on the extent of agriculture, which may vary from nearly zero to the order of 100 per cent of direct benefits in some localities. The economic benefits to the businesses and industries that service agriculture may be dramatic, as may be the effect on the general economy of the region (Ackerman, 1978).

Potential disbenefits of increased precipitation include greater erosion and downstream sedimentation damage. Such erosion is a function of when the added precipitation occurs (season) and its intensity and duration. Additional disbenefits may occur in the form of downwind reductions in precipitation. Also, if weather modification is not carefully controlled, it may lead to flooding from increased runoff, or to hail damage from a major intensification of the weather system.

In Israel, the benefits to agriculture have been defined to include the following components: increase in agricultural product, reduction of pumping and conveyance costs resulting from a reduction in irrigation requirements and a "stored value" of the unpumped water left in reservoirs. The reduction in reservoir exploitation would have a positive effect only if reservoirs were not full and thus the rainfall was not lost through overflow. When there is a water shortage, the rainfall contributes to both an increase in agricultural production on unirrigated land and a savings on irrigation for irrigated land.

Following statistical analysis, it was found that out of the total cultivated area in Israel of 370,000 hectares, approximately 190,000 hectares were affected by cloud seeding. The remaining 180,000 hectares consist partly of control and buffer zones and partly of other unaffected lands. Given the effect of cloud seeding estimated at a 15 per cent increase in overall precipitation (significance level of 1.2 per cent) and the cost of seeding estimated at $600,000 per year (1981), the findings of the analysis were as follows:

(a) For a year of average rainfall, the additional rainfall resulting from cloud seeding is equivalent to 39 million m^3 per year;

(b) Assuming a water shortage equal to or greater than this amount, the estimated increase in Gross National Product (GNP) giving to the enhanced rainfall utilized directly by the crops is $11.5 million per year. The net benefit of the seeding activities for their direct benefit to crops is therefore about $10.9 million per year. This does not include the contribution from the replenishment of reservoirs.

Thus, the Israelis have concluded that precipitation enhancement is fully justified even on the basis of the benefit derived solely from the effect of the direct rainfall on the cultivated land, even without taking into consideration replenishment of reservoirs (Kloner, 1981).

(b) <u>Other affected economic sectors</u>

Water supply can be a substantial beneficiary of precipitation enhancement, particularly in the below-normal years. Water supply has an established value based on existing sources and thus, if the added runoff associated with cloud seeding could be measured, the direct value could be readily determined.

Snowpack enhancement is a major economic factor in the United States, Switzerland, the Federal Republic of Germany and other locations. Businesses providing winter recreation services may depend on adequate snowfall. Moreover, while the water is stored in the snowfall of the mountains during winter, when the snow melts it is used downstream for water supply including irrigation. The increased runoff also provides benefits to the hydropower industry, which can be measured in terms of increased generation of electricity. Indirect benefits would include an improvement in water quality and aquatic life resulting from increased dilution.

Among the industries that might be affected negatively by precipitation enhancement are construction and other outdoor work activities such as lumbering and mining. Economic losses resulting from soil erosion, sedimentation of streams and reservoirs and flood damage must also be taken into account.

In order to determine benefits to water supply, it would be useful to evaluate the effect of cloud seeding on hydrological parameters such as runoff, ground water or soil moisture. In fact, many cloud-seeding experiments have not even been efficiently designed to evaluate the effect upon precipitation with statistical satisfaction.

A few models have been developed to simulate the hydrologic response to a precipitation increase. The Stanford watershed model is based on hourly rainfall, daily potential evapotranspiration and the physical characteristics of a watershed. This model was calibrated against actual flow records, and then precipitation events were increased uniformly by 10 per cent. This was carried out for two streams in the United States and one in Australia. During 15 simulations representing five years on the three streams, runoff was increased from 16 to 57 per cent owing to a uniform 10 per cent increase in rainfall. It seems that a larger proportion of normal rainfall is used to satisfy evapotranspiration demands and to recharge soil moisture, while a much larger percentage of augmented rainfall becomes runoff. The capture of such increased precipitation may depend on having reservoir capacity to store the added runoff. It is obviously important to avoid producing too much moisture if the watershed is already saturated. While the most important time to seed clouds would be during a drought, that is exactly the time when atmospheric moisture and cloud conditions are least conducive to successful cloud seeding (Ackerman, 1978).

In Israel, analysis and models have been developed to estimate the increased volume of water flowing into Lake Galilee. The differences in summations of mean annual rainfall with and without cloud seeding indicated an average increase of 43 mm per year under seeding and a potential additional increase of 35 mm per year if the seeding were applied on all days. The application of those annual rainfalls to the prediction model of the net flow to Lake Galilee indicated an average increase of 103 million m^3 per year and an additional potential increase of 83 million m^3 per year (Ben Zvi and others, 1981). As noted earlier, however, Israel has a particularly uniform cloud régime which responds well to seeding.

(c) Benefits and costs

In seeking to estimate and evaluate economic benefits and other societal impacts, it is apparent that very little work has been done. With few exceptions, studies of the economics of weather modification have focused on individual experiments and have been conducted with almost no funds. Furthermore, these were mainly related to hail suppression and were based on damage reduction.

As noted above, there have been a few analyses in various countries related to the agricultural benefits that can accrue from precipitation enhancement. Specification of the exact economic value of weather modification to agriculture or any economic sector has been difficult for two reasons: the exact capabilities of weather modification are not known and socio-economic studies have not been completed. However, general values, benefits and costs can be estimated, and these seem to indicate that potential economic returns are attractive.

Because of the widespread interest in benefit-cost ratios, a brief review of a few analyses are given below. The range offered represents differences resulting from varying assumptions as to modification capabilities and differing economic values. Moreover, the methods used to compute these were not uniform.

In the United States, for the simultaneous decrease in hail and increase in rainfall, the ratios varied from 1:1 up to 15:1; for added snowpack in the Colorado Basin, from 1:1 to 3:1; and for added snowpack in the Sierras, from 1.8:1 to 6:1.

Under the Sierra Co-operative Pilot Project, potential water increases in the Sierra Nevada mountains from cloud seeding are estimated at 15 to 16 per cent . This would boost seasonal runoff over 10 per cent in the American River Basin and about 20 per cent in the Truckee-Tahoe Basin.

In the American River Basin, it has been estimated that a 10 per cent increase in precipitation would provide over 120 million m^3 of additional water to California's Central Valley (World Water, February 1983). That could augment local ground water supplies and sustain 16,000 to 20,000 ha of irrigated crops. If the total additional water were used for hydro-electricity, an additional 30 million kWh of electric power could be generated. Moreover, the increased precipitation would contribute to reducing salinity in sensitive estuaries in the San Francisco Bay area. It was estimated that the benefit-cost ratio could be as high as 23:1, depending on how the water was used.

An economic analysis of the results of the western Victoria (Australia) experiments was carried out in the late 1970s by CSIRO scientists. The economic aspects of the experiment were examined by establishing a relationship between wheat yield in the region and rainfall in the growing season. This was achieved by regressing wheat yields in the Wimmera area against various rainfall variables for the period 1914 to 1967. It was shown that the total August to November rainfall was the best predictor of wheat yields and that, together with a time variable (to allow for improvements in varieties and technology), 63 per cent of the variance could be explained.

Using this technique it was possible to assess the monetary benefits that would be derived from the increased wheat yields caused by seeding. In an average year, for example, it was shown that a 10 per cent seasonal increase in rainfall would yield about $1,000,000 (1978 prices) in benefits or about five times the cost of staging the seeding experiments. Since the benefits from an operation, rather than an experiment, would be higher than this, those figures were considered quite favourable.

During the 1979 and 1980 seasons, when field experiments were carried out, very few days suitable for seeding were identified. The two seasons were close to normal, so the low number of seeding opportunities could not be explained on grounds of abnormality of season. It had become apparent from the 1979 and 1980 field data that the number of seeding opportunities, based on data from the first two years, was less than 1.5 per season.

If the number of real opportunities for seeding were only one per year, then the economic benefit of the experiment would be reduced to the same level as costs in 1978 terms. From 1978 to the end of 1982, however, aircraft costs had risen by 25 per cent per year, while wheat returns to farmers had increased at a rate of only 5 per cent per year. Even if the experiment had proceeded as originally planned with an average of five seeding opportunities per year the benefit-cost ratio would have been severely eroded by the completion date of 1983.

In other areas of Australia, the opportunities for seeding were also found to be extremely limited. The inland plains of Victoria, New South Wales and south Australia are not as exclusively tied to cereals as is western Victoria, but prices for beef and wool followed similar trends to wheat.

It thus appeared that the use of cloud seeding as a water resources tool in the inland slopes and plains of south-east Australia was not a feasible proposition considering the lack of seeding opportunities and continuing adverse economic conditions. While other possibilities for seeding were explored, it was decided that none exhibited sufficient potential opportunities or benefits to continue the experiment. It was therefore decided in 1981 that there was little justification in continuing the seeding experiments of CSIRO at least for the next few years (King, 1982).

(d) <u>Areas of potential benefit</u>

A relatively comprehensive synthesis was carried out by Huff in the early 1970s on 14 river basins in the mid-western United States which had a minimum of 30 years of continuous records. After developing simulations involving the entire record, he concluded that precipitation augmentation would most likely be restricted to those periods of near normal to somewhat below normal runoff conditions. When consideration is given to operational constraints, the best available information indicated that no more than 50 per cent of the potential seeding-induced runoff could be utilized, on average, in near-normal periods in the mid-western United States. In below-normal periods during the cold season this constraint might be lowered to approximately 10 to 20 per cent.

It was nypothesized by Huff and Chagnon (1972) that the greatest potential benefits from cloud seeding in the flat lands may well be to satisfy soil moisture deficiencies and thus benefit agriculture. They concluded that for mid-western United States conditions cloud seeding during the warm months would be economically beneficial in 9 out of 10 years. Because of the improved crop response and yield, and because of the low cost of cloud seeding, benefit-cost ratios of the order of 10:1 to 20:1 could be expected.

Aside from hydrological measurements, other methods of evaluating the effect of precipitation enhancement, especially in the agriculture sector, involve such economic measures as unit crop production figures in the target, control and off-site areas and income earned.

Operating costs of cloud seeding are relatively low, and the capital equipment is neither excessively costly nor specialized to a single use or area. As a short-term, flexible measure to meet some of our water demands, weather modification could become a most useful tool in increasing water supply (United States Department of Commerce, 1978).

C. Evaporation suppression

1. Historical background

Research has been carried out on alternative means to prevent evaporation from large surface reservoirs, particularly in arid areas, in order to conserve existing water supplies. Various methods and techniques aimed at reducing evaporation have been considered since the beginning of this century. Spreading of oils to form a multi-molecular layer for reducing evaporation was first reported in 1941. Extensive research on the subject began in the 1950s and continued through the 1960s.

The various evaporation suppression methods fall into two main groups:

(a) Formation of a monomolecular layer on the water surface, which reduces evaporation by forming a physical barrier to the flow of vapour from the water surface to the air;

(b) Covering the water with insulating materials that reflect or filter some of the radiation reaching the water, thus forming an energy barrier which reduces the evaporation.

2. Technical considerations

(a) Monomolecular layers

During the late 1950s there was general optimism about the potential for using a chemical monomolecular film over the water surface to prevent evaporation. The main chemicals used in experiments carried out in the United States were hexadecanol, octadecanol and ethanol. These were spread on the surface of the reservoir and looked like an oil slick. Tests in the laboratories indicated that evaporation could be reduced by about 90 per cent. However, in order to get good results from using such materials, the monomolecular layer must be maintained under wind and wave conditions outside the laboratory.

Various spreading techniques have been used for the monomolecular materials, such as pipelines with portable or fixed sprayers along the shore, boats and aircraft. The material may be spread in crystal or powdered form, in an alcohol suspension or emulsion or as melted alcohols. Spreading from the air is partricularly suited to large areas, where the wind velocity can be used to advantage.

Two large-scale experiments to spread alcohol layers were conducted in 1965-1966 at Lake Hefner in Oklahoma and in 1969-1970 at the Kishon reservoir in Israel. The experiment at Lake Hefner was conducted over an area of 10 km^2. The sprayer was done by fixed sprayers in the lake, not far from the shore. The experiment resulted in an average of only about 20 per cent coverage of the lake surface by the monomolecular layer. In the second experiment, in the Kishon reservoir, the alcohol suspension was spread by floating sprayers, which allowed a smaller discharge and a finer spray from each sprayer resulting in an average 80 per cent coverage of the target area (about 64 per cent of the entire lake). Inverse relationships between area coverage and wind velocity and between wind velocity and the quantity of the alcohol required per running metre were observed.

In the Kishon reservoir experiment a 22 per cent reduction in evaporation was observed at the beginning of the season. This declined and stabilized at about 10 per cent during the course of the season. The recorded decrease in the evaporation reduction resulted from causes that were coincidental and unrelated to the nature of the experiment. However, it is clear that the accumulation of heat in the water significantly reduces the real efficiency of the method.

In the field it was found that when the monomolecular material was tested, wind and waves would cause it to compress and pile up on the shore, in ribbons. In the United States, evaporation was reduced by only 8 to 10 per cent at the cost of an operation using very expensive materials. There were some slightly more positive results in Australia, however, where field studies were carried out in low wind areas.

There seem to be problems in applying and maintaining any of those materials. In the United States, negative results were obtained when using paraffin in some of the experiments. The paraffin was melted at 38° C to become a liquid and was sprayed through a small nozzle to spread it over the reservoir. When it became a solid again, it was like a thin scummy material which began to cause water quality problems. The paraffin accumulated onshore where bacteria fed on it. It was feared that the bacteria would pollute the local water supply.

(b) <u>Radiation-reflecting materials</u>

The use of radiation-reflecting materials has the advantage of reducing the net quantity of energy reaching the water body, although with insulated radiation-reflecting materials, a relative increase in water temperature was observed in the morning.

In the first experiments with floating microspheres, it was found that the materials used actually increased evaporation because of their rotation; winds and waves cause the particles to drift and pile up. Other experiments showed that the resistance of the floating particles to dispersion depended on their size and shape. In Italy it was found that increasing the diameter of particles reduced the rate of evaporation and in Chile it was found that expanded polystyrene spheres reduced the evaporation by 40 per cent. It was also found that several types of floating plastic rafts could be very effective in controlling evaporation losses. Experiments with floating solid and granular materials (for example, perlite ore) showed that these could provide practical means of reducing evaporation from open water surfaces. In one experiment a reduction of 35 per cent of the evaporation rate was achieved by covering about 50 per cent of the water surface with styrofoam panels.

Other experiments carried out in the United States tested small star-shaped styrofoam pellets, floating blocks of styrofoam and lightweight concrete to reduce evaporation. All of those materials were defeated by the wind and waves, however.

Another major problem with using radiation-reflecting layers to reduce evaporation is that they interfere with oxygen passage into the water body. This had been observed in previous studies, and additional research is required. Because of stability problems, this method is not yet applicable to medium- and large-sized reservoirs. Broad use of this technique would be possible only after a significant technical breakthrough makes it possible to spread particles in reservoirs to form a continuous cover which is stable under various wind and wave conditions.

3. Recent technological advances

Following the experiments carried out with the various monomolecular and radiation-reflecting materials in the 1960s and 1970s, it was concluded that none of the materials tested could withstand the effects of wind and waves and reduce evaporation. Thus, most research programes have been shelved until a new method is proposed for suppressing evaporation.

4. Application in developing countries

It is unlikely that the technology for evaporation suppression would be used by any developing country before it has been thoroughly tested and proved in developed countries. As with most of the other technologies discussed in the present volume, the countries that could benefit from evaporation suppression would be the relatively wealthy, arid areas of the Middle East, and the Caribbean and other island areas that utilize reservoirs for their water supply.

5. Economic considerations

With all the methods of evaporation suppression, it is necessary to apply the materials daily, even when the wind is not too strong. Even under ideal conditions, it has to be renewed, because the bacteria consume it and it is affected by movement.

Moreover, the cost of the petroleum-based products had risen four- or fivefold from the early 1970s to the early 1980s, making it a very expensive technology. The researchers at the now-disbanded United States Department of Interior's office of Water Research and Technology could not convince themselves that any of those methods would become economically practical. Thus, they dropped them from active consideration.

At the present stage, no one seems to be using evaporation suppression methods, because none of the technology has reached the point of practical application. Additional technical research would certainly be necessary to produce a technique that is feasible from an engineering and economic point of view.

V. CONCLUSIONS

A. General

With the exception of weather modification, the other non-conventional methods of increasing water supply discussed in the present volume are basically intended to assist countries with water resource problems in specific small geographical areas. Desalination, water reuse and the other techniques are usually designed and built to supply water to a specific city, town or other limited area, although by repeating the installations or extending pipelines, the water could be distributed, at a cost, over a relatively large region.

Saudi Arabia is an example of a country that is heavily dependent on non-conventional water resource techniques. It has utilized desalination to convert its large supplies of brackish water and sea water into potable water. Desalination has been used to supply both individual locations as well as large regions. In the latter case, large desalination complexes have been built along the undeveloped sea coast and the desalted water produced is transported long distances to major cities by pipeline. The 950,000 m^3 (250 mgd) Al-Jubail desalting facility on the Arabian Gulf is used to produce water which is piped 485 km (300 mi) inland to the city of Riyadh.

As discussed throughout the present volume, non-conventional water resource techniques are generally characterized by more complexity, generally higher costs and greater risks of failure than conventional techniques. Where at all possible, conventional techniques should be employed to improve or augment existing sources or supplies. Because of this, caution should be exercised if planning suggest the complete abandonment of existing methods of water supply and places full reliance on non-conventional techniques, unless a very careful study has indicated that this is in the long-term best interest of a particular locality.

These are instances where a non-conventional water resource technique such as desalting could be a very appropriate application. Desalination plants can be used effectively to provide potable water to small isolated coastal communities in arid areas in place of constructing long pipelines from areas where conventional sources of water (from wells or runoff) exist. Tankers can be an excellent quick-response solution to dealing with emergencies caused by unseasonal drought conditions.

B. Comparison of methods

Each of the non-conventional water resource alternatives discussed in the present volume have various characteristics relative to technical, economic and political feasibility. These are summarized in table 26.

Table 26. Comparison of non-conventional water resources: technical, economic and political criteria

Criteria	Desalination	Transport-tankers
Representative costs	Cost of water (including capital recovery) Brackish: $0.25-1.00/m^3 (0.95-3.80/1,000 gal) Sea water: $1.30-8.00/m^3 (4.90-30.30/1,000 gal) Cost of water using renewable energy sources (based on total capital costs) $4.00-50.00/m^3 (15.00-190/1,000 gal)	Transportation $1.00-6.00/m^3 (3.80-23.00/1,000 gal) Water at source $0.25-1.50/m^3 (0.95-5.70/1,000 gal) Cost of water $1.25-7.50/m^3 (4.75-28.40/1,000 gal)
Stage of development	Moderate to high; widespread experience	Low to moderate; some experience
Special physical requirements	1. Source of clean brackish or sea water 2. Method or place to dispose of a brine solution	1. Reliable source of potable water in another area or country 2. A need for water adjacent to a port or coastal area 3. Port facilities to unload tanker 4. Large storage facilities
Advantages: Technical	1. Proven systems available 2. Cost of equipment and production could be reasonably predicted 3. Wide range of suppliers	1. Low level of technology required, except for initial investment in port facilities
Political	1. Can develop own water resources	1. Can provide a quickly implemented solution to a water shortage
Disadvantages: Technical	1. Requires skilled technicians for operation and repair of equipment 2. Energy-intensive process 3. Delay in repair or lack of operating supplies can damage capital equipment	1. Water arrives in large quantities necessitating high capacity pumps and large storage tanks to permit the tankers to unload quickly 2. Deep drought channels and facilities needed for large vessels
Political	1. Generally requires use of foreign exchange to purchase equipment 2. Involves continual high energy usage	1. Must depend on sources and transporters outside country. The potential for a supply interruption because of storms, conflicts, boycotts or strikes is relatively high 2. Can be expensive
Certainty of operation	High	High
Typical applications for water	Potable Industrial	Potable Agriculture Industrial

Transport-icebergs	Water reuse	Weather modification
Total capital requirements estimated <u>for Saudi Arabian project</u> $16-80 billion <u>Cost of water</u> $0.02-0.85/m^3 (0.08-3.20/1,000 gal)	<u>Cost of water</u> $0.07-1.80/m^3 (0.30-6.85/1,000 gal)	<u>Costs of application</u> $1.50-5.00/ha/season <u>Costs of water</u> (based on Israeli estimates of increased water supply) $0.01/m^3 (0.04/1,000 gal)
Very low; still in conceptual stage	Moderate; experience in various areas	Low; still experimental
1. Large tugboats 2. A need for water adjacent to a coastal area 3. Deep draught channels 4. Some storage facilities 5. Machinery or mechanism to melt ice and collect water	1. Source of waste water	1. Suitable clouds 2. Scientific staff 3. Structures and land use to take advantage of increased rainfall
1. It could be an economical method to produce fresh water	1. Proven techniques available 2. Cost of equipment and production could be reasonably predicted 3. Wide range of suppliers 4. Only a moderate technical skill level needed	1. Can supply water over a wide area, thus reducing distribution costs 2. Only a moderate to small capital investment needed
1. It would attract world-wide attention	1. Can supply a moderate cost alternative for water used in non-potable applications 2. Can reduce problems associated with present method of waste-water disposal, including pollution	1. Has the potential to reduce arid conditions over a large area
1. An essentially untried method in which all the details have not been worked out 2. Would require a large investment without assurance of success 3. Not suitable for small-scale experimentation	1. Requires some skill in operation and maintenance of facilities 2. Improper operation could create the potential for adverse public health effects 3. Will only work in areas where waste water is collected in a coastal location	1. Still in the research stage with many uncertainties 2. Requires scientific support 3. Cannot really control results 4. Must have infrastructure and land use to take advantage of additional rainfall
1. Untried - no assurance of success 2. Could be blamed for changes in weather, fishing and marine environment	1. May not be aesthetically or culturally acceptable	1. No assurance of success 2. Very difficult to measure or quantify success 3. Likely to be blamed for all problems with weather
Low	High	Low to moderate
Potable Agriculture Industrial	Agriculture Industrial	Potable Agricultural Industrial

C. Prospects for the future

Prospects for wider application of non-conventional water resource techniques are promising, mainly as the result of two factors. The first is that the reliability, and possibly the cost, of many of the techniques should improve with further investigation and use. The second factor is that the continued increase in population and per capita water use will put stress on existing supplies and increase the cost of developing sources and supplies by conventional means. This will provide opportunities for the economic application of non-conventional water resource techniques.

In many cases, non-conventional techniques can be successfully integrated into conventional development schemes. Several islands in the Caribbean combine ground water extraction, desalination of sea water and the reclamation of waste water for irrigation purposes within their overall water resources plans.

1. Desalination

Desalination is one of the most viable of the non-conventional techniques. Over the past 30 years, various distillation processes, reverse osmosis and electrodialysis have become commercially viable, reliable techniques to desalinate saline waters.

In the future, it can be expected that continued research and development of components for reverse osmosis and electrodialysis should help to increase reliability and reduce relative operating costs. New membranes for both brackish water and sea-water reverse osmosis units should continue to reduce energy usage and extend membrane life. The widespread use of energy recovery devices, which has only begun in recent years, should provide the hardware and experience needed to utilize them routinely with reverse osmosis units. The production of large capacity reverse osmosis and electrodialysis membrane modules should also aid in cost control.

In the area of distillation, it can be expected that the use of the process will continue despite claims by the proponents of reverse osmosis that the latter process is more economical. The increasing use of high-temperature additives in place of acid for MSF plants should permit increased efficiencies, greater reliability and longer plant life which will be translated into lower production costs.

The initial success of the low-temperature, aluminium-tubed multiple effect distillation units in the Caribbean may provide an impetus to use this design for other applications where back-pressure steam from turbines or other waste heat is available. The apparent simplicity of operation of those units makes their use in developing countries attractive.

It appears that there will be a continuing application for small vapour compression units for the desalination of sea water which has suspended matter that may not be easily removed in pre-treatment by SWRO units. Research on those units continues in order to increase the time between cleaning as well as to increase their thermal efficiency.

2. Transport by tanker

The future of tanker transport of water is less a matter of technology, which is relatively straightforward, and more a matter of economics under actual market conditions. Most of the cost data in the present report are based on projections by the tanker industry and these need to be confirmed in actual practice. The current excess capacity of very large tankers cannot be expected to continue forever, as surplus vessels are being sold for scrap and as the world's need for oil increases. The removal of the extra vessels from the market may have a negative effect on the economics of this mode of water transport, or transport of water may develop into a satisfactory market for the tanker fleet.

3. Transport by iceberg

Although the basic concept of floating an iceberg to a water-short area and melting it to produce water sounded simple, in-depth studies have shown that it is a rather complex scheme. Since considerable capital is necessary to fund a project of this type, and considerable risk is involved, it is doubtful that augmentation of water supplies by utilizing icebergs will occur any time in the near future. It is an idea that awaits a person, agency or Government willing to invest in a trial run.

4. Water reuse

The future prospects for the widespread application of water reuse in the developing world depend on a number of important factors. The first is the installation and use of waste-water collection systems (sewers, pump stations etc.) to provide a source of waste water. The second will be further research into the long-term public health implications of various levels of water reuse. The final factors will be the cultural acceptance of the reuse of water for various beneficial uses and the desire to treat waste-water discharges so as to minimize their effect on the environment and the public health.

The reclamation of waste water for certain agricultural and industrial purposes can be expected to increase in the future where alternate sources of higher-quality water are either unavailable or too expensive.

The future prospects for the reclamation of waste water for potable purposes is hindered by concerns over the long-term effect of trace organics and other constituents on public health. The degree of caution now being exhibited in the industrial nations should slow any widespread acceptance of the concept. The careful research work on potable reuse being undertaken by the city of Denver, Colorado, and by a number of countries should aid in developing standards for this type of reuse.

5. Weather modification

The many complex variables involved in weather modification will probably hinder its widespread application in the near future for increasing rainfall in most areas. Questions concerning the amount of control over and actual effect of cloud seeding, as well as the potential for long-term modifications in weather of a region should keep its practical application limited. It can be expected that, as the body of knowledge on the causes and effects of weather patterns increases, the ability to make predictive changes in weather will increase. The current work being carried out under the World Meteorological Organization's Precipitation Enhancement Programme should contribute considerably to that body of knowledge.

6. Summary

In summary, there appears to be a role for some of the non-conventional water resource techniques discussed in the present volume. The selection and use of a non-conventional technique must be done carefully with full recognition of the potential positive and negative implications that could be involved. This is difficult, as evaluations must be made of the technical, economic and political aspects of any project. In some areas, and with some techniques, there is incomplete information available and the final decision must be heavily based on subjective considerations.

The pressure from growing water requirements in the industrialized countries will force many of them increasingly to consider and use non-conventional water resource techniques. This will be beneficial to all, as it will create a market and provide funding for products and research to develop those techniques. With increased use and knowledge, the unpredictability involved with some of those techniques, such as weather modification, will diminish, allowing a better evaluation of the feasibility for a given application.

While the best course of action for any area is to develop its low-cost conventional water resources first, the increasing scarcity of such resources will drive up their costs, making non-conventional development economically feasible and necessary in the foreseeable future.

Annex I

DISTILLATION

A. Technical background

There are three essential steps in the production of potable water by distillation: vapour production, transportation of vapour to a condenser and condensation.

1. Vapour production

Evaporation (or vaporization) is a surface phenomenon in which water molecules accumulate sufficient energy to allow them to escape from the bulk liquid and enter the space above it as vapour. If energy, such as heat from the sun, is continually added, the liquid continues to evaporate slowly. Natural saline water contains no other substances in significant quantities, apart from potable water, which will vaporize in the temperature range used for distillation.

Under any circumstances, the amount of vapour that can be produced is limited by the available energy, but evaporation can be accelerated by applying energy more rapidly or by increasing the surface area available for the molecules to escape.

Sufficient addition of heat to the liquid causes the formation of vapour bubbles in the body of liquid, or boiling. As the pressure on the liquid is increased (as in a steam boiler), the boiling temperature increases above the normal boiling point (100° C or 212° F at atmospheric pressure). As the pressure is reduced, the boiling temperature decreases. It is actually possible to reduce the pressure on water sufficiently that water will boil at its freezing point (0° C or 32° F).

For water to undergo a phase change from liquid to vapour, it is necessary to acquire energy equal to the heat of vaporization, a very significant concept in the distillation of water. On the other hand, in order for water to condense to a liquid, it is necessary that the heat of condensation (equal to the heat of vaporization) be removed.

For distillation to work efficiently, it is necessary to recover or reuse as much of the heat of condensation as possible. This is often done by condensing water vapour on one side of a heat transfer surface while simultaneously utilizing the other side of the surface (such as a tube) for the heating and/or evaporation of a cooler liquid (such as sea water) so that the heat is recovered and productively reused.

2. Transportation of vapour to a condenser

Vapour produced during vaporization must be transported to a place where condensation can occur. To promote vapour production, the vapour must be removed rapidly, thereby reducing the vapour pressure above the boiling liquid. The vapour itself is usually transported by pressure or temperature differentials or by mechanical means.

3. Condensation

Condensation generally takes place on the inside or outside of tubes made from materials that are capable of a high degree of heat transfer. The heat of condensation, which must be removed from the water vapour for condensation to occur, is used either to heat or to vaporize saline water.

For efficient condensation to occur, the surface must rapidly remove the heat and allow the condensed liquid to flow to a collection point. If condensed liquid remains as a film on a surface, it acts as an insulator and reduces performance.

B. Process description

In order to promote boiling, the distillation process takes advantage of the relationship between the boiling point and the applied pressure on the liquid in question. By successively reducing the pressure of a saline solution it can be made to boil successively many times without adding additional heat. This technique is used to one degree or another in almost all commercial distillation processes since reducing the pressure is less costly than adding heat.

There are three major distillation processes being used in the industry today: multiple-effect evaporation, multi-stage flash and vapour compression.

1. Multiple-effect evaporation

Multiple-effect evaporation has been widely used in producing boiler feed water for land-based power plants and ocean-going vessels, as well as in the sugar and salt industries since the nineteenth century. The early designs were adapted to the potable water industry with few initial changes and helped the industry begin.

In each effect of the evaporator, steam is condensed on one side of a tube and the heat of condensation derived from this is utilized to evaporate saline water on the other side of the tube wall. Thus, the heat of vaporization imparted to the water to produce the initial vaporization is efficiently reused through the subsequent exchange of the heats of condensation and vaporization in later effects. The subsequent use and reuse of the heats of vaporization and condensation to promote boiling is accomplished by reducing the pressure in each of the effects relative to the one preceding it. This allows the brine to boil at lower and lower temperatures as it flows through the plant. Because of this, the multiple-effect plant has a steam economy (ratio of water produced to steam used) which is proportional to the number of effects.

The early multiple-effect potable water plants usually contained two to six effects, and the water was heated using submerged tubes. This process is shown in figure X. However, the submerged-tube units were not as efficient as other configurations since the brine pool could not be as easily vaporized because of the smaller relative surface area and scale which often formed on the hot submerged tubes.

The vertical-tube evaporator (VTE), as shown in figure XI, was developed to resolve some of the problems of the submerged-tube configuration. In the units

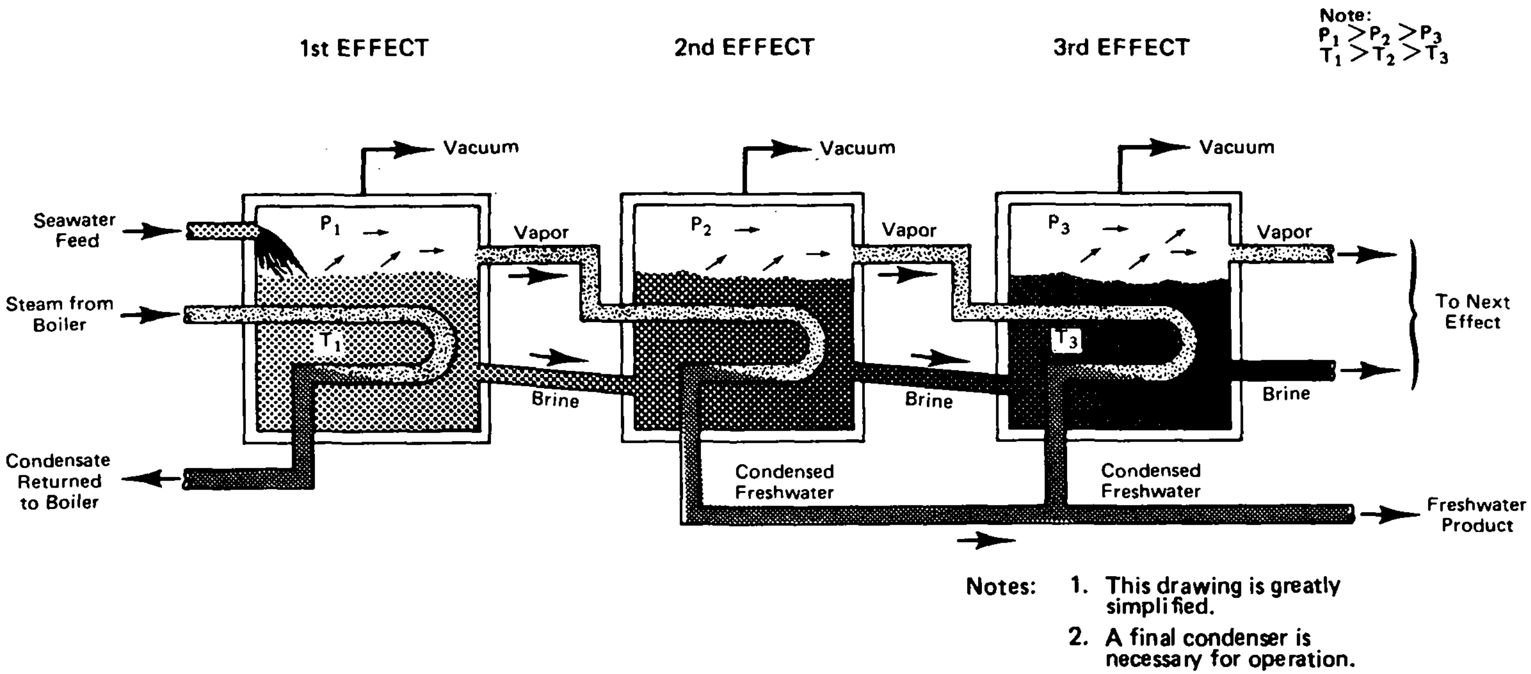
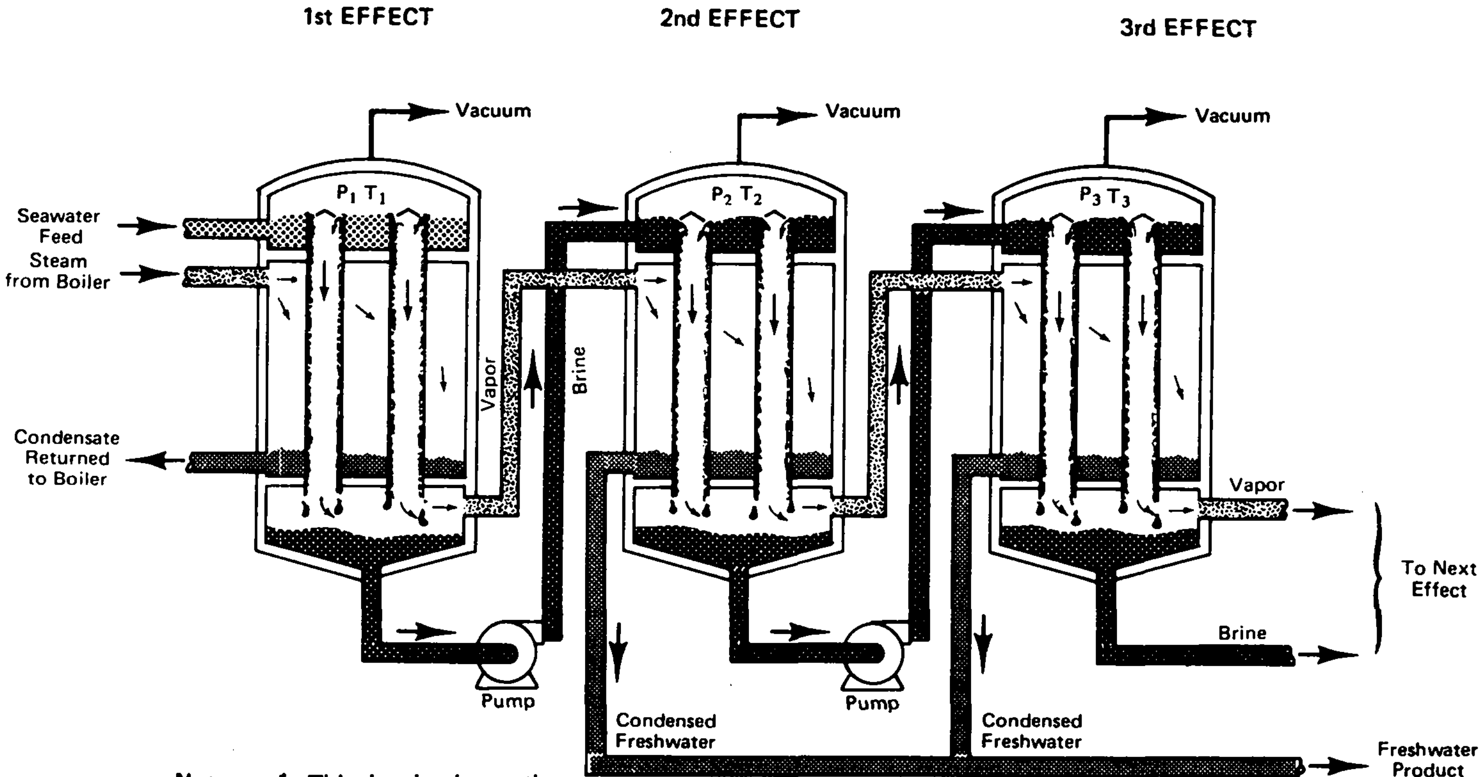


Figure X. Conceptual diagram of a submerged tube (ST) multiple-effect distillation plant

Source: This figure courtesy of the United States Agency for International Development. From O.K. Buros and others, The USAID Desalination Manual (Washington, D.C., prepared for USAID by CH2M Hill International Corporation, 1980).



Notes: 1. This drawing is greatly simplified.
2. A final condenser is necessary for operation.

$P_1 > P_2 > P_3$
$T_1 > T_2 > T_3$

Figure XI. Conceptual diagram of a vertical-tube evaporator (VTE)

Source: This figure courtesy of the United States Agency for International Development. From O.K. Buros and others, The USAID Desalination Manual (Washington, D.C., prepared for USAID by CH2M Hill International Corporation, 1980).

illustrated in the figure, vertical tubes are suspended above a brine pool, and brine flows on the inside of the tube (tube side), while vapour is condensed on the outside (shell side). The heat of condensation is conducted through the tube wall and used to heat the water flowing on the inside of the tubes. In general, the brine flow in the tubes is downward, although upward flow units are also used.

External steam must be supplied to the first effect to add sufficient heat to permit boiling and evaporation to take place in that effect. This external steam represents the major energy input to the process. The steam is generally condensed and returned to the boiler for reheating and recycling.

Compared to the submerged-tube configuration, the vertical-tube units have the potential for increased thermal efficiency and reduced scaling. The vertical-tube plants are more complex and usually require considerably more external piping and pumps than the submerged-tube facilities. Pumps and associated piping are usually necessary to pump brine between effects. For efficient operation and the minimization of scale formation on the tube surfaces, it is necessary that the brine feed be continuous and that the brine be evenly distributed during operation among and inside all the tubes.

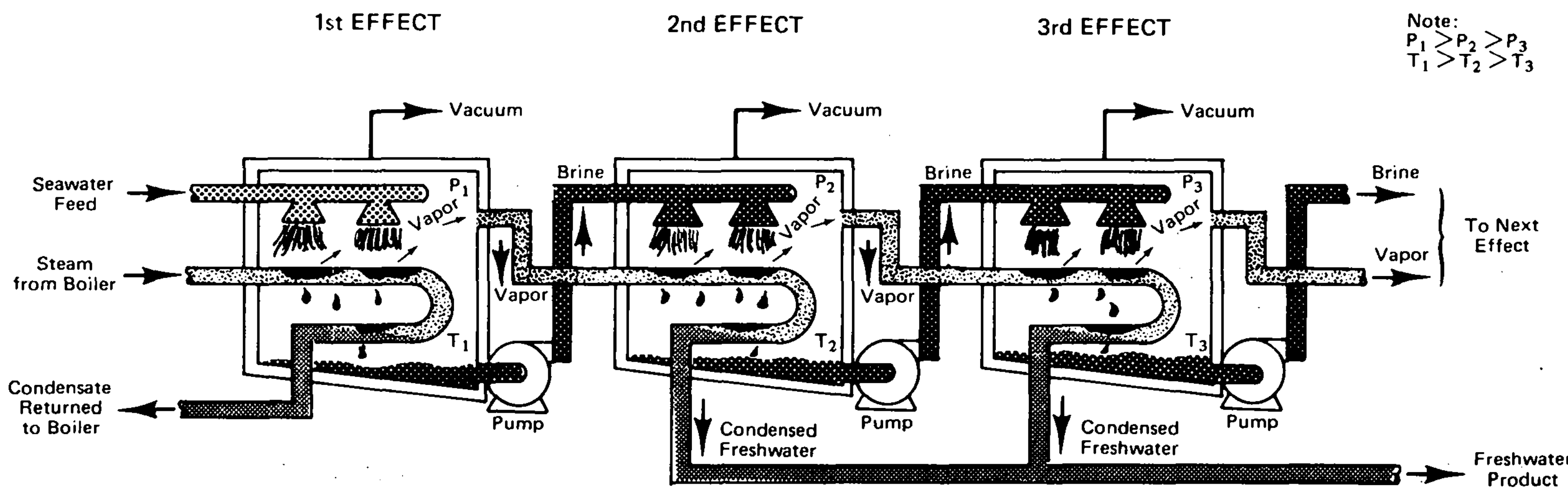
The principle of operation of the horizontal-tube multiple-effect (HTME) evaporator, shown in figure XII, is the same as for the vertical tube evaporator; the brine and steam are applied on opposite sides of the tubes in the two systems. The brine is distributed as a film on the outside of the tubes, where it is partially evaporated by heat derived from condensation of vapour (to fresh water) on the inside of the tubes. The effects may be stacked both vertically and horizontally rather than just horizontally as is the case with the VTE units. This permits greater use of gravity to move liquid between effects than in the vertical-tube units.

2. Multi-stage flash

The multi-stage flash distillation units are based on the following principle: when the pressure in the chamber above heated water is suddenly reduced below the boiling vapour pressure at that temperature, the water violently boils. This boiling occurs rapidly, releasing significant quantities of vapour until the temperature falls (owing to the loss of the heat of vaporization) below the boiling point for that pressure condition. The vapour produced by flashing is condensed on the outside of tubes which are conveying cooler brine to the hot end of the plant. This serves to recover much of the heat of vaporization.

A number of single-stage flash units were built during the 1960s and 1970s. These were mainly used on brackish water in conjunction with power plant installations and generally were designed for less than 950 m^3/day (250,000 gpd). Those plants are seldom used for potable water producion, as the termal efficiency is rather low, except for some designs which utilize waste heat as an energy source.

The real potential for the use of flash distillation for potable water production was demonstrated in the 1950s, with the basic design of the multi-stage flash process being developed by R. S. Silver. A conceptual diagram of this process is shown in figure XIII.



Notes: 1. This drawing is greatly simplified.
2. A final condenser is necessary for operation.

Figure XII. Conceptual diagram of a horizontal-tube multiple effect (HTME) distillation plant

Source: This figure courtesy of the United States Agency for International Development. From O.K. Buros and others, The USAID Desalination Manual (Washington, D.C., prepared for USAID by CH2M Hill International Corporation, 1980).

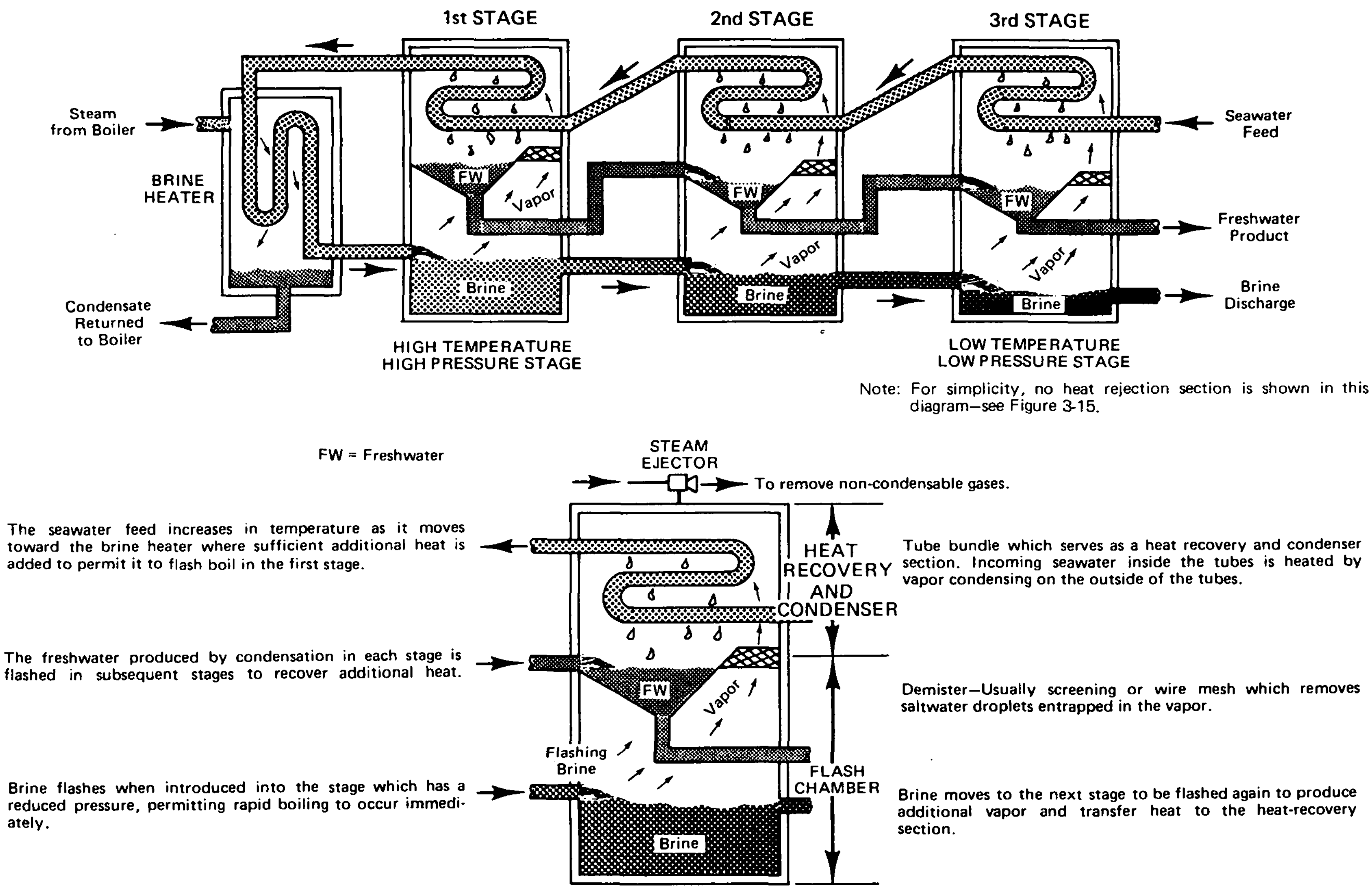


Figure XIII. Conceptual diagram of the multi-stage flash (MSF) process

Source: This figure courtesy of the United States Agency for International Development. From O.K. Buros and others, The USAID Desalination Manual (Washington, D.C., prepared for USAID by CH2M Hill International Corporation, 1980).

In the late 1950s and early 1960s, the MSF plant was the only type that could operate relatively scale-free for extended periods. Since they could be built in large capacities, they became very popular and by the early 1980s accounted for about two thirds of the world's desalination capacity (El-Ramly and Congdon, 1981).

In the multi-stage flash unit, the incoming sea water is heated in the heat recovery sections of each stage as well as in the brine heater using externally supplied steam. This raises the feed water to its top temperature, after which it is passed through the various stages where flashing takes place. The vapour pressure in each stage is controlled so that the heated brine enters each chamber at the proper temperature and pressure combination, so that instantaneous and violent boiling occurs. In each stage the vapour is condensed in the heat recovery section of the stage on the outside of tubes carrying the saline feed water to the brine heater at the head of the plant.

The fresh water formed by condensation of the vapour is collected in each stage and is passed on from stage to stage in parallel with the brine. In each stage the product is also flashed so that it can be cooled and the heat recovered for heating the feed water.

The percentage of brine actually vaporized in each stage is small, because the energy required to reach the heat of vaporization is derived from the temperature drop of the brine in each stage (since, after the brine heater, no additional external heat is supplied to the process). Under ideal conditions, less than 1 per cent of the water flowing through a stage could be vaporized. Thus, the MSF process is characterized by high flows through the plant relative to the amount of water produced. An average high-temperature MSF plant recovers as fresh water only about 25 to 50 per cent of the flow through the plant. This contrasts with a well-designed multiple-effect plant, which recovers from 40 to 65 per cent of the feed. However, when the water required for rejecting heat from the plants is included, the total quantities of saline water used by the multi-stage or multiple-effect plants are nearly the same.

The number of stages in an MSF plant varies according to the application, efficiency desired, temperature of the plant and other factors. The number usually falls into the 20 to 50 range, with the higher number of stages generally corresponding to improved efficiency of heat recovery. Unfortunately, an increase in stages also means an increase in the overall capital costs of the plant, although operating costs will be lowered, since less external heat will be required per unit of fresh water produced.

Because of the large amount of heated brine required in an MSF plant, a portion (50 to 75 per cent) of the brine from the last stage is often mixed with incoming feed water, recirculated through the heat recovery sections to the brine heater and then flashed again through all the stages. A plant of this type is often referred to as a "brine recycle", "recycle", or "recirculation" plant. This mode of operation reduces the amount of heat and water-conditioning chemicals that must be added, and thus can significantly reduce operating costs. On the other hand, it increases the salinity of the brine at the hot end of the plant, thereby increasing the boiling point rise and, most importantly, increasing the danger of corrosion and scaling in the plant, especially in the brine heater. A plant which does not recirculate a portion of the brine is referred to as a "once-through" plant. Once-through plants require a greater amount of water treatment chemicals than the recirculating plants, but their operation is easier and there are fewer problems with scaling. Because of its operational stability, this type of plant has considerable merit for use in areas where operation and maintenance may be a problem. The majority of plants built during the last 15 years have been recirculation plants, although some of the operational advantages of the once-through plants may begin to reverse this trend.

The major advantages of an MSF plant are: the ability to be constructed in large capacities and achieve economies of scale; the fact that boiling does not take place on a hot tube surface (it flashes instead); the considerable design and operational experience accumulated over the past 25 years; and the widespread manufacture of the units throughout the world.

Its disadvantages are: the potential for scaling and corrosion (which has been alleviated somewhat by new anti-scale chemicals); the difficulty involved in start-up; the inability to operate the plant below 70 to 80 per cent of design capacity; the sensitivity of product water to salt contamination by pinpoint leaks in the heat recovery (condensing) tubes; and the necessity for pumping, treating and heating large quantities of salt water relative to the product.

3. Vapour compression

The vapour compression process differs from the other distillation processes in that it does not utilize an external heat source, such as steam, as its primary energy for distillation. It instead compresses water vapour, using a compressor or steam jet, to increase the vapour's pressure and condensation temperature. The condensation of the vapour takes place on one side of a tube which acts as a heat transfer surface. Feed brine is applied to the other side of the tube (generally in the form of a thin film), and the heat of condensation that is released at the tube surface on one side is utilized as the heat of vaporization on the other side to boil the brine and produce water vapour. The spray film vapour compression process is shown in figure XIV.

Because the heats of condensation and vaporization are recycled across the heat transfer surface, the only major energy required during operation is that necessary to drive the compressor. The compressor serves a dual purpose: it compresses the vapour, raising its condensation temperature, and at the same time it lowers the pressure on the feed water brine and hence reduces its boiling temperature.

There are two basic methods used to compress the water vapour. The first is to use a compressor which can be powered by any rotating source such as an electric motor, diesel engine or steam turbine. The second method is to use a steam ejector, which is often considered feasible where a quantity of surplus waste steam exists. Both methods of compression produce the same result - fresh water. The steam ejector plant is easy to install and start up, and it requires considerably less care and attention than a plant using a compressor. However, it is not as thermally efficient in producing water as a compressor-operated plant. In spite of their relative inefficiency, steam ejector compression plants are widely used at construction sites because of their high reliability, low manpower requirements and low attention requirement.

Plants using a compressor system have more moving parts than steam ejector plants and are therefore more susceptible to mechanical failure, especially with

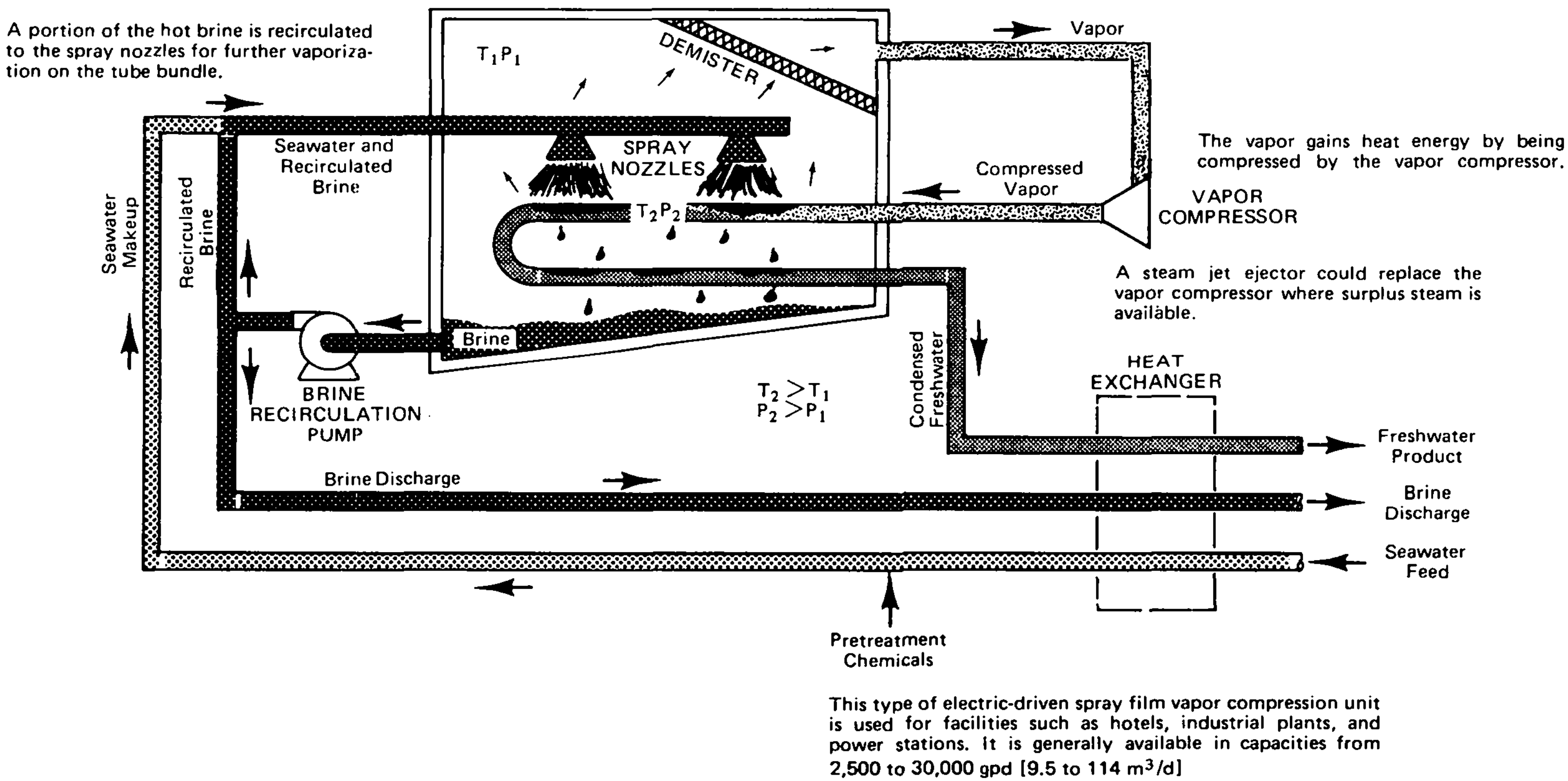


Figure XIV. Simplified flow diagram for a spray-film vapour-compression process

Source: This figure courtesy of the United States Agency for International Development. From O.K. Buros and others, The USAID Desalination Manual (Washington, D.C., prepared for USAID by CH2M Hill International Corporation, 1980).

regard to the compressor itself, which runs at high speeds and is prone to corrosion. Steam ejector systems are often used in the chemical processing industry and on offshore oil rigs, where dependability is more critical than water cost.

4. Waste heat recovery evaporator

This is a class of specialized distillation units which operate at relatively low temperatures and normally use waste heat to heat the brine feed. The process is illustrated in figure XV. The waste heat can be obtained from hot process water, turbine exhaust, surplus steam and similar sources. The heat is usually transferred to the feed water by submerged tubes. Low pressure is maintained in the evaporator so that the heated sea-water feed boils at a low temperature (50° to 65° C), thus minimizing costs on chemicals for treatment of feed water as well as the potential for scale formation.

The efficiency, or performance factor, of this type of plant is generally low. However, the energy cost is also low, with the heat portion considered at no cost and the electrical power consumption low. Furthermore, the waste heat recovery evaporator is simple to operate and maintain. The only significant moving parts are standard pumps to circulate water and an educator to reduce pressure in the evaporator. Chemicals are generally not used.

Those units are often installed on ships, barges and offshore drilling rigs. They require a continuous source of both heat and electricity and an unrestricted supply of sea water. They could be installed in a land-based facility where waste heat is available from an industrial operation or generator operated almost continuously.

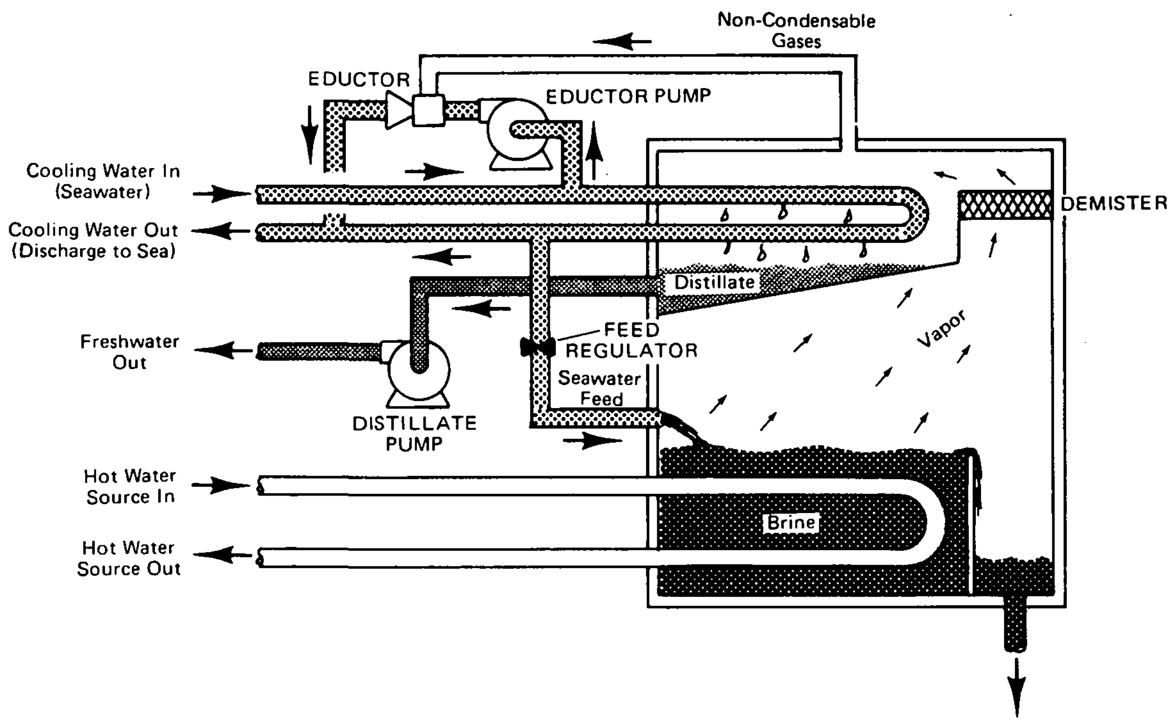
5. Hybrid systems

A number of hybrid systems have been built or proposed which contain a combination of the basic units described above.

For example, the vertical-tube evaporator multi-stage flash unit uses an MSF process with its heat recovery sections as a feed heater to increase the feed water temperature efficiently. After passing through the recovery section in the highest temperature stage, the feed goes to a series of vertical-tube evaporators. The product water is flashed through the MSF unit to recover its heat, and vapour from each effect passes to the appropriate MSF stage to help heat the feed.

Another possibility is the vapour compression-multiple effect unit, which could lower the costs for a large-capacity single effect vapour compression plant. The capacity (and costs) can be reduced in direct proportion to the number of series effects served by the compressor. The heat energy produced by the compressor is sufficient to make up all the heat losses and to keep the plant operating continuously.

Another combination that has been proposed is the horizontal-tube multiple-effect topping unit, which would place an HTME unit before the hot end of an existing MSF plant. The MSF unit would then be operated at lower than the design temperature, and vapour from the last effect of the HTME unit would provide



Operating Parameters for a 2.4-kgal/day [9-m^3/d] Waste Heat Recovery Evaporator*						
	Temperature		Flow		Power	
	(°F)	(°C)	(gpm)	(m^3/d)	(kWh/kgal)	(kWh/m^3)
Cooling water	85	29.3	53	289	--	–
Hot water	180	82.2	100	545	--	--
Feedwater	--	--	3.3	10	--	--
Freshwater	--	--	1.6	8.7	--	--
Electricity	--	--	--	--	15	4

*Data from Mechanical Equipment Company Bulletin No. 117C

Figure XV. A waste heat recovery evaporator

Source: This figure courtesy of the United States Agency for International Development. From O.K. Buros and others, The USAID Desalination Manual (Washington, D.C., prepared for USAID by CH2M Hill International Corporation, 1980).

the heat in the brine heater for the MSF plant. Another proposal would place an MSF unit in series with a vapour compression unit. A variety of other combinations for distillation plants have been discussed or tested on a small scale but none have enjoyed commercial success. Except in very large plants or for special conditions (that is, solar power), increased energy efficiency is frequently offset by the difficulties caused by the increase complexity of operation and/or design.

C. Major engineering considerations

1. Scale formation and control

The major problem in operating sea-water distillation plants is the formation of scale caused by some of the dissolved constituents within the sea water. As temperatures and concentrations are increased, certain constituents, such as calcium carbonate, magnesium hydroxide and calcium sulphate, become less soluble and deposit scale which creates problems. Normally when scale forms, it deposits on heat exchange surfaces, thus increasing the resistance to heat transfer. Also, it may accumulate in pipeline orifices and other flow passages, thereby impeding the flow of process fluids. Both the increased heat-transfer resistance and the fluid pressure drop increase the energy input necessary per unit of product water.

Scale formation is promoted by the high temperatures and concentrations used to obtain higher efficiencies in many plants. Thus, current technological developments in distillation mainly centre around methods of scale control.

Scale formation in distillation processes falls into two main categories: alkaline and non-alkaline. The alkaline scales of concern are calcium carbonate and magnesium hydroxide and the major non-alkaline scales are various types of calcium sulphate.

(a) Alkaline scaling

Alkaline scales, which may form when the temperature of a saline solution rises above 70° C (158° F) may be removed by mechanical means, such as brushing, hydroblasting or thermal shocking. In the submerged-tube plants, scale formed on the outside surfaces of the tubes was removed by either shutting down the units and cold shocking them or chipping the scale off by hand. However, the most common method is to dissolve them by reducing the pH of the feed water through the addition of acid. The use of corrosion-inhibiting acid decomposes the alkaline scale and aids in minimizing damage to plant materials.

The formation of alkaline scale can be prevented by controlling the temperature, controlling the pH and introducing additivies.

Controlling the temperature to restrict the upper operating temperature to be in the 70° C (158° F) range, means that, unless large amounts of heat transfer surface are used, the performance factor (thermal efficiency) will be low. Lowering the pH is often used to control scale, but the precise control of pH is often difficult. Operation at the incorrect pH, owing to over- or under-feeding of acid, can be extremely detrimental to the materials used in the plant, even if it occurs only for a short period.

Two classes of additives are now in use: polyphosphates and polymers. Beginning with the early plants, polyphosphate-based chemicals have been used to inhibit scaling. Although these are generally effective, they limit the upper operating temperatures to about 82° to 88° C (180° to 190° F), because of thermal decomposition of the polyphosphate above that point. This temperature limitation in turn limits the plant's thermal efficiency. A major advance was made with the use of acid (generally sulphuric acid), which was added to the feed water to break down the bicarbonate in sea water to prevent alkaline scaling. This allowed operating temperatures of up to about 113° to 121° C (235° to 250° F) before sulphate scaling (which cannot be inhibited by known additives) could occur.

The polyphosphates inhibit, but do not prevent, calcium carbonate and magnesium hydroxide scale. A soft type of sludge forms which requires cleaning (generally with acid) periodically. One of the earliest plants in which acid was used commercially was the 9,500 m^3/d (2.5 mgd) submerged-tube multiple-effect plant built in Aruba in 1958 (Watson, 1976). The polyphosphate method of scale control has been used extensively in many large plants in the Middle East (Wade, 1979) and the Caribbean.

Although the acid plants have been able to achieve high thermal efficiencies, they require careful control and operation. Acid accelerates corrosion of materials, especially some of the less expensive materials such as steel, which were utilized in an effort to reduce material costs. Nevertheless, multi-stage flash plants using acid became a standard offering in the industry. Their high theoretical efficiency and often lower capital cost (owing to the reduced heat transfer surface needed) made them extremely competitive in the world market. Acid was also used in multiple-effect and other configurations to allow higher operating temperatures.

The result of the extensive use of acid plants has been that a significant number of those plants suffered severe damage as a result of the use of acid combined with poor operation, design and/or materials selected. None the less, there are acid plants that have operated and are operating in top condition.

The major problems with the use of polyphosphate dosing are the cost of the chemicals and, most importantly, the restriction on the upper operating temperature of the plant. The operating temperature limits the performance factor possible and hence tends to raise the cost of water production.

In the mid-1970s, the use of organic polymers (polyelectrolytes) to control scale was introduced into the industry. The polymers apparently work by inhibiting and distorting crystal formation. They are meant to substitute for acid and supposedly will inhibit scale formation at high operating temperatures without causing the corrosion problems associated with acid. Operating experience is now being accumulated on their use. The initial results appear to be quite favourable. Their potential for operating at high temperatures allows high performance factors to be obtained without the associated severe corrosion and handling problems encountered in acid plants. Many large plants in the Middle East have now been designed around the use of those polymers. Although the use of additives has been shown to be effective for various MSF plants, there has been some variability in the results between plants, locations and products. Thus, it is possible that an additive will not always be suitable for a given facility, and caution should be used in specifying them.

(b) Non-alkaline scaling

Non-alkaline scale consists mainly of calcium sulphate compounds. The major scales that could crystallize are: calcium sulphate anhydrite, calcium sulphate demihydrite and calcium sulphate dihydrate. The formation of non-alkaline scales is dependent on the temperature and concentration of saline solutions.

Since recycling of brine, with its increased concentration factors, is often used for high-performance (high-temperature) multi-stage flash plants, the plants can be subject to sulphate scaling. The most vulnerable part is the brine heater, where the highest temperatures occur. If the brine heater tubes become plugged with calcium sulphate anhydrite (the most common type), they generally require replacement.

Once formed, the non-alkaline scale is extremely difficult to remove. The scale is very hard and must be removed mechanically, as no known safe solvent exists that can be used in conjunction with copper alloys. For distillation processes there are no known additives or pH controls, such as those used for alkaline scale, to prevent non-alkaline scale formation. The major method for preventing scaling is to avoid operating in the concentration and temperature range where it can occur.

Other methods have been tried or suggested to minimize non-alkaline scale formation or its effect. The most experience has been gained on the use of a calcium sulphate seed slurry, which is circulated with the brine to provide preferential precipitation sites. Other systems suggested have been the use of small fluidized beads (Veenman and others, 1978) and the removal of sulphate or calcium ions from the sea-water feed by using ion exchange (De Maio and others, 1979).

Plant applicability

The forms of scale control discussed above are primarily applicable to multi-stage flash plants. For horizontal-tube, multiple-effect, vapour compression, and falling film types of vertical-tube evaporators, additives do not appear to be as effective as acid, because the turbulence of the film is too low (Wade, 1979); with additivies other than acid, a sludge is deposited that interferes with the very high heat transfer coefficients.

2. Heat transfer surface

The stage or effect efficiency in a plant is directly related to the effectiveness of the heat transfer surfaces (primarily the tubes), and depends on the design. The heat transfer efficiency, in turn, depends on the type of material, amount of area, configuration of the surfaces, thickness of the tubes, brine velocity and (when in operation) the degree to which heat transfer is inhibited by scale formation.

The efficiency of heat transfer surfaces of the tubes can be improved by varying their shape. Two methods often used are fluting and roping of the heat transfer tubes. Fluted tubes are used in the vertical-tube evaporators, in which the steam condenses on the outside and the salt water evaporates on the inside. The fluting, which forms ridges and troughs on the tube wall parallel to the centre line of the tube, causes the condensate to flow from the ridge to the trough, leaving the ridges relatively dry and thus having a high film coefficient (Yorkshire Imperial Metals, 1976). This improves the heat transfer.

Roped tubes are used in some MSF heat recovery sections in which the horizontal tubes condense steam on the outside while heating sea-water feed on the inside. The tubes are formed with a helical groove. This groove causes some turbulence in the flow on the inside of the tube, breaking up the flow of sea water adjacent to the inner tube wall. This increases the heat transfer coefficient.

3. Materials of construction

The item that most significantly influences the capital cost and eventual life of distillation plants is the selection of the construction materials. Sea-water distillation plants are exposed to high temperatures, concentrated brine solutions and often corrosive chemicals. They are generally located on sea-coasts, where they are exposed to a high-humidity salt environment.

Many of the materials that were used satisfactorily in shipboard units were found not to be suitable for land-based installations, owing to differences in feed water. The feed water of the land-based units often contained silts and sands which removed the protective coatings on brasses and bronzes internal to the plant, severely diminishing the performance and life expectancy of those installations.

The ultimate selection of materials is often heavily influenced by the overall capital cost constraints of the project. However, whatever is saved in initial costs by using less expensive materials may be lost many times over in later repairs, replacements and lost production.

The most common materials used for various parts of the evaporator in MSF plants are titanium, copper-nickel alloys, aluminium brass and carbon steel. Each of these has different characteristics with regard to cost, plant life desired, operating temperature, resistance to corrosion and many others. The major materials used for the brine heater are titanium and copper-nickel alloys and for interconnecting piping carbon steel, fibreglass, carbon nickel and stainless steel. Materials must be carefully selected according to the process selected, the other materials used and the environment. It is imperative that, in the purchase and/or design of any distillation plant, expert advice be obtained in the selection of materials.

4. Corrosion

Corrosion is more than just rust. It is defined as "the deterioration of a substance (usually a metal) because of a reaction with its environment" (Bosich, 1970). There are many types of corrosion in a distillation plant and all of them cause operational or maintenance problems of one kind or another and shorten the life of the unit.

The type and extent of corrosion depend primarily on the materials chosen for the components of a plant and their compatability. Therefore, the design, selection and fabrication of materials in a distillation plant are critical to its overall performance and longevity. Because of the complexities involved, it is very difficult to predict how some variations in fabrication or materials will hold up under extended service. This is one reason that many purchasers of desalination plants insist that the manufacturer have prior experience in building plants of the type specified and that they have a plant of the same approximate capacity in operation for at least a year.

Annex II

ELECTRODIALYSIS

A. Technical background

Desalination by electrodialysis is based on the following principles:

(a) Most of the salts dissolved in water are ionic in nature;

(b) Those positively or negatively charged salts are attracted by an opposite electrical charge, that is, positive ions (cations) will be attracted to a negative pole or electrode;

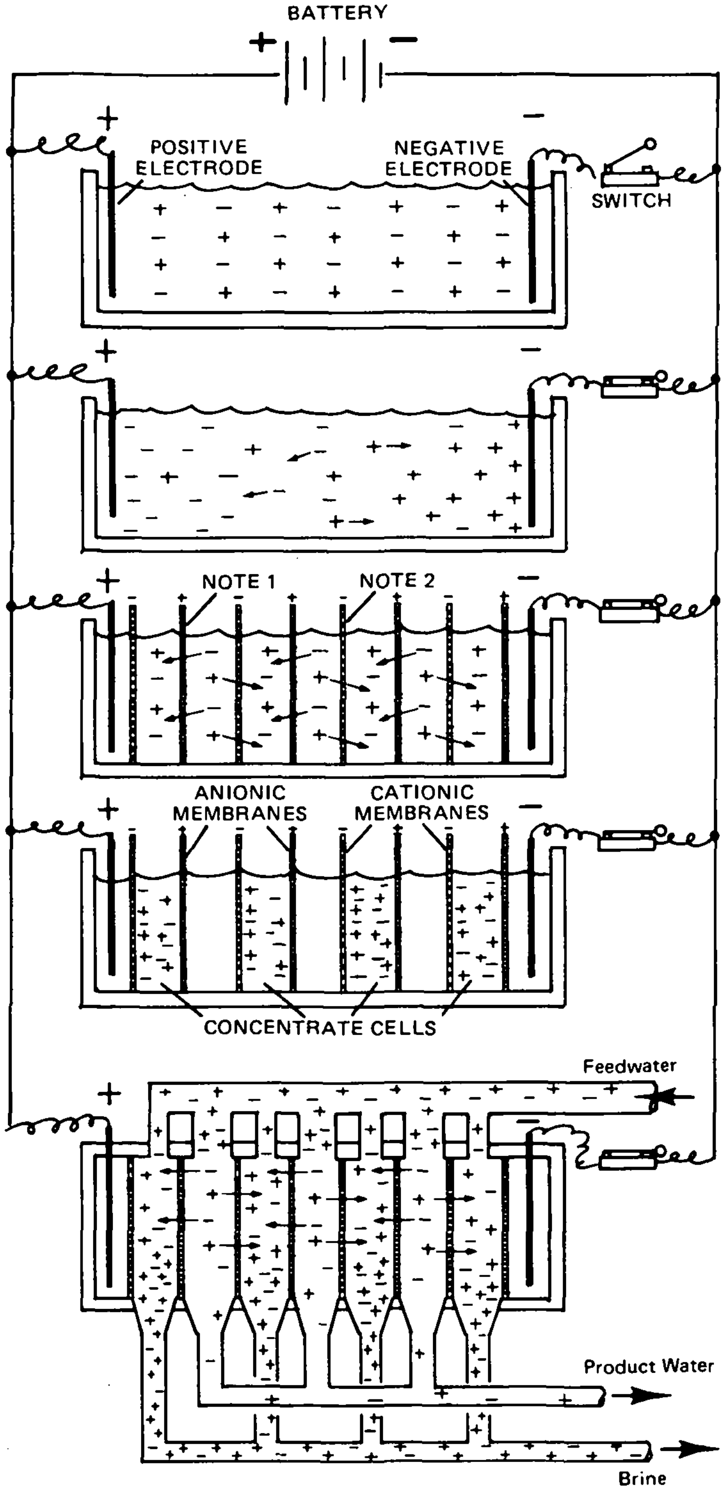
(c) Membranes can be devised which will be selective in the type of charged ion that, they will pass or reject, that is, membranes can be made which allow negative ions (anions) to pass but reject cations. This type of membrane is referred to as an anion-permeable membrane, and one which rejects anions is called a cation-permeable membrane.

1. Physical principles

Most of the dissolved constituents in saline water are ionic. Those constituents dissociate and are dispersed in water, effectively neutralizing their individual charges (see figure XVI). When electrodes, connected to an outside source of direct current, are placed in a container of saline water, the current is carried through the solution (a mild electrolyte owing to the ionized salts), and the ions tend to migrate to the electrodes that carry the opposite charge. Thus anions such as chloride (Cl^-), migrate towards the positive electrode, and cations, such as sodium (Na^+), migrate towards the negative electrode.

To utilize this phenomenon to desalinate water, membranes that will allow either cations or anions (but not both) to pass are placed in the solution between the electrodes. Those membranes are arranged alternately, an anion-selective membrane followed by a cation-selective membrane. As the electrodes are charged, the anions are diverted from the main product stream and pass through the anion-selective membrane into the concentrate (or brine) cell. The anions are prevented from moving through the adjacent cell wall, as it is a cation-selective membrane and prevents their passage. Similarly, cations move from the dilute stream on the other side of the cation-selective membrane into the concentrate cell. Here they are prevented from moving further towards the negative electrode by the anion-selective membrane. By this arrangement, concentrated and dilute solutions are formed in the spaces between alternating membranes. Those spaces, bound by two membranes (one anionic, the other cationic), are called cells. A cell pair consists of two cells, one from which the ions migrated (diluting cell for the product water) and the other in which the ions concentrate (concentrate cell for the brine stream).

A typical network (or stack) has several hundred cell pairs (one dilute and one concentrate cell) so that the proportion of ions removed from the feed stream relative to the current carried by the ions between the electrodes is very large.



Many of the substances which make up the total dissolved solids in brackish water are strong electrolytes. When dissolved in water they ionize; that is, the compounds dissociate into ions which carry an electric charge. Typical of the ions in brackish water are Cl^{-1}, Na^{+1}, HCO_3^{-1}, Mg^{+2}, SO_4^{-2}, and Ca^{+2}. These ions tend to attract the dipolar water molecules and to be diffused in time , fairly evenly throughout a solution.

If two electrodes are placed in a solution of ions, and energized by a battery or other direct current source, the current is carried through the solution by the charged particles and the ions tend to migrate to the electrode of the opposite charge.

If alternately fixed charged membranes (which are selectively permeable to ions of the opposite charge) are placed in the path of the migrating ions, the ions will be trapped between the alternate cells formed.

Note 1: A positively fixed charge (anionic) membrane will allow negative ions to pass, but will repel positive ions.

Note 2: A negatively fixed charge (cationic) membrane will allow positive ions to pass, but will repel negative ions.

If this continued, almost all the ions would become trapped in the alternate cells (concentrate cells). The other cells, which lack ions, would have a lower level of dissolved constituents and would have a high resistance to current flow.

The phenomenon illustrated above is used in electrodialysis to remove ions from incoming saline water on a continuous basis. Feedwater enters both the concentrate and product cells. Up to about half of the ions in the product cells migrate and are trapped in the concentrate cells. Two streams emerge from the device: one of concentrated brine and the other with a much lower concentration of TDS (product water).

Figure XVI. Movement of ions in the electrodialysis process

Source: This figure courtesy of the United States Agency for International Development. From O.K. Buros and others, The USAID Desalination Manual (Washington, D.C., prepared for USAID by CH2M Hill International Corporation, 1980).

In operation, feed water passes simultaneously in parallel paths through all of the cells to provide a continuous flow of product water and brine stream, thus washing out the concentrated ions.

2. Elements of an electrodialysis unit

An electrodialysis unit is made up of the following basic components: DC power supply (rectifier), membrane stack, circulation pump and hardware, and pre-treatment. These components are illustrated in figure XVII.

(a) DC power supplier (rectifier)

The main element of the power supply is usually a rectifier which converts alternating current (AC) to direct current (DC). Direct current is applied to the electrodes on the membrane stack to remove the ions from the feed stream.

(b) Membrane stack

The stack includes the electrodes, membranes (both anion- and cation-permeable), spacers, plumbing necessary to transport water to and from the stack, and the hardware necessary to hold the stack together.

The membranes are flat sheets, usually made of a plastic film formed on a fabric backing of dynel, glass or other material to provide strength. Ion transfer sites are added to the membranes with the site charge differing between the anion- and cation-permeable membranes to give each type the characteristics to pass selectively either anions or cations.

The thickness of the membrane depends on the application, and its selection is a trade-off between membrane properties. Thicker membranes usually have greater strength, increased erosion resistance and longer life, whereas thinner membranes have lower electrical resistance and hence reduced energy requirements. Typically, membranes are about 0.56 mm (0.022 inch) thick.

Cells are made up of two membranes with a spacer in between. Cells are stacked with alternating concentrate and dilute cells. Spacers can be formed to provide different types of flow paths. The sheet flow and tortuous path flow are two of the most commonly used designs, but work is now being done on the use of slanted strap spacers, a modification of the tortuous path (Mattson and Lundstrom, 1979). These three types of spaces are illustrated in figure XVIII.

One pair of electrodes is required for each electrical stage with, typically, two hydraulic stages per electrical stage. A reaction occurs at each of the electrodes. Hydrogen ions and oxygen and/or chlorine gas are formed at the anode (positive electrode), and hydrogen gas and hydroxyl ions are formed at the cathode (Mason and Kirkham, 1959). Where the pH increase (at the cathode) could cause the formation of a calcium or magnesium precipitate, acid is often added to the electrode stream to keep the cathode stream acidic and maintain the precipitate in solution.

In the electrodialysis reversal process (described below), the anode and cathode are electrically reversed several times per hour, thus alternating the environment at the electrodes from acidic to basic on a regular basis. This acts to reduce scale formation significantly.

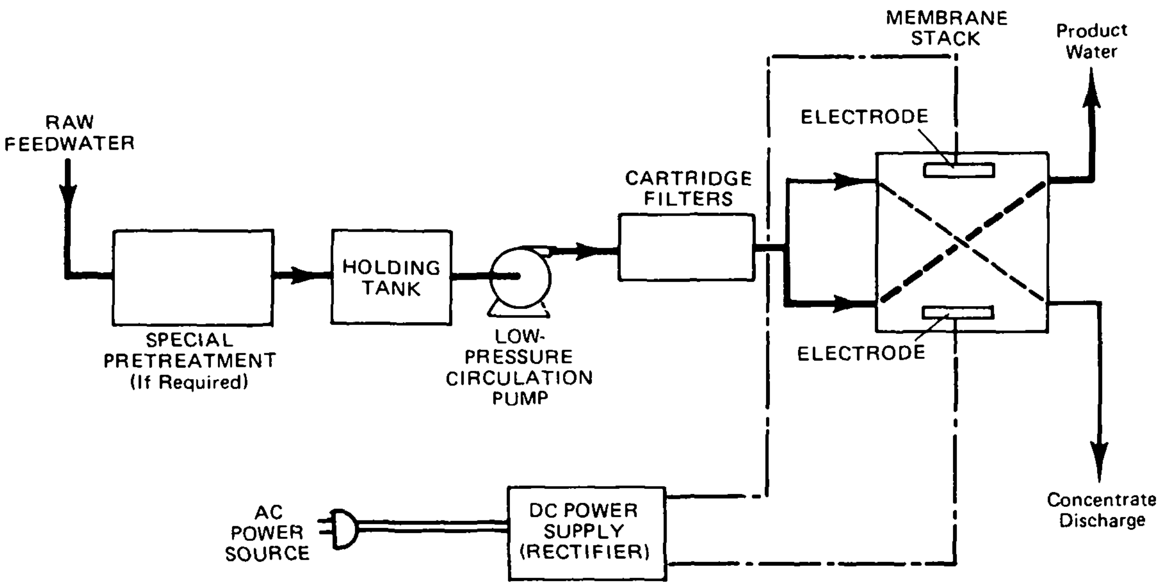


Figure XVII. Basic components of an electrodialysis unit

<u>Source</u>: This figure courtesy of the United States Agency for International Development. From O.K. Buros and others, <u>The USAID Desalination Manual</u> (Washington, D.C., prepared for USAID by CH2M Hill International Corporation, 1980).

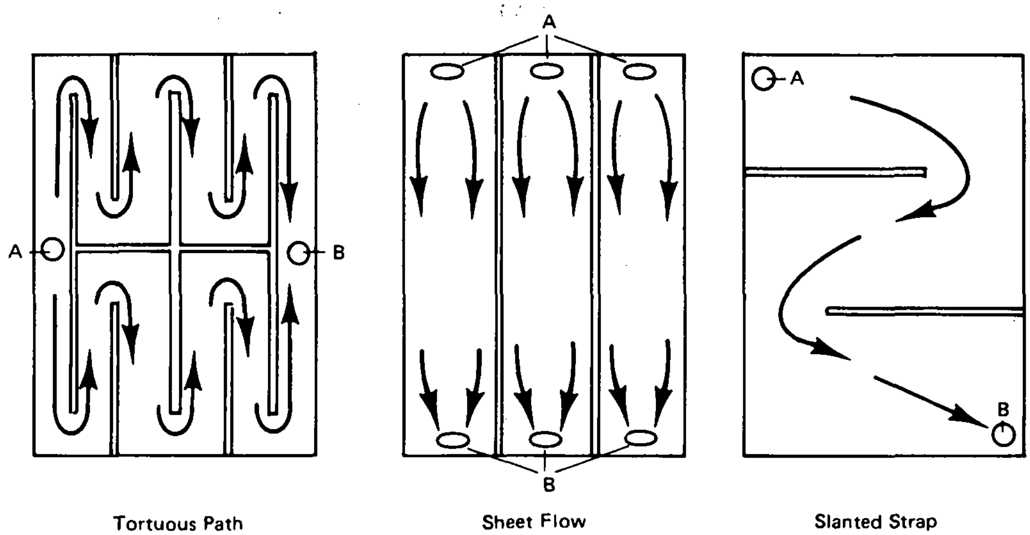


Figure XVIII. Three types of spacers

Source: This figure courtesy of the United States Agency for International Development. From O.K. Buros and others, The USAID Desalination Manual (Washington, D.C., prepared for USAID by CH2M Hill International Corporation, 1980).

(c) Circulation pump

In the electrodialysis process the water pump is used only for circulation of the water through the stack. Generally, a pumping pressure of only about 3.5 to 5 atm (51 to 74 psi) is needed. This is considerably lower than the 17 to 27 atm (250 to 400 psi) required in the brackish water reverse osmosis process. Because of the reduced pressures involved, the connecting piping, valves etc. can be made with material and tolerances suitable for the lower-pressure range. This has allowed the use of a great deal of standard plastic pipe and fittings. The use of plastic pipe produces benefits regarding lower cost (compared to stainless steel etc.), high resistance to corrosion in a saline environment and ease of construction.

(d) Pre-treatment

A certain degree of pre-treatment of the feed water supply is necessary in order to prepare it for desalination in the stacks. Pre-treatment depends on the specific water being treated, but it usually includes the removal of suspended or dissolved solids which could adversely affect the surface of the membranes or mechanically block the narrow passageways in the individual cells. With the electrodialysis reversal process, the need for standard pre-treatment is greatly reduced.

B. Process description

The two major processes commercially in use today are electrodialysis and electrodialysis reversal.

1. Electrodialysis

As described above, this is the process in which feed water is pumped to the stacks, where it passes through the cells located between the electrodes. The electric charge on the electrodes provides the force to induce the ions to migrate through the membranes from the main feed water stream into the concentrated brine stream. The two streams, product water and brine, are continually transported from the stacks in their respective pipleines.

This system often requires the addition of acid and/or polyphosphate to the brine stream in order to inhibit the precipitation of sparsely soluble salts in the stacks. To maintain performance, the membrane stacks need to be cleaned periodically to remove scale and other surface-fouling matter. In most electrodialysis units, this is done in two ways: (a) cleaning in place and (b) stack disassembly. Using a cleaning-in-place system, special cleaning solutions are circulated through the membrane stacks. These aid in cleaning but at regular intervals the stacks need to be disassembled and mechanically cleaned to remove scale and other surface-fouling matter. Those units without a cleaning-in-place system generally have shorter intervals between stack disassembly.

2. Electrodialysis reversal

The reversal process operates on the same basic principles as the standard electrodialysis unit, except that both the product and the brine cells are identical in construction. At intervals of 15 to 20 minutes, the polarity of the electrodes is reversed and the flows are simultaneously switched by automatic valves in the stacks so that the product cell becomes the brine cell and the brine cell becomes the product cell. The salts are thus transferred in opposite directions across the membranes.

Following the reversal of polarity and flow, the product water is discharged until the cells and lines are flushed out and the desired water quality is restored. This takes approximately one to two minutes. The reversal process aids in breaking up and flushing out scale, slimes and other deposits in the cells.

This automatic cleaning action eliminates the need to add acid and/or polyphosphate, and scale formation in the electrode compartments is minimized owing to the continuous alternation of the environment from basic to acidic. This greatly extends the intervals between the rather time-consuming job of stack disassembly and reassembly. The overall result is reduced maintenance time.

C. Major engineering considerations

1. Specific energy usage

The major energy uses in an electrodialysis unit are for applying a charge to the membrane stacks and for pumping the product and waste streams through the stacks. As a rule of thumb, the electrical energy used in the membrane stack is 0.7 kWh/m^3 (2.5 kWh per 1,000 gallons) product per 1,000 ppm of TDS removed. To this must be added about 0.5 to 1.0 kWh/m^3 (1.9 to 3.8 kWh per 1,000 gallons) for pumping the product through the stack and an additional 5 per cent of total energy consumption for losses in the power supply. Generally, overall energy usage is proportional to the amount of dissolved solids removed in the process.

For any given water, the efficiency of the process depends on many factors, including: efficiency of motors, pumps and rectifiers; stack losses; and water temperature. Efficiency in the motors and pumps is obtained not only by direct electrical and mechanical efficiency but by matching the motor or pump to the application. Ideal matching of components is not always possible within the range of units commercially available.

Manufacturers are continuously conducting research on ways to reduce stack losses, through developments such as thinner, lower-resistance membranes, thinner water flow spacers and engineered flow paths within the spacers.

Water temperature affects the conductance in cells, so that as the temperature rises, the conductance increases and thus the resistance (and power consumption) decreases within the stack. Mineral removal increases at the rate of a little more than 1.8 per cent per degree C (1.0 per cent per degree F). Many electrodialysis membranes are stable up to 38° C (100° F) and are often operated at or near this temperature when relatively low-grade thermal energy is available at low cost. However, increases in temperature primarily affect power consumption in the stacks and not in the pumps and other components. For cases in which energy utilization by pumping is high relative to tack usage, changes in temperature will have a relatively small effect on energy consumption. Thus the effect of temperature is more pronounced in larger, high TDS plants than in smaller, low TDS installations.

2. Pre-treatment

In electrodialysis, as in reverse osmosis, pre-treatment of water to remove suspended solids may involve sand filters or cotton, polypropylene or other cartridge filters ahead of the membranes. The cartridge filters are used more as a safety filter and are not meant to take on the major burden of filtration in water with excessive solids.

Acid or an inhibiting agent such as polyphosphate may be added to the brine stream to reduce the pH and/or minimize precipitation of sparsely soluble solids. The overall requirements for pre-treatment in electrodialysis are somewhat less rigorous than for reverse osmosis owing to the nature of the salt separation and the larger passages provided. The electrodialysis reversal process reduces the necessity for chemical pre-treatment for many applications, but removal of suspended solids, iron and manganese is still critical to avoid fouling and/or other problems with the system. In each case, of course, a careful examination of the prospective feed water would be necessary to determine suitability and pre-treatment. Hydrogen sulphide can also be a problem as it can oxidize in the stack, leaving deposits of sulphur.

Pre-treatment may also be necessary to prevent the formation or deposit of organic growth (slime) on the inner surfaces of the membrane stack. Those surfaces provide a place for organisms to grow if sufficient suitable material is present for them to metabolize in the feed water. A chlorination-dechlorination step may be used if the problem is of sufficient magnitude; otherwise the organic slimes are removed in the cleaning step. The dechlorination step is necessary to protect the membranes from continuous exposure to free chlorine. Another method that has been used to remove the bacterial growth in the stack is the shock treatment of the solution for short periods of time. This has proved to be an effective method.

3. Post-treatment

Post-treatment depends on the type of feed water and pre-treatment provided at the installation. With the electrodialysis reversal units, the amount of post-treatment can be usually reduced to only disinfection.

4. Equipment optimization

In optimizing the design and construction of a facility, a balance must be achieved between the equipment purchased and the power used. Since the amount of dissolved solids removed is proportional to the current utilized, the higher the current density, the more desalination is possible with a given membrane area and the lower the capital investment.

The maximization of dissolved solids removal per unit of power by increased current application is limited by polarization effects. Polarization occurs during electrodialysis in the dilute (or product) cells when a high enough rate of ion transport takes place to create a depletion of ions in the water adjacent to the membrane. This reduces the conductance value of the water (electrolyte), and the resistance increases sharply, resulting in higher energy usage in the stack.

In the absence of ions in the boundary layer, the continued high current density causes a dissociation of water molecules adjacent to the membranes and the diffusion of the hydrogen and hydroxyl ions through the membranes. As those ions enter the concentrating cell, they alter the pH and, in the case of the anion transfer membrane, this can result in a higher pH that will encourage the scaling of precipitates such as calcium carbonate and the formation of a high resistance gas layer on the membrane surface (Mason and Kirkham, 1959).

The problems associated with polarization have limited the practical current densities obtainable. In an effort to increase the current density at which polarization becomes a serious problem, some manufacturers have incorporated turbulence promoters into the spacers. These create turbulence at the surface of the membrane and tend to break up the boundary layers, thereby allowing higher current densities.

5. Operating problems

A variety of operating problems can be experienced with electrodialysis facilities. Some of the major ones are discussed below.

(a) Scaling

Scale is formed in the membrane stacks owing to polarization, the supersaturation of the brine stream or other factors. Scale fouls the membrane surfaces, blocks passages in the stack (changing flow patterns) and creates areas of resistance. Those areas of high resistance, called "hot spots", occur when the feed water flow is stopped or slowed in its passage through the product cell. The slowly moving water then becomes highly desalted owing to the longer period of exposure to the electromotive force. The highly desalted water has a low conductivity and offers a high resistance to current flow. Hot spots can consume excess power and reduce the efficiency of the stack.

Some scale can be removed by introducing special chemicals, such as acids, into the stacks in an attempt to dissolve or loosen the scales so that they can be washed out. In more severe cases the stack is disassembled and the membranes and spacers soaked in cleaning solution and/or scrubbed to remove the scale. Stacks are designed to be readily disassembled for this cleaning procedure. However, disassembly is a time-consuming job because of the large number of membranes and spacers involved.

(b) Leaks

Operating and/or maintenance problems can result from leaks in two parts of the electrodialysis stacks: (a) between the stacked membranes and spacers and (b) through the membranes.

Since stacks using membranes and tortuous path spacers are assembled much like a deck of cards, without a sealant or special gaskets, the ability of the stack to remain water-tight is dependent on the material fitting tightly together, which, in turn, depends on the spacers and membranes being uniform in thickness and the stack being uniformly pressed together. This can be a problem, since some stacks contain a total of 1,200 to 1,800 membranes and spacers (300-450 cell pairs).

Other leaks can develop through cracks or tears in the membranes or spacers as a result of manufacturing defects, improper handling, excessive tightening of the stacks, aging and other causes. The immediate result is usually an intermixing of water between the dilute and concentrate cells, and the ultimate result is reduced product water quality. Normally, stacks are operated with a slightly higher pressure on the product water side to prevent this intermixing.

(c) Electrode degradation

The electrodes at each end of the electrical stage within a stack distribute the current over the membranes. These electrodes are flat plates of metal (such as niobium or titanium) or carbon and are usually plated with platinum or (in the case of cathodes) stainless steel. In the electrodialysis reversal process, both electrodes are platinum-plated since both alternate in being the cathode and anode. The electrodes are exposed to separate rinse water streams and in the course of operation oxidation and reduction reactions take place at the anode and cathodes, respectively. Those reactions create problems which result in (a) the degradation of the electrodes, especially at the anode, where oxidation can result in the erosion of the metal, and (b) the production of chlorine and/or oxygen, depending on the pH and constituents in the rinse stream. The effect on the cathode is not quite as severe and usually results in the formation of hydrogen gas. This in turn could create a high pH that may favour the formation of scale.

In operation, the rinse streams are usually acidified to inhibit scaling. The rinse streams from the anode and cathode compartments are often combined and then recycled to reduce the amount of acid additive necessary. The electrodes must be replaced periodically.

In the electrodialysis reversal process, the electrodes alternate from being a cathode to an anode several times per hour. This serves to equalize the wear on the electrodes and chemically removes scale formed during the cathode operation by means of acid generated during its anodic cycle.

Annex III

REVERSE OSMOSIS

A. Technical background

Reverse osmosis is a membrane separation process in which water from a pressurized saline solution is separated from solutes and flows through an appropriate membrane. The permeate (the liquid flowing through the membrane), which generally emerges near atmospheric pressure, is reduced in salt content while the feed solution, which is pressurized on the other side of the membrane, concomitantly increases in salt content.

As no heating or phase change takes place, the major energy usage in the process is that required to pressurize the feed water. For brackish water desalination, the operating pressure generally ranges from 17 to 27 atm (250 to 400 psi) and for sea-water desalination it generally averages from 54 to 68 atm (800 to 1,000 psi).

In the actual process, saline water is pumped to pressurize it against a membrane in a closed container. As pure water passes through the membrane, the brine solution becomes more concentrated. At the same time a valve allows a portion of the feed water to be discharged without passing through the membrane. This discharge, or blowdown, is necessary to avoid precipitation of supersaturated constituents in the brine and to prevent concentration of dissolved salts in the feed solution which would increase the natural osmotic pressure. The elements of a reverse osmosis system are shown in figure XIX.

1. Overall system

A reverse osmosis system consists of four major components or processes, as discussed below. A flow diagram of the process is presented in figure XX.

(a) Pre-treatment

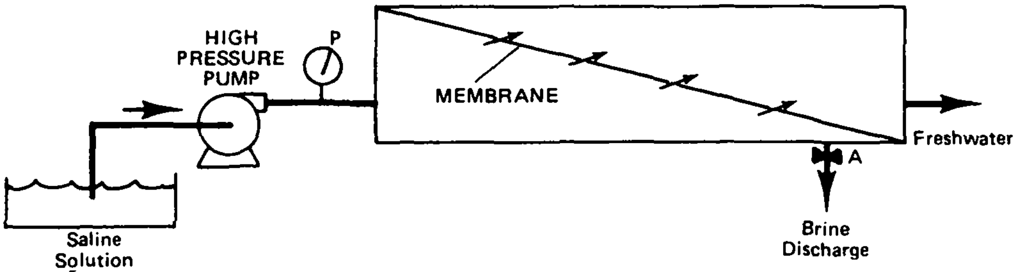
The incoming feed water is treated to specifications of the membrane in order to protect the membranes. This treatment usually consists of the removal of suspended solids, the adjustment of pH and the addition of a threshold inhibitor for controlling scaling owing to calcium carbonate and sulphate. Pre-treatment systems are discussed in more detail below.

(b) High-pressure pump

The pump raises the pressure of the pre-treated feed water to the level appropriate for the membrane and feed water being used.

(c) Membrane assembly

The semi-permeable membranes inhibit the passage of dissolved salts while permitting almost salt-free water to pass through. Feed water applied to the membrane assembly results in a fresh water product stream and a concentrated brine reject stream. No membrane is perfect in its rejection of dissolved salts, so a small percentage of salts does move through the membrane and appears in the product.



A membrane assembly is generally symbolized as a rectangular box with a diagonal line across it representing the membrane.

Figure XIX. Elements of a reverse osmosis system

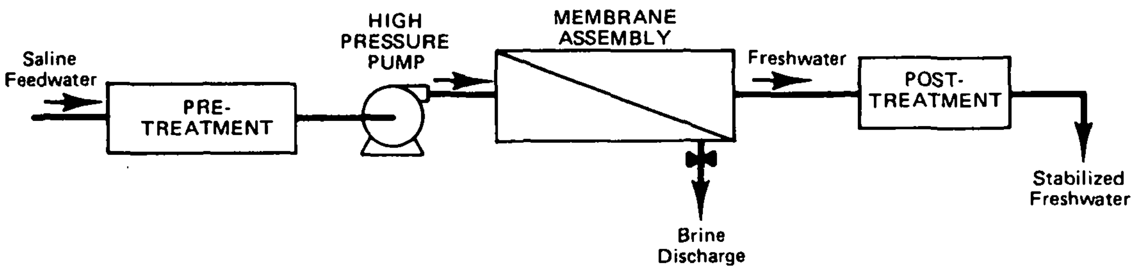


Figure XX. Flow diagram of a reverse osmosis system

Source: These figures courtesy of the United States Agency for International Development. From O.K. Buros and others, The USAID Desalination Manual (Washington, D.C., prepared for USAID by CH2M Hill International Corporation, 1980).

(d) Stabilization

The product water from the membrane assembly usually requires pH adjustment and/or degasification before being transferred to the distribution system or tank for potable use.

2. Membranes

Membranes and membrane elements used for reverse osmosis must operate at high pressure and must restrict the passage of dissolved solids. Moreover, they must remain physically and chemically stable in a saline aqueous environment. There is no perfect membrane currently being manufactured and the ones in use today vary in quality with regard to those characteristics.

Membranes are made from a variety of materials. Cellulose acetate was used in much of the original development work in the 1950s, but these had some drawbacks owing to their lack of hydrolytic stability and their tendency to lose flux by compaction. The original cellulose acetate material has been largely displaced by various blends of other cellulose acetates, polyamieds and other polymers, which have been found suitable for commercial applications.

Most, but not all, of the membranes now produced are asymmetric in cross section in that they have a variation in physical structure from one face to the other. Those membranes are not reversible in action, that is, salts are rejected efficiently only when a saline solution is applied on the surface layer and not the other way around.

3. Membrane characteristics

Some of the important characteristics of membranes include flux, salt rejection and recovery.

Flux indicates the quantity of water which can flow through the membrane. The Flux depends on the water transport coefficient, the pressure differential across the membrane and the osmotic pressure differential across the membrane.

The water transport coefficient is determined by many factors, including the type and thickness of the individual membrane. The flux and salt passages for any membrane are measured at a reference temperature, pressure and concentration. The flux and rejection can then be calculated under actual operating conditions.

For any given membrane, the flux will be proportional to the net applied pressure. The osmotic pressure for moderately brackish water is approximately 0.7 to 3.4 atm (10 to 50 psi), compared to 24 to 27 atm (350 to 400 psi) for sea water. Hence, in order to obtain reasonable fluxes, brackish water systems must be operated somewhat above those pressures, usually in the range of 17 to 27 atm (250 to 400 psi). In order to decrease operating pressures, it will be necessary to develop membranes with more efficient transport coefficients; however, owing to the actual solution osmotic pressures, there is a limit to how far pressures can be reduced.

In order to permit economical desalination of water, the flux must be relatively high to reduce the amount of membranes needed, thus keeping the cost at a reasonable level.

There is a considerable difference between the fluxes of the spiral and the hollow fine fibre membrane configurations, but this is offset to some degree by the amount of membrane surface area available in a given volume and the cost of producing the various types of membranes.

Salt rejection indicates the ability of the membrane to reject dissolved salts. Since no membrane is perfect in this respect, they all allow transport of some salts through the membrane. Rejection can be determined by comparing the level of total dissolved solids in the product water and the feed water by a standard formula. Individual constituents in solution have different rejection levels depending on the membrane, constituent and local environment.

Recovery in an RO system can be defined as the percentage of feed water flow which is recovered in the product water flow. The higher the percentage of recovery, the greater the conversion of saline water into fresh water. Normally, the recovery for a single stage brackish water RO system is about 45 to 55 per cent and for a sea-water system about 20 to 30 per cent. The remainder which is not recovered is rejected as brine waste. The percentage recovered may be considerably increased with multiple staging, where reject brine from one stage is subsequently used as feed water to a following stage so as to recover additional water. This is often done with brackish water systems to increase the recovery to the range of 65 to 80 per cent.

B. Process description

The two key elements of the process are the membrane assemblies and the configuration in which the assemblies are connected.

1. Membrane assemblies

There are four basic membrane assemblies which are used for reverse osmosis, as discussed below.

(a) Plate and frame

The plate and frame membrane configuration was offered for sale commercially in 1966. The membranes were placed between circular plates which were stacked in a large high-pressure vessel. Those membranes were heavy, bulky and inconvenient to operate and were not a commercial success. They were soon replaced by tubular and other membrane designs.

This type of membrane is now produced by some manufacturers in Europe, but with a different mounting arrangement (see figure XXI). They are being used in brackish water and sea-water applications but they do not make up a significant amount of the world's installed capacity. The new European design has eliminated the need for a massive high-pressure vessel and enables the manufacturers to use a variety of sheet membranes. Those membranes are usually used in specialized industrial applications.

(b) Tubular

The development of the tubular membrane configuration solved some of the problems and permitted the production of membranes for commercial use, in about 1965. The membranes are tubular in shape with a diameter of about 0.7 to 2.5 cm (0.3 to 1 inch) and are formed or inserted on the inside of rigid tubes or pipes. Generally, the feed water is pressurized on the interior of the tubular membrane and the desalted permeate moves through the membrane to be collected from the outer surface of the tube, as shown in figure XXII. Holes and/or porous supports on the outside permit the passage of water once it passes through the membrane. The tubes are normally in discrete diameters corresponding to tubing and piping used for plumbing. The most common commercial membrane is 1.3 cm (1/2 inch) in diameter. All of these configurations require a large physical volume relative to the surface area of membrane that can be incorporated.

Tubular membranes have generally not been a commercial success for large-scale water production in developed countries, mainly because the membranes are expensive to produce and they have a large physical volume to production ratio. However, they may become feasible for use in developing countries, because of their simplicity, ease of operation and rugged construction. Furthermore, they can be mechanically cleaned after fouling and can be operated with a turbulent flow to minimize scaling and fouling. Tubular units have been built and operated in India, Mexico and other countries for potable water production.

(c) Spiral

The spiral membrane assembly uses flat sheet membranes (such as those in the plate and frame configuration), but they are combined in a design which eliminates many of the problems that made the plate and frame membranes uneconomical. Spiral membranes were commercially available in the late 1960s, and they rapidly displaced the tubular membranes for use in water production.

Figure XXIII shows the construction of this type of membrane assembly. The membrane is cast on a fabric support and then two of those fabric-supported membranes are placed on either side of a porous material (the product water carrier) and glued together. The porous material (usually a resin-impregnated Dacron tricot) provides a route for the product water, which has passed through the membrane. The membrane "sandwich" or leaf is glued together on three of its four edges. The fourth edge is joined to a tube which acts as a collector for product water. Usually 2 to 26 membrane leaves are attached to this central tube. Between each pair of leaves, a feed water channel spacer is inserted. This spacer is a mesh screen designed to provide a passage through which the feed water reaches the membrane surface and the remaining brine exits.

The leaves and spacers are then rolled to form a compact cylinder. Each of these cylinders forms a unit called an element or module, which ranges from approximately 5 to 30 cm (2 to 12 inches) in diameter and 30 to 150 cm (12 to 59 inches) long depending on the manufacturer and model. Two to six of these elements are usually placed in series in a long tubular pressure vessel to make up a single production unit.

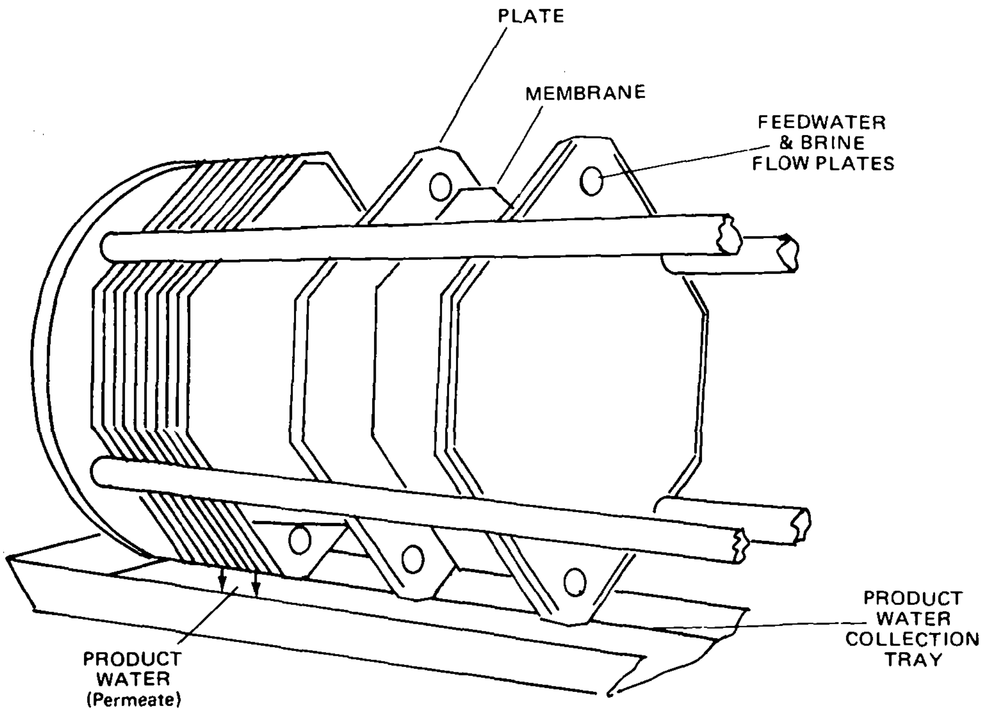


Figure XXI. Construction of a plate and frame membrane

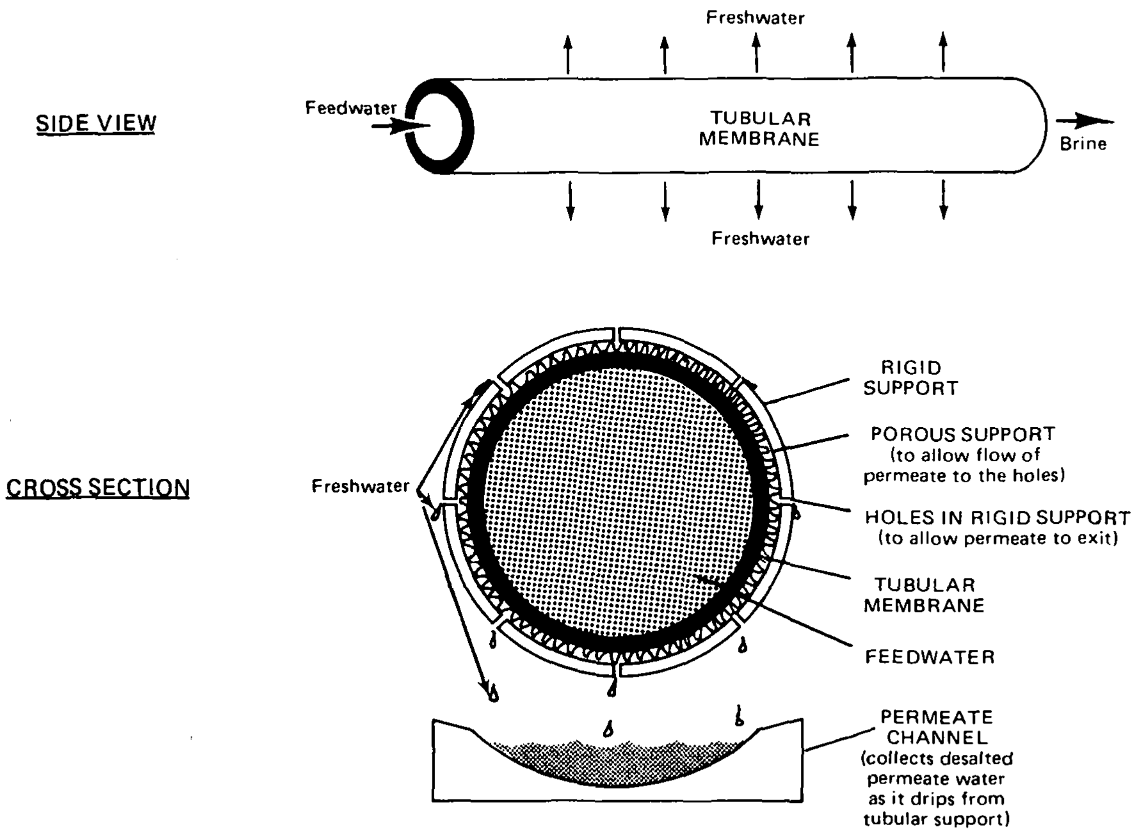
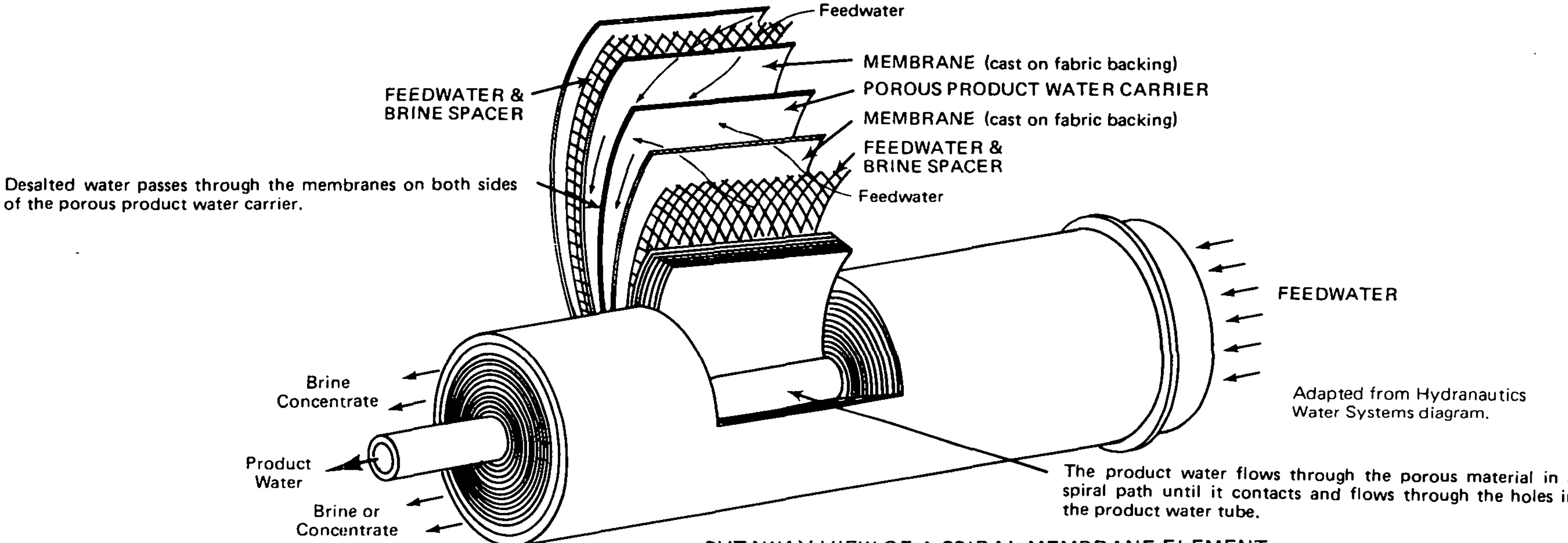
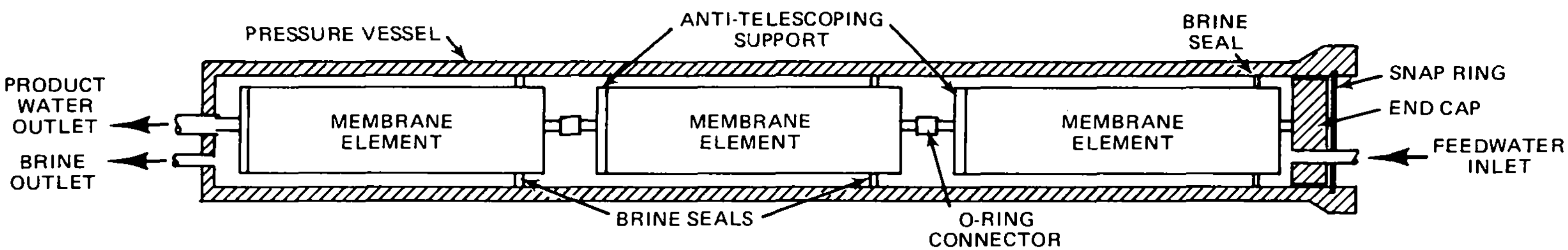


Figure XXII. Construction of a tubular membrane

Source: These figures courtesy of the United States Agency for International Development. From O.K. Buros and others, The USAID Desalination Manual (Washington, D.C., prepared for USAID by CH2M Hill International Corporation, 1980).



CUTAWAY VIEW OF A SPIRAL MEMBRANE ELEMENT



CROSS SECTION OF PRESSURE VESSEL WITH 3-MEMBRANE ELEMENT

Figure XXIII. Spiral membrane cut-away view with elements in a pressure vessel

Source: This figure courtesy of the United States Agency for International Development. From O.K. Buros and others, The USAID Desalination Manual (Washington, D.C., prepared for USAID by CH2M Hill International Corporation, 1980).

(d) Hollow fine fibre

The hollow fine fibre membranes were first put into commercial production in about 1969. They are produced as long capillary tubes with the diameters approximating that of a human hair. As shown in figure XXIV, saline water is applied to the outside of the tubes and desalinated water is collected and carried away in the inner capillary. The capillary tubes are made with thick walls (the ratio of the outside to the inside diameter is about 2:1), giving the fibres the strength to resist the high pressures involved in reverse osmosis without additional physical support.

For commercial application, the fibres are arranged as a bundle of short loops tightly packed inside a sealed cylindrical pressure vessel. This assembly is called a permeator. Saline water is introduced into the vessel and circulates around the fibres while the product water is collected at one end of the vessel from the open ends of the fibre loops.

2. Process configurations

There are four basic process configurations in which membranes can be arranged for the production of desalted water: single, parallel, reject staging and product staging. These are shown in figures XXV and XXVI and are discussed below.

(a) Single

The simplest configuration for a small system. It is limited in production by the capacity of the membrane assemblies available.

(b) Parallel

Capacity is added to the process by adding membrane assemblies in parallel to increase production. This modification does not change the overall salt rejection, nor the percentage of recovery of the system.

(c) Reject staging

Also referred to as a multiple-stage, cascade, pyramidal, or tapered array configuration, it is used to increase the recovery of a system. The reject (brine) from one stage is used as feed water to a following stage so as to recover additional water. Owing to the high pressure in the reject stream, no additional pumping is necessary between stages. This configuration entails a slight sacrifice in salt rejection and an increase in overall power usage compared to a parallel system with the same feed rate, although the power per unit of product water is lower.

The quality of the feed water must be such that the brine delivered as feed to the additional stages does not cause scaling or other problems with the membranes in the latter stages.

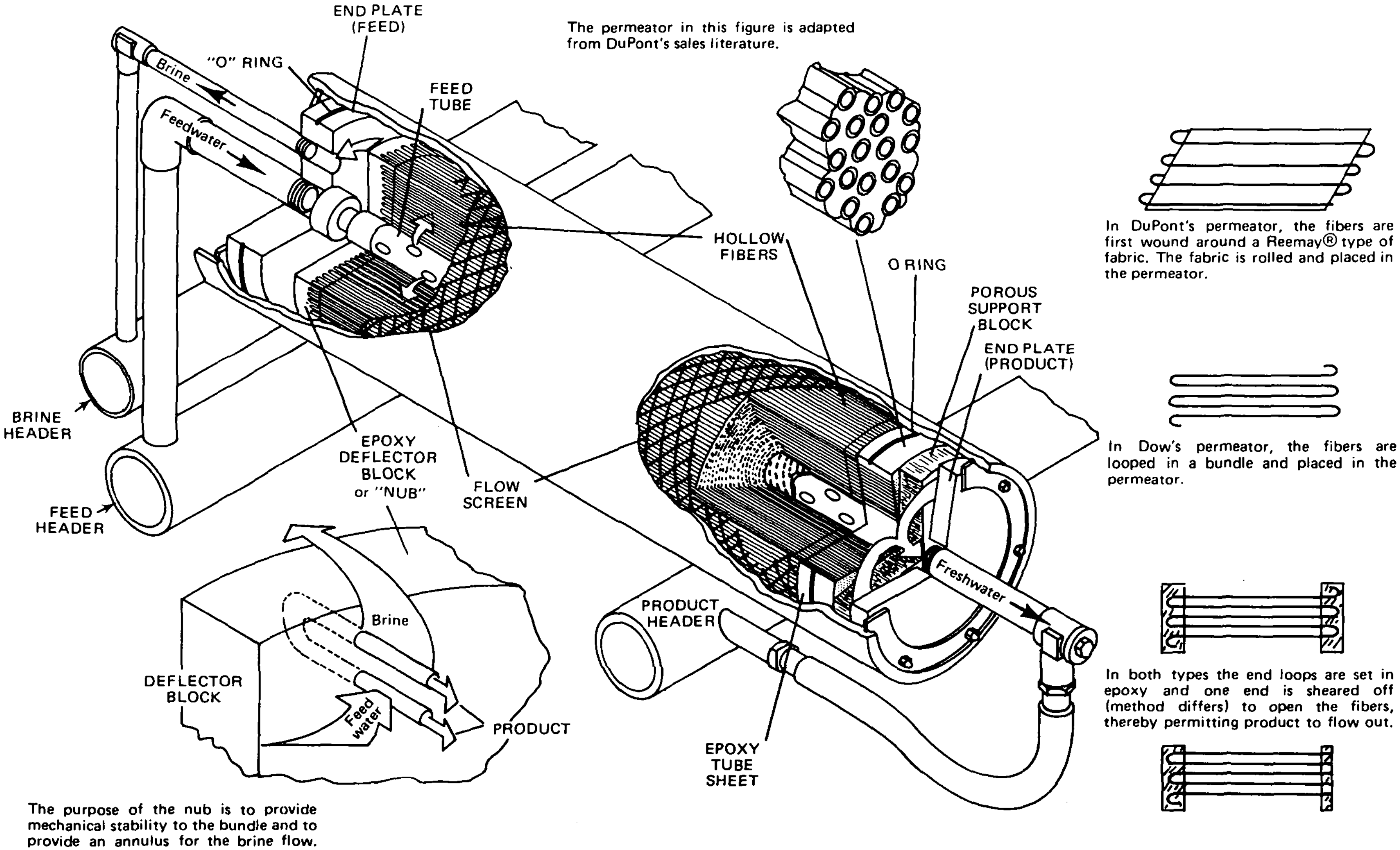
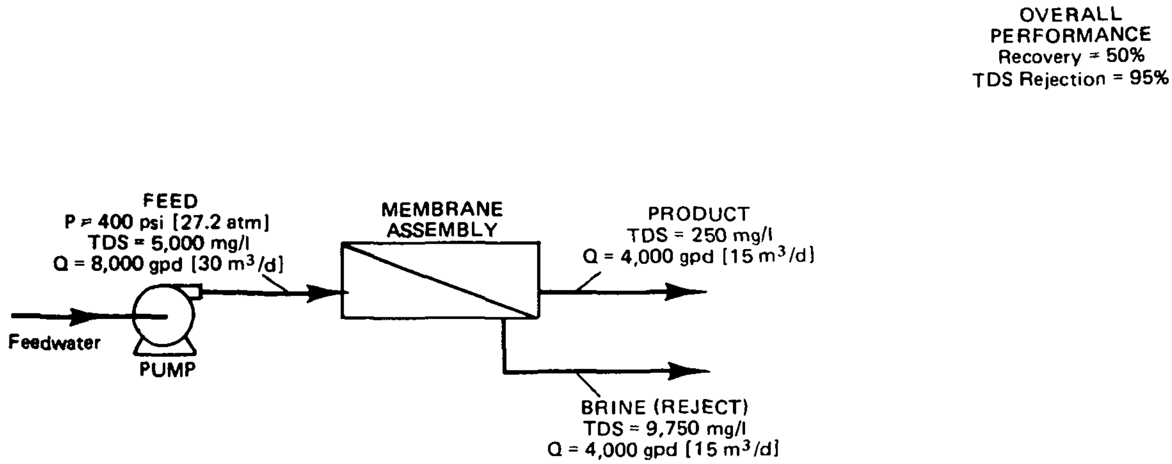
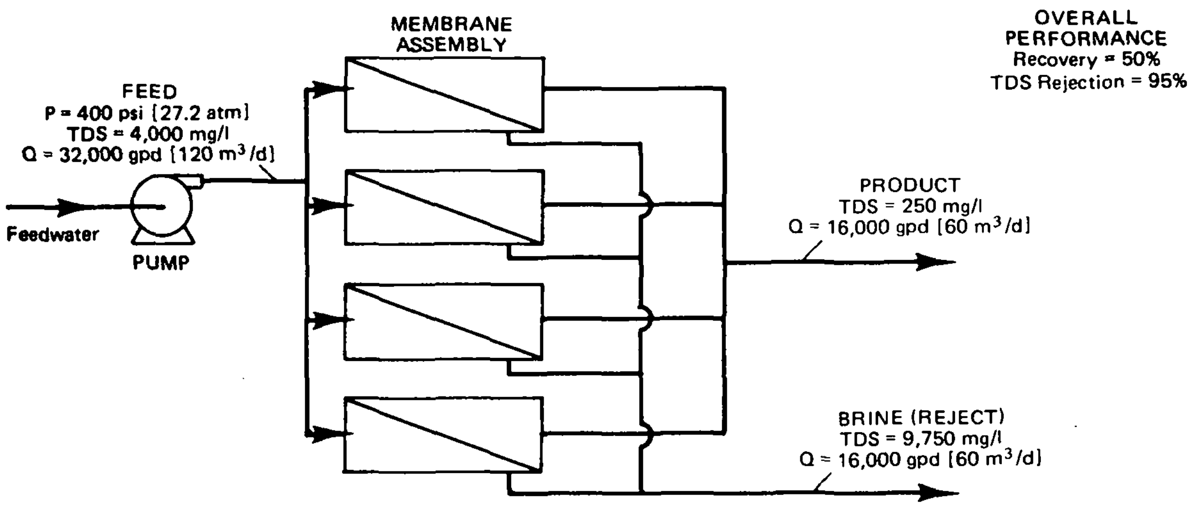


Figure XXIV. Permeator assembly for hollow fine fibre membranes

Source: This figure courtesy of the United States Agency for International Development. From O.K. Buros and others, The USAID Desalination Manual (Washington, D.C., prepared for USAID by CH2M Hill International Corporation, 1980).



SINGLE STAGE WITH A SINGLE MEMBRANE ASSEMBLY



SINGLE STAGE WITH PARALLEL MEMBRANE ASSEMBLIES

Figure XXV. Single stage RO plant configurations

Source: This figure courtesy of the United States Agency for International Development. From O.K. Buros and others, The USAID Desalination Manual (Washington, D.C., prepared for USAID by CH2M Hill International Corporation, 1980).

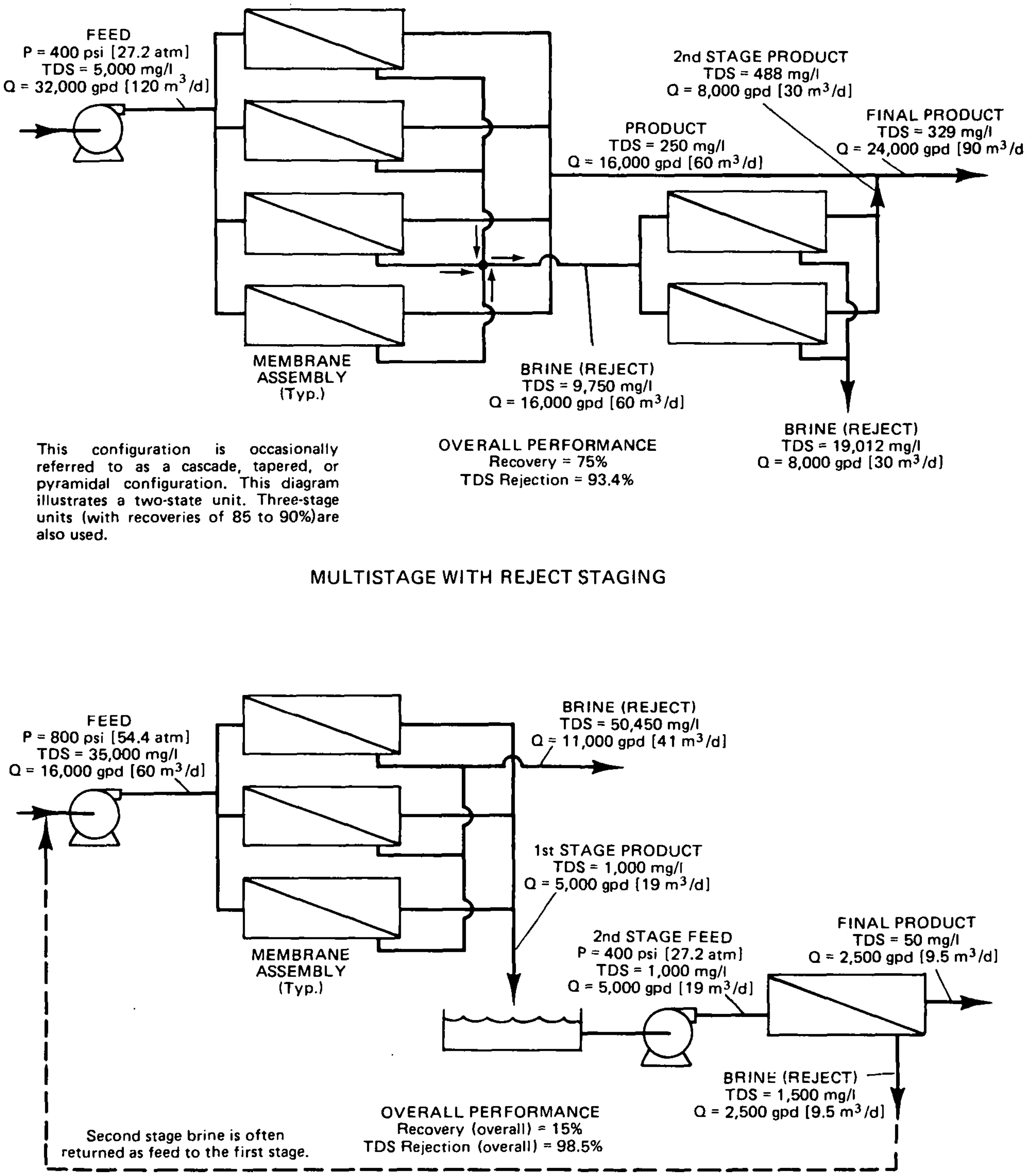


Figure XXVI. Multi-stage RO plant configurations

Source: This figure courtesy of the United States Agency for International Development. From O.K. Buros and others, The USAID Desalination Manual (Washington, D.C., prepared for USAID by CH2M Hill International Corporation, 1980).

(d) Product staging

This system, which is well-suited to the desalination of sea water, is actually two separate process trains run in series. The product from the first stage is used as feed to the second stage, thus allowing the first stage (using sea-water membranes and high pressures) to reduce the total dissolved solids of the water to a moderate level. The second stage then can use brackish water membranes to produce a lower TDS.

Operation of the second stage is simplified because passage through the membranes in the first stage prepares the water, so that very little pre-treatment is necessary and thus high recoveries can be achieved. The reject from the second stage can be blended with the raw feed water for reprocessing.

C. Major engineering considerations

1. Raw water source

Defining the characteristics of the raw water supply to be used is the most important item in the proper design of an RO system, including the pre- and post-treatment facilities and the selection of an appropriate membrane. The chemical and physical characteristics and their variability should be fully tested before design is completed. In the case of surface water sources, it is essential that samples be taken under varying conditions with regard to such factors as tides, storms, wind directions and seasons to ensure that the widest range of water quality conditions is determined.

2. Product water

Information on the desired quality and quantity of the finished water is needed. The desired quality of the product water in terms of TDS will determine the salt rejection required. Other product water information has to do with the water usage requirements, including average and maximum daily flows, peak periods, required pressure and available storage.

3. Pre-treatment

The proper preparation (pre-treatment) of the water before it reaches the membrane is the key to successful operation of a reverse osmosis plant. Membranes can be sensitive to pH, temperature and the presence of certain chemicals, and are highly sensitive to fouling and clogging. Proper design of the system and pre-treatment of the water can greatly minimize those problems and hence protect the membranes, which are the heart of the reverse osmosis system.

Pre-treatment and post-treatment (or stabilization) processes involve simply the application of standard water treatment and chemistry techniques. Since the flows in most reverse osmosis systems designed to date are not large, the pre-treatment techniques and components are generally adaptations of those used on small package water treatment plants rather than full-scale unit operations seen in large water treatment systems. In many cases, especially with ground water, pre-treatment may be unnecessary or at least relatively simple, involving only in-line chemical addition or filtration.

The parameters most affected by pre-treatment are precipitates, colloids, particulates and micro-organisms.

Precipitation of such constituents as calcium and iron on the membrane can create problems. Precipitation can be minimized by reducing the concentration of the constituents. This can be accomplished by prior removal through softening, ion exchange and/or aeration-filtration or by reducing the recovery rate. Prior removal is more expensive owing to higher capital and operating costs, and reduction of the recovery rate is often used where sufficient raw water exists. The most common way to minimize precipitation is to lower the pH by adding acid, thereby increasing the solubility of the dissolved substances or reducing their concentration by conversion to a more soluble form. A threshold inhibitor is often added to the raw water to reduce precipitation of calcium, barium or strontium salts, by preventing the formation of crystals.

Colloids, which occur as suspended solids, are tiny particles which, owing to their small size pass through standard filters and thus cannot be readily removed by ordinary mechanical processes. They are most often present in surface waters and wells improperly developed in clay strata and are usually removed by coagulation followed by filtration. In large systems, coagulants such as alum, lime and polymers can be used in a standard coagulation, flocculation, sedimentation and filtration system. The standard safety filter is not a reliable device for removal of colloidal particles.

Particulates can be removed by sedimentation and filtration methods used in standard water treatment plants. When surface water is the raw water source, particulate contamination can be minimized by proper construction and placement of the intake structure and by proper selection of materials. For ground water, proper well construction and development techniques and materials selection can substantially reduce particulates in the feed water.

Where dissolved substances such as hydrogen sulphide or ferrous salts exist, which can be readily oxidized into particulates (sulphur and iron oxides) by exposure to oxygen, they must either be deliberately oxidized and filtered out or prevented from oxidizing. The latter method is frequently employed and requires that the well and feed water piping be constructed so that air or other oxidants are not introduced into the system.

Micro-organisms can cause fouling of membranes by growing within the elements and permeators. Disinfection is used to remove them. Chlorine has been the most frequently used disinfectant for reducing the presence of micro-organisms. Membranes differ in their compatibility with chlorine, and disinfection must be performed carefully. Cellulose acetate derivatives can tolerate chlorine in reasonable doses, but polyamides usually cannot.

Other effective disinfectants that can be used periodically on a regular schedule are sodium bisulphite and hydrogen peroxide.

Safety filter

In almost every type of reverse osmosis system, an in-line pressure filter is placed just before the membrane as part of the pre-treatment system. The purpose of the pressure filter is to protect the membranes from any filterable matter that may have inadvertently passed through the pre-treatment process. Replacing cartridge filters more often than every one to three months usually indicates a problem with the pre-treatment. However, the safety filter is not meant to be a major component for the removal of high amounts of filterable solids.

4. Post-treatment

The product water emerging from the membrane assembly generally needs some type of post-treatment before being distributed as potable water. Such post-treatment includes pH adjustment, usually by the addition of a base, removal of dissolved gases such as H_2S and CO_2 by air stripping and/or disinfection.

5. Materials of construction

Materials of construction must be selected to be compatible with the pressures, potential for corrosion, and vibration that exist in the system.

(a) Pressures

The reverse osmosis system is a dual pressure system - the membrane section is operated at high pressure, and the pre- and post-treatment sections are operated at low pressures. For the latter sections, low-pressure fittings and construction techniques can be used. Polyvinyl chloride piping is often employed in those sections.

The section from the high-pressure pumps into the membrane pressure vessels must be designed and constructed to withstand pressures from 17 to 68 atm (250 to 1,000 psi) depending on whether brackish water or sea water is being processed. In this section, stainless steel, high-pressure flexible hoses, and lined or coated piping have been used.

(b) Corrosion-resistance

Owing to the high TDS of the feed water and brine stream, plus the potential instability of the product water, materials must be carefully selected to avoid both their damage by corrosion and damage to the membranes owing to fouling by corrosion products. For those reasons, polymeric materials, stainless steel and polymeric liners and coatings are widely utilized.

In most cases, the pH of the feed water is reduced upstream of the high-pressure pumps and thus the pumps and piping should be carefully selected for resistance to corrosion. Both stainless steel and aluminium bronze have been used satisfactorily. In at least one case, pumps made of conventional materials were used, and acid for pH control was injected into the high-pressure feedline downstream of the pump with good results.

In the design of sea-water plants in particular, care must be taken to avoid situations where stagnant sea water will remain in contact with stainless steel, as serious corrosion can occur if an improper stainless alloy has been used.

(c) Vibration

Inherent in the use of high-pressure pumps is some vibration which can create stress on piping, machinery, control systems, and their directly or indirectly connected instrumentation. This can be especially noticeable on small installations where all the components are mounted on a single skid.

6. Recovery

The selection of an overall recovery factor for the desalination system is a key design parameter. While normal recovery for brackish water is about 45 to 55 per cent of the feed water per stage, with reject staging (cascade, tapered or pyramidal arrays), recoveries of 75 to 90 per cent are possible with certain feed waters. Only a marginal increase in total energy is required, compared to a single-stage unit. Capital costs per unit of product water are also generally reduced.

Although theoretically there is an economic incentive to use a high recovery system to reduce energy costs, this advantage must be weighed against the disadvantages. The major disadvantages include: (a) the increased complexity of the system including pre-treatment and, more importantly, (b) the increased potential for fouling and scaling of the membranes owing to precipitation of sparsely soluble salts. The potential for the latter increases as the concentration of the brine increases for each successive stage. This is, of course, highly dependent on the chemical constituents in each individual water source and must be examined on a case by case basis.

Apart from economics, other factors contributing to the desirability of higher recoveries could include a restricted raw water supply or the need to minimize the quantity of brine being discharged.

7. Brine disposal

The method of disposal of the concentrated brine stream which leaves the reverse osmosis system needs to be ascertained early in the conceptual planning of a project. The brine in a brackish water reverse osmosis plant can amount to 20 to 50 per cent of the water produced and, where it can be discharged to the sea or other saline body, it is generally not a problem. However, since the brine has the potential for polluting the ground water and causing other environmental problems if discharged improperly, its disposal should be carefully considered. The necessity for special disposal techniques could make the system very costly.

8. Operating problems

Most failures in reverse osmosis plants occur because materials are deposited on the membrane surfaces or in the membrane elements, preventing the membranes from functioning efficiently. Other problems occur as a result of mechanical failures, membrane failure and poor operation. One of the most important factors in the successful operation of a reverse osmosis plant is the training and attitude of the operator.

(a) Fouling

Fouling is the deposition of materials within the plant resulting in reduced performance of the system. As mentioned above, these deposits are from four major sources: precipitates, colloids, particulates, and micro-organisms. Other sources of fouling can be oils, greases and organics. The membrane surface is especially sensitive to fouling, which can reduce the water flux to a major degree.

(b) Mechanical failures

Owing to the high pressures needed for the transport of water across the membranes, the piping, supports and machinery can be subjected to major mechanical stresses. Pumps at those pressures tend to be high speed, especially for sea water, and can cause significant vibrations depending on the pumps, their mounting and the design of the system. This vibration places stresses on joints, instrumentation and pipes. A well-designed plant will have minimal vibration-related problems.

(c) Corrosion

Corrosion of materials is a significant factor in reverse osmosis facilities. The feed, brine and product streams can all be corrosive. Many of the chemicals used in the treatment process such as acids and bases can also be sources of corrosion.

(d) Membrane failure

Although operating problems may focus on the failure of a membrane to function properly, they often have other causes, usually a problem in the pre-treatment system.

The manufacture of membrane assemblies requires a number of components, materials, chemical reactions and production steps. This results in some variations between individual membranes from the same manufacturer. Overall, however, the quality of membranes has been good and most manufacturers are willing to stand behind their products. Guarantees on membrane life, of course, are based on certain operational requirements that must be met in order for the guarantee to be valid.

Owing to the different materials and methods used in fabricating membrane assemblies, their operational life and performance can be affected in various ways by the temperature, pH, existence of chlorine and storage conditions.

(e) Poor operation

Poor operation can destroy even the best units. Operators must be trained in the performance of their duties and the capabilities of their plant.

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Page xvii line 13

For NW read NM

Page 46, paragraph 5, line 6

For membrane of a read membrane or a

Page 51, paragraph 4, line 5

For Director read Directorate

Page 54, Table 5

In the column headed "3,800 m^3/d", the item "Interest during construction" should read 144

Page 56, Table 6

The seventh item, first column should read Annual O and M

Page 63, paragraph 4, line 5

For availability or fuel of other read availability of fuel or other

Page 95, paragraph 1, line 5

For coller read cooler

Page 125

Replace map 2 by map 1 on page 137

Page 137

Replace map 1 by map 2 on page 125

Page 139, paragraph 4, line 1

For Under read Other

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Page 149, paragraph 4, line 4

For 1980 read 1890

Page 163, paragraph 3, line 8

Delete where industrialized countries

Page 163, paragraph 5, line 5

For plan read plant

Page 166, table 17, footnote b/

For biological read biochemical

Page 185, table 24

In the column headed "Loading rate", for (g/ft¯/d) read ($g/ft^2/d$)

Page 187, paragraph 1, line 4

For includes read depends on

Page 188, paragraph 5, line 1

For method read effect

Page 212, paragraph 1, line 4

For sprayer read spraying

Page 216-217, table 26

In the column headed "Water reuse" the item "Disadvantages: technical," point 3 should read Will only work in areas where waste water is collected.

Page 271 References

For twelfth reference, for Metcali read Metcalf

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