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# Water Resources Technology in the Middle East

By

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EXECUTIVE SUMMARY

1. The purpose of this research has been to define the technology available for resolving water problems in the Nile, Jordan, Litani, Orontes, Euphrates, and Tigris drainage basins. In each of these watersheds, the discharge is seasonally dependent, and both the flow and the water quality decrease downstream as a result of evaporation losses, infiltration, and nonconsumptive uses. Because of these quality and quantity issues, long-term economic growth depends upon aggressive water resources management. Superimposed upon these quantity and quality limits is an agricultural system which requires a significant and continuing hydrological and energy investment for its sustenance.

2. The domain of water technology is the conception, planning, design, construction, and operation of facilities to control and use water, and to manage its quality. The technologies addressed here are those designed to solve one or more of the regional water problems. These include techniques for improving the quality of water such as desalination and reclamation and/or the quantity such as storage facilities, conservation, storm water interception, groundwater recharge, and cloud seeding. In this volume, desalination is the center of attention.

3. An expanding water demand in the face of limited supplies leads one to consider progressively poorer quality sources. Desalination is one possible solution since salty water is plentiful. These technologies, based on distillation, membranes, and ion exchange, are used to reduce total dissolved solids (TDS). The type of technique chosen depends largely on the TDS of the raw water and the desired product (typically no more than 500 mg/L). The focus of this report is on design and economic issues associated with the desalination processes.

4. Distillation is based on evaporation and recovery of purified water by condensation. It is often coupled with electrical generation in dual-purpose plants. The design of distillation units has become very complex with detailed computer programs being utilized to carry out the thermodynamic and heat transfer calculations. The exergy, or available energy, is often used as the basis for the design. Using this method, the design is optimized by a process of dividing the plant into zones such that each zone performs a function. Boundaries are placed between the zones, and all streams of exergy and matter across the boundaries are identified, quantified and optimized.

4.1. Multi-stage flash distillation (MSF) is the most common evaporative process and the one with the greatest (two-thirds of the total) worldwide operating capacity, about 6.76 Mcm/d. MSF is used to desalt waters of up to 45,000 ppm TDS, and it can yield a 25-50 mg TDS/L product. The design of MSF evaporators centers on flash chamber evaporative efficiency, salt water entrainment, heat transfer, and product losses .

4.2. Multi-effect distillation (MED) is an evaporative process which has recently been developed into a highly efficient technology with further potential. The MED process is usually used for seawater and yields a 20 mg TDS/L product. The world's largest MED was started up in March 1983, at Ashdod, Israel.

4.3. Vapor compression (VC) is a single stage compact evaporative system. It is a new process, still undergoing development, which is highly efficient, and most likely the least energy consumptive of the evaporative processes. It is often used in conjunction with MED. Rational design is based on the feed to distillate ratio, brine feed heater effectiveness, feed temperature, evaporator temperature, and the temperature difference between the heating steam and the boiling brine.

4.4. In addition to fossil and nuclear sources, solar energy may be used to drive desalination processes. In commercial applications, either flat or concentrating collectors are used in conjunction with either MED or MSF distillation plants. Solar ponds provide another method for collecting solar energy.

4.5. There is some potential for geothermal energy to power distillation processes in the study area, particularly in Israel.

5. In the membrane processes, saline water is forced through a barrier which passes water but not solutes. Thus, two fractions accumulate, one lower and the other higher in TDS than the feed water.

5.1. Reverse osmosis (RO) relies upon an external pressure to reverse the osmotic flow through a semipermeable membrane. The worldwide installed capacity is about 2.3 Mcm/d. The semipermeable membrane is a key part of the RO plant. Spiral wound cartridges and hollow fine-fiber modules are the most widely employed, and they have been used interchangeably in all applications. Pretreatment is needed to minimize membrane fouling. The pressure needed to desalt commonly occurring brackish waters is approximately 1400 to 4100 kPa, and, for seawater, approximately 5500 to 8300 kPa. The size of installed RO systems has steadily increased over the years. The early notion that RO was suited only for small plants has been replaced by the understanding that the process is competitive in large scale operations as well. High levels of recovery are typically achieved by the use of a staged design in which the reject from one stage passes to the next stage in series fashion In seawater RO plants it is possible to recover energy which would otherwise be wasted. Such an effort takes advantage of the fact that rejected brine is discharged from the reverse osmosis at nearly the same pressure to which the feed water is subjected.

5.2. Electrodialysis (ED) is a membrane process which has been applied primarily to brackish waters. The ED process consists of alternating anion and cation exchange membranes. The application of a direct current voltage results in the demineralization of one stream and concentration of another. Membrane fouling is a recurrent problem in ED which is solved by interrupting the process and cleaning the membranes.

5.3. Electrodialysis reversal (EDR) is similar to ED except the polarity is periodically reversed. The process is thus self-cleaning because the films and scale are carried away with the waste when the polarity is reversed. Virtually all electrodialysis equipment installed since the mid-1970s has used polarity reversal. EDR has been used successfully to desalt brackish water, and has entered the market for seawater desalination. Long term stability and membrane life have been shown for EDR desalination of both seawater and brackish water. The world-wide installed capacity of EDR technology has reached approximately 0.33 Mcm/day. Many of these installations are relatively small and most are institutional or industrial.

5.4. Ion exchange occurs when ions in solution are exchanged for other ions on a solid surface. Water to be desalinated is passed through a bed of anionic and cationic exchange material. Once the exchangeable ions on the resin have been replaced, the resin must be regenerated.

6. A variety of combinations of processes are possible to meet the particular constraints of an individual situation. Increasing attention is being paid to hybrids of RO and distillation. Systems have also been developed which combine RO and ion exchange for a more efficient desalination process.

7. Dual purpose plants are those installations which combine power generation and water production. Most MSF and other distillation facilities are operated in this mode, because they require low pressure steam. Dual purpose plants can also utilize membrane desalting. It has recently been shown that RO can function competitively in a dual purpose electricity/water production facility.

8. Energy requirements are substantial for the desalination processes. The available data indicate that energy consumption for seawater desalination is 25-30 MJ/cu m product for RO with energy recovery; and, for MSF, 45-60 MJ/cu m product. The energy requirement for RO desalting of brackish water is approximately 6-8 MJ/cu m. Energy consumption in the EDR process is quite low, typically 3-6 MJ/cu m of product for brackish water and 32-48 MJ/cu m product for seawater. The Ashdod MED plant consumed 33-37 MJ/cu m during the first year of operation.

9. Process economics currently favor the use of reverse osmosis for most situations involving the desalination of either seawater or brackish water. Furthermore, RO is competitive in all cases including large-scale and dual purpose installations. Recent data indicate that the cost to produce water via RO is in the range of $1.11-1.41 (1986 U. S. dollars) per cu m. The principal reason that RO has become competitive has been a significant reduction over the past decade in operating costs, most notably in terms of energy, membrane replacement, and chemicals.

10. Regarding the future of desalination, it is important that countries use the cheapest and most manageable system available to them. It is concluded here that RO will grow in importance in the study area both due to the construction of new installations and the replacement of retiring ones. Widespread application of RO in both brackish water and seawater applications is anticipated. EDR will continue to have a role in the handling of certain brackish water situations. In distillation, the low temperature multi-effect process and the vapor compression system are very promising and will probably also become more important in the future.

## A. WATER RESOURCES ENGINEERING

Water resources engineering refers to the conception, planning, design, construction, and operation of facilities to control and use water. The principal issues of water resources development are the control of water (flood control, land drainage, sewage conveyance), the use of water (hydropower, drinking, irrigation, navigation), and the management of water quality (pollution control).

The use to which water is put determines the amount needed, the timing of the need, and the requisite quality. The technologies addressed over the course of this research have included hydraulic structures, and those aimed at controlling the quantity and quality of water. The hydraulic structures of particular importance are dams, hydroelectric facilities, and the infrastructure required for flood control, drainage, and irrigation. In the regulation of water quantity, the objective is to match the supply of water with the demand for it. Thus, these technologies are used to control either demand (*e. g.*, conservation, drip irrigation techniques, etc.) or supply (cloud seeding, storage, etc.). On the quality side, the technologies of interest are designed to either alter the nature of the water (*e. g.*, desalination) or to change the nature of its use (development of salt-resistant crops, wastewater reuse). In the course of the present effort, we have concentrated on technologies dealing with the quantity and quality of water with particular emphasis being placed on desalination.

B. TECHNOLOGIES FOR THE MIDDLE EAST

The extent of water resources development varies substantially from basin to basin within the study area, with the Jordan being the most highly developed. Existing plans for further development of the Nile, Euphrates, and Tigris rivers suggest that demands on and competition for available water will increase markedly over the next two decades in these basins. Typical consequences will be water of decreased quantity and quality for downstream users.

The design and operation of water resources systems in the study area is complicated by a number of factors. Water quantity and quality are limited by the combined effects of climate, soil chemistry, and nonconsumptive use. Superimposed upon this is an agricultural system which requires a significant and continuing hydrological investment for its sustenance. Problems of water use are aggravated by the tradition of agriculture pursued through application of massive energy and water subsidies. The historical and ideological commitment to agricultural self-sufficiency is a major determinant of the pattern of water utilization in this region. In economic terms, considerations of security, ideology, and politics are used to rationalize the provision of water at costs that exceed its marginal value.

The various technological options which are suitable for the study area are designed to solve one or more of the water problems encountered there. These include techniques for improving the quality of water such as desalination and reclamation, as well as the quantity such as dams and other large-scale facilities, conservation, storm water interception, groundwater recharge, and cloud seeding.

The pressures of expanding demand for water in the study area are inevitably leading managers to consider using water of progressively poorer quality. Desalination is one possible solution since most of these countries have coastal or other saline water supplies available. In fact, approximately two-thirds of the global installed desalination capacity is found in the Middle East proper, although only an estimated two percent is in the study area. However, it is our opinion that desalination is the single most important technological option for the future of the study area.

Israeli water planners have forecasted an increase in water demand of at least 700 million cubic meters (Mcm)/yr by the end of the century (24). This additional demand will have to come from alternative supplies since virtually all fresh water is currently used. In the early to mid-1980's, water costs 40 to 45 cents per cubic meter so that the cost of desalination is less forbidding than it once was. It is claimed by key Israeli officials that desalted water will be necessary to meet national and social goals, and that, as a consequence, Israel will need to operate a desalination plant with capacity of 50 to 100 Mcm/yr by the end of the century (24).

Other countries face a similar situation. Some Egyptian experts, for example, say that desalted water is needed in their efforts to reclaim more land for agriculture (13), although it is difficult to justify the expense of desalination when the use of the water is for irrigation.

A considerable amount of desalination research and practice is already in place in the Middle East. The following summarizes municipal and total desalination capacity of several countries of the study area. Total capacity includes municipal, industrial, power, tourism, demonstration, irrigation, and military (428). The amount of desalinated water used for agricultural purposes is probably low because of the economics.

| | Municipal (cu m/day) | Total (cu m/day) |
|---|---|---|
| Iraq | 674 | 92,413 |
| Israel | 32,668 | 35,871 |
| Jordan | | 1,488 |
| Syria | | 781 |
| Turkey | | 631 |

This list is derived from the Water Supply Improvement Association's inventory of desalination plants able to produce at least 100 cu m/day that were delivered or under construction as of December 31, 1984.

For some countries, the most recent information available was from the U. S. Department of the Interior Office of Water Research and Technology's list of desalting plants in operation or under construction as of January 1, 1977 (322).

| | Municipal (cu m/day) | Total (cu m/day) |
|---|---|---|
| Egypt | 7,986 | 10,875 |
| Sudan | | 227 |

This reference (322) also lists a non-municipal capacity of 519 cu m/d in Lebanon. Attempts to verify the existence of this capacity have not succeeded. In any event, the total installed desalination capacity in the study area is at least 50 Mcm/yr, roughly one to two percent of the worldwide installed capacity of 10 Mcm/d (H).

Historically, much of the global desalination technology has been developed in the United States, Japan, and Western Europe. Countries in the Middle East also do a considerable amount of desalination research and development. A low temperature vapor compression process was developed by Israel Desalination Engineering, as was the horizontal aluminum tube multi-effect process. Other Israeli research and development is done by Mekorot, the National Water Company; Technion - Israel Institute of Technology; Ben-Gurion University of the Negev; and, the National Council for Research and Development. In addition, the Joint U. S.-Israel Desalination Project Authority, Ltd., has built low temperature multi-effect plants in the U. S. Virgin Islands and Ashdod, Israel.

Egypt is also actively pursuing a research and development program. Some of these efforts are aimed at providing clean water to small communities. The Egyptians are investigating such possibilities as solar desalination, diesel powered reverse osmosis, wind powered reverse osmosis, and biogas technology for scattered and remote places without conventional water sources.

## C. DESALINATION PROCESSES

In general, the desalination technologies are directed towards reducing the concentration of total dissolved solids (TDS). Fresh water typically possesses less than approximately 1000 mg TDS/L. Most published drinking water standards include a prescribed maximum of 500 mg TDS/L, and many municipal supplies in the United States contain as little as 50 mg TDS/L. Certain industrial applications, most notably boiler feed water, require ultra-pure water with no more than about 5 mg TDS/L. Sea water is typically on the order of 33,000 mg/L, with deviations depending on local rates of dilution and evaporation which, of course, are very important in the study area. Sea water may contain up to 45,000 mg TDS/L, and the concentration in the Dead Sea is 250,000 mg TDS/L. Brackish water is usually defined in an intermediate position, at approximately 1000 to 3000 mg TDS/L, although some would put the upper limit at about 10,000-15,000 mg TDS/L. The term brine is usually reserved for waters which are more saline than seawater, *i. e.*, with more than about 35,000 mg TDS/L.

The type of desalination technique appropriate for a given situation depends in large part on the raw water TDS and the desired product TDS. The appropriate technologies are based on distillation, membranes, and ion exchange. As a general rule, the distillation based processes can be used to achieve very high purity water (less than 50 or so mg TDS/L), whereas the membrane based processes can achieve TDS levels in the range of several hundred mg/L. More detailed qualitative descriptions of the processes may be found in the companion volume. The focus of the present discussion is on design issues and process economics.

**C.1 Distillation**. The distillation processes are based upon evaporation followed by condensation of the purified water. Distillation plants operate on the principle that water vapors are salt free and that purified water can be produced by condensing these vapors. The distillation technologies are energy intensive because of the need to drive the change of state.

The design of distillation units has become very complex with detailed computer programs being utilized to carry out the thermodynamic and heat transfer calculations. The exergy, or available energy, concept is often used as the basis for the design (BJ). Using this method, the design is optimized by a process of dividing the plant into zones such that each zone performs a function. Boundaries are placed between the zones, and all streams of exergy and matter across the boundaries are identified. A cost vector at each boundary is defined such that it is the same when viewed from either side of the boundary and such that the cost of capital, matter, and irreversibility in a zone is allocated to the principal product of that zone. An exergy balance and an economic balance for each zone is developed, and the exergy balance is substituted into the economic balance. The resulting equations are then solved for the unit cost of the principal product as a function of such items as capital cost, entropy generation, exergy forms used up, and material converted to useless form. The entropy generation terms in each equation are represented as either functions of efficiencies or conductances for rate processes. The capital investment terms are allocated to each form of entropy creation, and the capital investment versus entropy generation is optimized, taking one mechanism at a time. When the optimization is complete, the costs of the various zones are balanced against one another starting with the most expensive pair.

The various technologies are described below, and they may be differentiated on the basis of how the heat energy is provided and on the basis of the physical arrangement for generating the vapor and condensing the product water.

C.1.a. **Multi-stage flash distillation.** Since its first commercial application in 1960, (MSF) has grown in use until today it is both the most common evaporative process and the one with the greatest total worldwide operating capacity (6.76 Mcm/day [H]). MSF is used for desalting high salinity waters containing up to 45,000 ppm TDS. It is thus applicable to even the saltiest seawater, and can yield a final product with as low as 25-50 ppm TDS. MSF achieves cost effectiveness only in large-scale applications, and, it has been said that MSF is cost effective only when used to process more than approximately 1000 cu m per day (16), although Teislev (F) discussed relatively economical small scale distillation units. These are based on the use of waste, and, therefore, low cost, energy to drive the process. The design of MSF evaporators focuses on the evaporative efficiency of the flash chamber, salt water entrainment, heat transfer, and product losses (BI).

C.1.b. **Multi-effect distillation** (MED) is an evaporative process which was exploited commercially very early (9, 16, 314). It then became less popular, but, in recent years, has been developed into a highly efficient technology with further potential. The MED process is usually used for seawater and yields a high purity product of about 20 ppm TDS. The two process variants are termed horizontal tube (HTE) and vertical tube evaporation (VTE), respectively, because evaporation occurs on a heat exchange surface made either of horizontal or vertical tubes. HTE plants are very flexible with respect to operating capacity, being operable over the range of 40 to 120 percent of nominal capacity, with only slight changes in specific energy consumption. This technology is used by Israel Desalination Engineers, and these plants use low grade steam as the heat source. Additionally, start-up and shut-down operations may be conducted in a relatively short time frame. Operating temperatures are higher for VTE than for HTE. This increases scale control costs and controls the type of metals which may be used for heat exchangers.

The world's largest MED was started up in March 1983, at Ashdod, Israel (AB), and the results of the first year's operating experience have been summarized by Fisher *et al.* (K).

**C.1.c. Vapor compression** (VC) is a third evaporation process. This technology which consists of a single stage compact system is a new one, still undergoing development. VC is a highly efficient process, most likely the least energy consumptive of all the evaporative processes. Vapor compression is used only in smaller operations, as it is economically favored at nominal capacities of less than 3800 cu m per day. It is often used in conjunction with an MED plant, particularly VTE units, for added energy efficiency. Aly (AX) stated that VC has potential in combination with reverse osmosis for small scale applications. Kamal *et al.* (W) concluded that this process may be the way for distillation to compete with membrane processes in single purpose (*i. e.*, water only) seawater desalination.

Matz and Zimerman (2265) discussed the impacts of design on operation and economics. A rational basis for the design of vapor compression systems has been developed by Elsayed (AZ). This approach is based on the feed to distillate ratio, effectiveness of the brine feed heater, feed temperature to the VC desalination system, evaporator temperature, and the temperature difference between the heating steam and the boiling brine in the evaporator.

**C.1.d. Distillation Energy**. Energy requirements for distillation processes are substantial due to the change of state of the water. The energy may be supplied by the combustion of fossil fuels. This is especially attractive in areas where the cost of such fuels is relatively low as it is in much of the Middle East. Alternatively, desalination may be combined with the generation of electricity in such a way that lower temperature, i.e., partly expanded, steam is used to drive the distillation process. Other possibilities include nuclear, solar and geothermal sources.

Solar energy may be used to impel desalination processes. Delyannis (AF) reviewed solar assisted desalination. The diffuse nature of solar energy makes collection the principal problem, and collectors are the most costly part of solar desalination. In commercial desalination plants, either flat or concentrating collectors may be used. The types of desalination plants used with such collectors are MED (both HTE and VTE) and MSF, although some work has been done with solar driven reverse osmosis. Solar powered desalination may be the most economic method of providing desalted water to remote arid regions (BD).

Advances in solar collection devices are rapidly narrowing the price difference between solar powered seawater distillation and conventional seawater distillation (L). A 600 ton/day (545 cu m/d) plant has been described. The solar collectors are non-metallic, being fabricated from warm water resistant polymeric film material. Distillation is achieved in this design through a multiple-effect process.

Solar ponds provide another method for collecting solar energy. Solar ponds are shallow artificial black-bottomed ponds or lakes. Energy from solar ponds can be used directly or combined with fossil fuel to operate low temperature MED plants. A problem with solar ponds is that their total output varies greatly with the seasons of the year. Peak clipping has been developed to deal with this problem. This method involves building a pond somewhat larger than would be necessary to collect the mean annual solar energy requirement and wasting some of the summer output.

Geothermal energy represents an energy source which could be used to drive distillation processes. Certain geological formations have been found in Israel which contain water saturated with salt at temperatures of at least 100°C.

C.2. **Membrane Processes**. The distinguishing feature of the membrane processes is that saline water at ambient temperatures is forced through a barrier which allows the passage of water molecules, but prevents the passage of dissolved materials. Thus, two fractions accumulate, one lower (the product water) and the other higher (the reject brine) in TDS than the feed water. Membrane processes are characterized by their recovery which is the ratio of product flow rate to feed water flow rate.

It is often convenient to categorize the membrane processes in terms of the potential gradient which provides the driving force through the membrane. This may be pressure as in reverse osmosis (RO), or hyperfiltration (HF) as it is also known, or ultrafiltration (UF). On the other hand, the process may be non-pressure driven as in electrodialysis (ED) or transport-depletion. The reader is referred to the works of Applegate (AA) and Belfort (T) for relatively recent reviews of membrane technology. In the following discussion, RO is heavily emphasized because of the important role it plays in the world-wide desalination picture.

C.2.a. **Reverse Osmosis**. HF was first commercially applied in the late 1960s, when it was used to desalt brackish water. The initial testing and development for seawater desalination began in the mid-1970s. Today, it is the second most widely used desalination process, behind only MSF in global installed capacity.

Hyperfiltration relies upon the application of an external pressure to reverse the osmotic flow through a semipermeable membrane. This results in the accumulation of low TDS water at atmospheric pressure on the output side of the membrane. An excellent monograph on the theory and practice of reverse osmosis has been edited by Bakish (N). The reader is referred to that document as well as the extensive document edited by Belfort (T), and only a brief summary of key points will be repeated here. These papers are lengthy ones with considerable detail which should be reviewed by the serious student of reverse osmosis.

The pressure needed to desalt commonly occurring brackish waters is approximately 1400 to 4100 kPa (200 to 600 psi), and, for seawater, approximately 5500 to 8300 kPa (800 to 1200 psi). These pressures are higher than those used in ultrafiltration. Such pressures necessitate efficient, and reliable pumping equipment, pipes, and pressure vessels.

Recent large scale work with low pressure desalting of brackish water has been reported by Glueckstern *et al.* (AV). This plant, located at Eilat, Israel, produces over 3000 cu m/d from brackish water at 6000-6500 mg TDS/L. The plant achieves 65 percent recovery and operates at 195 psi (1344 kPa). During a full year of operation, permeate TDS was always less than 300 mg/L, and the power consumption was approximately 1 kWh/cu m of product (3.6 MJ/cu m).

The scale of installed RO systems has steadily increased over the years. The early conventional wisdom that RO was suited only for small plants has been replaced by the understanding that the process is competitive in large scale operations as well. An example is the Malta seawater RO facility at Ghar Lapsi which, at an installed capacity of 20,000 cu m/day, is the world's largest RO facility (BC). The cost of water from this facility is $1.08 per cu m produced (BB).

**C.2.a.1. Module Types**. As discussed in more detail in the companion volume, there are four basic module units: block and frame, tubular, spiral wound, and hollow fiber. Hollow fiber membranes are produced by DuPont (aromatic polyamides), Dow Chemical (cellulose triacetate), and Toyoba of Japan (cellulose triacetate). The spiral wound design is the most popular application. It is produced by a number of manufacturers. Generally speaking, the hollow fiber system and the spiral wound modules are competitive, and the choice depends upon such factors as the feed water quality, the desired quality of the product water, and the nature of the environment within which the system will operate (P). In RO plants, spiral-wound cartridges and hollow fine-fiber modules have been used interchangeably in all applications.

A considerable experimental effort has been underway at the DROP (Doha RO Plant) facility in Kuwait. Water is produced in parallel processing trains consisting of spiral wound, hollow fiber, and plate and frame configurations. Preliminary comparative data are beginning to appear. Sources of data include Malik *et al.* (AK), Grigoleit and Schottler (AL), Nagel (AM), and Nieszen (AN).

**C.2.a.2. Feed Water Quality and Pretreatment**. Feed water quality is an important issue in RO design. Continuous long-term operation requires the appropriate selection of pretreatment processes (AG). In some cases this is necessitated by the properties of the membrane itself. Thus dechlorination is often important for aromatic polyamides, and pH adjustment is usually needed for cellulose acetate.

Pretreatment of the feed water is also practised in order to prevent fouling of the membrane. Chemical treatment is undertaken to prevent scaling (due to carbonates and sulfates), fouling by metal oxides (due to the oxidation of trace metals, such as iron (BF), to insoluble products), device plugging (due to suspended particulates), colloidal fouling, and biological fouling. Pretreatment design is fundamental to all successful RO performances in order to minimize problems associated with fouling of the membranes.

One of the long-standing problems with membrane desalination is the buildup of scale due to carbonates and sulfates. This problem can be minimized by the addition of acid (usually concentrated sulfuric acid) to the feed water. Prior to the early 1980's, the addition of acid was controlled by maintaining a constant feed water pH (usually about 6.5), without formal consideration of the conditions under which scale would form except for the relatively simple Langelier Saturation Index which is widely used in the water supply industry. In the early 1980's, DuPont began to recommend the use of the Stiff and Davis Stability Index as a control parameter. Its use has made it possible to achieve significant reductions in the amount of acid added (in some cases, as much as 85 percent) with a corresponding decrease in chemical costs (Z).

**C.2.a.3. RO Design**. Klinko *et al.* (D) discussed the various factors influencing the design of seawater reverse osmosis systems. They consider site-specific items, such as energy costs, finance charges, feedwater salinity, feedwater temperature, chemical costs, and O&M rates. Non-site specific parameters include membrane performance, array configuration, feed pressure, system water recovery, equipment choice, feedwater pH, and pretreatment. The design of HF facilities involves a number of trade-offs and constraints. These may be enumerated (D):

> As feedwater temperature increases (with constant recovery, flow rate, and membrane area), membrane flux, and salt passage increase. All other factors held constant, a rough rule of thumb states that each 1°C temperature rise results in a 3 percent increase in water flux. Thus, more elements are needed to achieve a given production rate for cold water than for warm water.
>
> Increases in recovery, with constant permeate flow and feed temperature, lead to reduced permeate quality.
>
> For constant feed pressure, the increased osmotic pressure associated with an increase in recovery causes an increase in the

required membrane area. This is because the flow of product is proportional to the difference between the feed pressure and the osmotic pressure, where the proportionality constant is membrane specific.

In order to maintain constant permeate flow and quality in the face of variable feed temperatures, a corresponding change in feed pressure or membrane area is necessitated.

Increased water recoveries will increase membrane replacement required to maintain quality.

With high salinity feedwaters, net driving pressures are low and, consequently, to achieve reasonable productivity from an element, high feed pressures are required.

As the recovery increases, the energy consumption falls, but at the cost of installing new membranes. Thus, there is a membrane vs power cost trade-off involved in RO design. Wade (AO) described a technique for optimizing between power costs and membrane costs. Ericsson *et al.* (AS) developed an optimization procedure for large scale RO seawater desalination which is based on water recovery as the principal parameter.

Matsuura and Sourirajan (O) presented a detailed analysis of RO theory based on the preferential sorption-capillary flow mechanism of reverse osmosis separation. They presented two sets of transport equations depending on whether the governing condition is the preferential sorption of solvent water or the more general case of preferential sorption of solvent water or solute. The first set of transport equations are useful for module and process design of the membrane separation process; the second set, for both process and membrane design. The membrane design problem may be stated in terms of membrane performance as a function of separation and product permeation rate. The attainment of these design criteria require that a suitable pore size and pore size distribution be achieved on the membrane surface. This may be accomplished by the solution structure-desolvation rate approach (O). Ohya *et al.* (AH) presented a generalized approach to RO process design which is based on a number of membrane parameters including hydraulic permeability, solute permeability, reflection coefficient, solute induced compaction coefficient, plasticizing coefficient of solute permeability, and mass transfer coefficient.

A large number of membrane materials have been applied to the reverse osmosis process. Matsuura and Sourirajan (O) reviewed the extensive literature on these materials and presented tabulated summaries of their important properties. Despite its limitations, the most widely used membrane characteristic is the solubility parameter. The solubility parameter, $\delta_{sp}$, is the square root of the internal pressure (also called the cohesive energy density) which represents the heat of vaporization per unit volume. As the $\delta_{sp}$ values of the polymer and the solvent approach each other, conditions become suitable for the dissolution of the polymer in the solvent. Thus, this parameter becomes a useful device for finding appropriate solvents for different polymers. Matsuura and Sourirajan (O) noted that $\delta_{sp}$ consists of three components, the dispersion, dipole, and hydrogen bonding components ( $\delta_d$, $\delta_p$, and $\delta_h$, respectively). They compiled an extensive listing of these parameters for various polymers, and they concluded that successful seawater membranes have values of $\delta_h$ between 4 and 10, and values of $\delta_d$ between 7 and 10, representing a balance between hydrophilic and hydrophobic behavior. This relationship may prove to be a valuable screening mechanism for establishing the value of polymers for seawater applications.

**C.2.a.4. Staged design**. High levels of recovery are typically achieved by the use of a staged design in which the reject from one stage passes to the next stage in series fashion (U). Another option for seawater hyperfiltration is the use of a two-stage system in which permeate from one membrane array is repressurized and fed to a second membrane array. Klinko *et al.* (D) compared this option with the single stage design. They concluded that the single stage system is favored at seawater salinities of 35-38 g/L. In this salinity range, the single stage system is preferred because of its simple design, and the lack of a requirement for interconnections and interstage pumps. At salinities above 42 g/L, the two-stage system is almost always favored. The principal cost factors which dictate this design solution are the lower pressure operation, lower feed flow rate due to higher first stage recovery, lower energy costs, and lower rate of membrane replacement. In the intermediate range of salinities, between 38 and 42 g/L, the choice between a single-stage and a two-stage system becomes dependent upon site-specific cost factors.

**C.2.a.5. Pressure Requirements**. Economically efficient seawater hyperfiltration depends upon the ability of the system to operate at high pressures. The osmotic pressure of a typical brine of 1500 mg TDS/L is approximately 104 kPa; of seawater at 35,000 mg TDS/L, 2415 kPa. Since the applied pressure must exceed the osmotic pressure, it follows that applied pressures must be large. As noted elsewhere, these are typically 5500-7000 (up to 8300) kPa for seawater, and 2800-4100 (down to 1400) kPa for brackish water.

As pointed out by Sackinger (A), the use of aramid hollow fine fiber membranes has provided an opportunity to operate at pressures as high as 8300 kPa with even higher pressures anticipated in the near-term. The higher pressures allow greater system conversions which in turn lead to cost savings in terms of the flow of source water, the size of pretreatment equipment, and the number of required membrane modules. Sackinger presented data resulting from an analysis of typical Middle East conditions in which systems operating at 30-35, 40-45, and 50-55 percent conversion are compared. Operation at higher pressures resulted in substantial improvements in various design parameters when compared to systems operating at 30-35 percent conversion, including membrane factor (0.53), source water flow factor (0.62), pretreatment filter area factor (0.62), RO pump horsepower factor (0.89), and pretreatment chemical consumption factor (0.62) (A). Winters (E) presented operating data from high pressure seawater HF plants (equipped with hollow fiber aramid permeators) which support the notion of improved costs at the higher pressures. The reduced operating costs were attributed to lower power costs and chemical costs.

C.2.a.6. **Energy Recovery**. Chief among the operating costs of an RO system is the energy cost of the feed pumps. It has been estimated that one third of the fresh water production cost is due to the electricity consumed by the feed water pumps (C). In seawater RO plants it is worthwhile to minimize this requirement by recovering energy which would otherwise be wasted. Such an effort takes advantage of the fact that rejected brine is discharged from the reverse osmosis at nearly the same pressure to which the feed water is subjected. It is this energy which is captured in RO energy recovery schemes. Although the recovered energy is usable for a variety of purposes, the usual arrangement is to assist in feed water pumping (Q). In order to minimize these operating costs, the turbine typically operates in tandem with the pump as a means of partially recovering the energy associated with the rejected brine. Such arrangements are feasible for plants with a product flow rate of at least 550 cu m/day (Z). Similar energy recovery options are not practical for brackish water desalination because the energy available for recovery is too limited. Mimura *et al.* (C) described an optimum control system to operate this equipment in a way which maximizes energy efficiency and thereby reduces operating costs.

**C.2.a.7. RO Materials**. The materials used in RO processing must be able to withstand the environmental assaults to which they are subjected. The principal factors of concern are the salinities of both the feed water and the reject brine, and the relatively high pressures. The class of materials used in such applications are the stainless steels. Their properties and uses in RO technology were discussed in a recent review by Bakish (R).

**C.2.b. Ultrafiltration**. UF refers to the use of asymmetric membranes which can be specifically designed to reject molecules in different molecular weight ranges. Applied pressures are generally lower (less than 10 atm [1013 kPa]) than for RO applications. This process can be designed to remove relatively high molecular weight organics. However, for present purposes, it is noted that UF does not separate low molecular weight organics or salt from water. Hence, the UF process is of limited value in the solution of the pressing water problems of the study area.

**C.2.c. Electrodialysis**. ED is a membrane process developed in the early 1950s which has been applied primarily to brackish waters. The ED process consists of alternating anion and cation exchange membranes. The application of a direct current voltage results in the demineralization of one stream and concentration of another. These streams are found in alternating compartments. Membrane fouling is a recurrent problem in ED. These films cannot be removed unless the desalination process is stopped and the membranes flushed with cleaning chemicals.

**C.2.c.1. Electrodialysis reversal** (EDR) works on the same principles as ED except for one important feature. In EDR, the direction of the DC field is periodically reversed by reversing the polarity of the electrodes. The process is thus self-cleaning because the films and scale are carried away with the waste when the flow is reversed. Virtually all electrodialysis equipment installed since the mid-1970s has used polarity reversal. The EDR process has been used successfully to desalt brackish water up to 4000 mg TDS/L with water recovery up to 93 percent. Electrodialysis processes have also entered the market for seawater desalination. Long term stability and membrane life (5 to 10 yr) have also been shown for seawater desalination by EDR.

The world-wide installed capacity of EDR technology has reached approximately 330,000 cu m/day (B). Many of these installations are relatively small and most are institutional or industrial. The particular advantages of the EDR technology include the following. This technology is able to tolerate fluctuating feed water conditions. EDR systems can handle relatively high levels of particulate matter (silt density index). Reversing the electric field helps to minimize the formation of calcium sulfate scale, and, as a result, EDR systems are useful in applications where the feed water is supersaturated with respect to calcium sulfate. The result of this is a savings in terms of pretreatment costs. The membranes used in the EDR process are reputed to be durable and easily maintained. Additionally, the membranes are tolerant of the chlorine which is often added in pretreatment.

**C.2.d. Transport Depletion**. The transport-depletion process is quite similar to ED. However, the anionic exchange membrane is replaced with a near neutral one. This eliminates some of the problems associated with the anionic exchange membranes. To date, the transport-depletion process has been used only at the laboratory scale.

**C.2.e. Ion exchange**. Ion exchange occurs when ions in solution are exchanged for other ions on a solid surface. Water to be desalinated is passed through a bed of ion exchange material. In desalination applications, both an anionic and a cationic resin would generally be used. Once the exchangeable ions on the resin have been exchanged, the resin may be regenerated. Systems have been developed which combine reverse osmosis and ion exchange for a more efficient desalination process.

## D. HYBRID SYSTEMS

A variety of combinations of processes are possible to meet the particular constraints of an individual situation. Increasing attention is being paid to hybrids of RO and distillation. The various advantages of RO/MSF have been discussed by Awerbuch (AQ). Very high recoveries have been shown to be possible using a hybrid system incorporating reverse osmosis and vapor compression distillation (M). The actual process train included pellet softening for the removal of calcium, reverse osmosis operating at 90 percent recovery, followed by distillation of the RO brine using vapor compression. The residual brine is evaporated in lined ponds. The costs associated with the evaporation ponds are substantial contributors to total process cost (2268). The authors pointed out that the costs of brine recovery were much less than the costs associated with the construction of the additional ponds needed to evaporate the entire RO brine flow. The estimated construction costs for the 50,000 cu m/day plant was 134.2 million SR (1985). The RO/VC combination is believed to be a promising one for remote areas or for small communities (AX). Solar powered RO is another promising possibility for small scale and remote locations (BE).

Systems have been developed which combine reverse osmosis and ion exchange for a more efficient desalination process. One example is to first treat seawater by RO producing a brackish permeate of 1600 ppm. The water then passes through a thermally regenerated exchange system. The resin is regenerated with the heat of the seawater upstream of the RO unit (311). The product is pH adjusted and combined with brackish permeate to yield a final product of 500 mg salinity/L.

A similar system was used for treating ground water that had high concentrations of silica, sulfate, alkalinity, and hardness. The ground water was processed by ion exchange followed by reverse osmosis. After pH adjustment and appropriate blending, the product contained 400 to 500 mg TDS/L. Process efficiency was such that 91 percent recovery of groundwater was possible (301).

In the case of a plant in the town of Eilat, Israel, on the Red Sea, ion exchange and reverse osmosis were combined (302). A pre-existing RO plant was used to desalt brackish water containing 6000 ppm TDS at 50 percent recovery, leaving a 12000 mg TDS/L reject brine. Process efficiency was improved by pretreating the reject brine with ion exchange and recycling it through the RO plant. The ion exchange resin is regenerated using seawater. Reuse of the reject cost $0.17 to $0.30 per cu m less than to desalt new seawater with reverse osmosis.

## E. DUAL PURPOSE FACILITIES

Dual purpose plants are those installations which combine power generation and water desalination(10, 308). These installations are thus special cases of cogeneration. Most MSF and other distillation type water conversion facilities are operated in a dual purpose system. This is done because evaporative processes require low pressure steam. The incremental cost to produce the high pressure steam needed to generate electricity is more than offset by the value of the electricity. Some low pressure steam is diverted from the production of electricity to the production of water.

Dual purpose plants can also utilize membrane desalination. It has recently been suggested that RO can function in a dual purpose electricity/water production facility (2267). In such an application, the full potential of the steam would be directed to the generation of electricity. A fraction of the generated electricity would then be diverted to run the RO plant. Because of the lower energy requirements of RO versus MSF, such a facility would be economically competitive.

F. ENERGY REQUIREMENTS

Regardless of the particular desalination process selected, there are a number of crucial operating cost factors. Of paramount concern is the energy required, either for the change of state of water or for overcoming the osmotic pressure gradient. Liberti *et al.* (H) stated that the energy consumption for multi and single effect evaporators has remained essentially unchanged in recent years at approximately a value of less than 210 MJ/cu m of desalted water corresponding to a performance ratio of no more than 12 lb water per 1000 BTU. For the reverse osmosis process, the energy requirement is no more than 100 MJ/ cu m (H). Most authors give energy inputs which are well within these upper limits. Ericsson and Hallmans (2730) presented energy consumption calculations which indicate that the yearly average energy consumption is 26.6 MJ/cu m product for RO with energy recovery; and, for MSF, 45.7-60.1 MJ/cu m product. These values also agree well with those of Wade *et al.* (J) who stated that the RO energy requirement without energy recovery is 34.9 MJ/cu m, and 23.4 MJ/cu m with energy recovery. RO desalination with energy recovery of seawater (approximately 42,000 mg TDS/L) at one Arabian Gulf Coast site required about 32 MJ/cu m (2266). The energy cost of RO for seawater applications, using today's technology, is thus approximately 25–30 MJ/cu m of product.

As noted in Section H, the allocation of costs and energy requirements at a dual purpose plant becomes a tricky problem. Depending upon how the energy requirements are allocated, the conclusions may differ. Darwish and Al-Najem have taken a new look at relative energy consumption data (AR). They concluded that the competitive advantage of RO over the distillation processes in this regard is not as substantial as indicated above. Their data suggested that energy costs for RO are essentially equal to those of a dual purpose MSF facility, and approximately 15 percent less than for a conventional multi-effect boiling system or a mechanical vapor compression facility (AR).

The energy requirements for RO desalting of brackish water are considerably less than they are for seawater. Applegate (AA) stated that RO treatment of brackish waters requires approximately 5.76-7.56 MJ/cu m.

Energy consumption in the EDR process is quite low, typically 3 to 6 kWh/1000 gal brackish water, including pumping (S). Assuming a recovery of 90 percent, this corresponds to an energy requirement of 3.2 to 6.3 MJ/cu m of product. EDR requires 30 to 45 kWh per 1000 gal seawater (31.7-47.6 MJ/cu m product at 90 percent recovery). The prime moving force for EDR is 0.3 to 0.5 v of direct current per cell pair compared to 5500 to 6875 kPa for

RO or a steam plant for evaporation processes. The electrolyzing power consumption in EDR is directly proportional to the ionic content of the feed water.

Kamal *et al.* (W) presented energy consumption data for the VTE/VC system. Their results suggested energy requirements of approximately 194-211 MJ/cu m of product depending upon the size of the plant.

In their analysis of the MED plant at Ashdod, Fisher *et al.* (K) showed that the total specific energy consumption for the first year of operation was 8.2 - 9.4 kWh/ton (32.5-37.3 MJ/cu m). They estimated that in an optimally designed dual purpose plant (combined with a 550 MW turbine), the energy requirement could be lowered to 5.7 kWh/cu m (20.5 MJ/cu m).

In summary, the available data support the contention that one of the principal advantages of RO relative to the distillation processes, especially MSF, is the reduced energy requirement.

## G. POST-TREATMENT REQUIREMENTS

Desalted water, whether derived from membrane or from distillation technologies tends to be aggressive, *i. e.*, corrosive in nature. Consequently, both distillates and permeates require a certain amount of post-treatment, especially for corrosion control and to improve the potability of the product water. A variety of different treatment methods are available (AY), but most typically, small amounts of alkali, such as lime, are added to the product to stabilize it, *i. e.*, to render the product less corrosive.

## H. COMPARATIVE COSTS

The decade of the 1980's has seen a shift in the prevailing wisdom regarding the economics of desalination. Glueckstern and Arad (V) analyzed the costs of membrane desalination in the early 1980's. Their data indicated that, at that time, membrane processes in general were favored over the distillations for the treatment of brackish waters. They also concluded that membrane processes would be preferred for seawater desalination for small scale operations and at sites where energy costs were high. At about the same time, Kamal *et al.* (W) stated that, except for dual purpose plants, RO was competitive with MSF distillation. The data which have become available since that time indicate that today, even for large scale seawater applications, the membrane based technologies have become competitive. The major reason is a reduction in the costs associated with RO. This has been due to operation at higher pressures, increased energy recovery, and decreased chemical and membrane replacement costs. The relative price of energy remains a critical criterion for the difference between the two competing processes.

A rather detailed cost comparison for desalting seawater was made by Ericsson and Hallmans (2730). Their analysis indicated that RO is competitive with MSF even in large scale applications. The results they obtained were sensitive to plant capacity (5, 10, 20, and 50 MGD plant sizes [19, 38, 76, and 190 k cu m/d] were used), interest rate (7 and 15 percent), membrane life (5, 8, and 12.5 years) for the RO process, and performance ratio (7 and 12) for the MSF facilities. Their results are shown in Figures 1 and 2. The spread in the costs (in first quarter 1982 U. S. dollars) was $1.19-2.24/cu m for RO and $1.51-3.29/cu m for MSF over the range of parameter values used. The results reflected the improved energy consumption and membrane durability changes which have evolved in recent years. The data presented by Debbas *et al.* (Z) substantiate this observation. They indicated that the production cost of water from a 10 MGD (37,850 cu m/d) plant would be decreased by 20 percent (from $1.61 to $1.28/ cu m) through the inclusion of energy recovery, reduced chemical costs, and lowered membrane replacement charges. The cost of water from the Ghar Lapsi, Malta, facility is $1.08 per cu m produced (BB). Sackinger (AC) compared RO with a dual purpose MSF plant for seawater desalination. The results showed RO to be competitive and to be associated with a definite energy savings.

In almost every case, desalinated water costs less when produced in a dual purpose plant as opposed to single purpose plant. The cost of desalted water from a dual purpose plant is largely a function of the allocation of costs between the two parts. The allocation may be expressed as the water power ratio which is water production divided by electric power production. El-Nashar (BG) applied the available energy (exergy) concept to the cost allocation problem. Economically, the decision of a single vs. dual purpose plant depends on the difference in investment required for the high pressure steam generator used in a dual purpose plant versus that required for the low pressure steam generator required for the single purpose plant. The economics also depend on the investment required for the back pressure turbogenerator for the dual purpose installation and on the income from electricity sales. It is most economical to have steady year-round water and power demands. The distillation plant does not respond very quickly to changes in the load so it is best to operate the system at full capacity, sending both the water and the electricity to a large-scale distribution network. If this is impossible, then pumping and storage of the desalted water is necessary. In the Middle East, the electric power station in the large dual purpose plants is almost always fossil fuel-fired. However, a recent analysis suggests that, even in oil rich Saudi Arabia, nuclear power has a competitive economic advantage (AU).

Leitner (AI) has provided an update of the earlier ORNL cost analysis (AT) of membrane versus distillation desalination. The analysis was conducted under Middle East conditions and the results were expressed in terms of 4th Quarter 1986 U. S. Dollars. Comparing dual purpose MSF with RO, he presented the results which are summarized in Table 1. Fisher *et.al.* (K) discussed the optimal design of a dual purpose plant combining a 550 MW turbine with a multi-effect low temperature desalination plant. They suggested that water production costs could be as low as $0.50/cu m. However, the basis of this estimate was not made clear. Recent studies have indicated that dual purpose plants need not be MSF; rather, the economics now suggest that a large scale dual purpose RO plant is competitive (2267).

Process control and the measurement of parameters for control purposes is a critical issue in the long-term stability of desalination operations. It should be mentioned that a special issue of <u>Desalination</u> was devoted to the publication of a book on this topic edited by Lior (BA).

The small scale distillation units discussed by Teislev (F) were based on the use of waste energy. He stated that standard configurations are available for production rates of 1.5 to 1000 tons per day (1.4 to 908 cu m/day). In 1985 U. S. dollars, he estimated total costs of $0.38 per cu m for the production of 1000 tons per day from seawater. This figure is very low and presumably reflects the fact that waste energy is being used. The details of the cost analysis were not provided.

The available cost data suggest that hyperfiltration, *i. e.*, reverse osmosis, is the most cost-effective process for the desalination of brackish waters in most cases. EDR also tends to be most economical in situations where the feed water is relatively low in dissolved salts. This is because the energy requirements are roughly proportional to the concentration of dissolved salts. For the other processes, energy, and, therefore, total operating costs, are much more independent of the salt concentration.

Fraivillig (Y) prepared a detailed comparison of RO versus EDR for 1 MGD (3785 cu m/d) plants producing a 500 mg TDS/L product. Feed water concentrations varied over the range of 1000 to 5000 mg TDS/L. The results indicated that RO was less costly over the entire range for the case where the product was blended with brackish water to achieve the desired concentration of TDS. For the case where there was no blending with RO, RO was less expensive over the range of feed water TDS concentration of 1400 to 5000 mg/L. The costs were apparently for early 1980's conditions. The costs varied approximately linearly as a function of feed water TDS. For EDR, the authors concluded that the cost of water would be $1.25 and $1.00 per KGAL ($0.33 and $0.26 per cu m) at a feed concentration of 1000 mg/L, for EDR and RO, respectively; for a feed concentration of 5000 mg/L, these costs would be $3.90 and $1.80 per KGAL ($1.03 and $0.48 per cu m), respectively.

Solar energy sounds like it ought to go very well with desalination since there is an abundance of it in the arid areas which could use desalination. However, it is rarely cheaper to use "free" solar energy than to use fossil fuel (18, 151, 293). In the paper by Crul and Bom (L) costs were developed assuming installation in the Caribbean area. The estimated investment costs were $2.33 million U. S., with amortized production costs of $3.90/ton ($4.30/ cu m).

Among the distillation processes, there is increasing support for the contention that MSF is not the least expensive. Greig and Wearmouth (AP) concluded that mechanical vapor compression is the cheapest, followed by thermal vapor compression. (It should be noted that they also concluded that RO is much more expensive than the competitors. At first glance this seems to conflict with the bulk of the data from the latter part of the 1980's. However, in their analysis, they assumed that the product water would have no more than 3 mg TDS/L, a standard considerably easier for a distillation process to meet than for a membrane process.) Leitner (AI) states that MED, either in the vertical or horizontal configuration, produces the lowest cost water among the distillation technologies.

In summary, the technological state-of-the-art and the current economic situation clearly favor the use of reverse osmosis for most situations in which the desalination of either seawater or brackish water is needed. Furthermore, RO is competitive in all situations including large-scale and dual purpose facilities. The principal reason for this has been a significant reduction in the operating costs of RO installations, most notably energy, membrane replacement, and chemicals.

## I. MARKET PROJECTIONS

The worldwide desalting production rate is approximately 10 million cu m/day, with about 67.6 percent coming from multistage flash distillation and about 23 percent from reverse osmosis plants. About two-thirds of the production is derived from seawater. The large facility sector is heavily dominated by MSF plants which account for 84.5 percent of the installed capacity. By comparison, reverse osmosis plants constitute 11.2 percent of the capacity of plants greater than 1.0 MGD (3785 cu m/day).

In 1985, Stone and Rogers (G) projected seawater desalination sales to the end of the century. The results of their analysis indicated that the market is becoming saturated for distillation processes. They projected annual sales of new and replacement plants of approximately 12 Mcm/d in the year 2000. For membrane based technologies, they predicted a continuing linear growth in sales over the decade of the 1990s, with a projected annual sales of new and replacement facilities of 0.25 Mcm per day. These market predictions were for total worldwide sales of seawater desalination plants. Relative energy prices will be an important determinant of the market share of the distillation vs membrane processes. As noted in Sections F and H on energy requirements and comparative economics, the reverse osmosis process has relatively lower energy requirements than do the distillation processes. Consequently, for high energy costs, the membrane processes become more competitive; conversely, when oil prices are low, this advantage of the reverse osmosis process may be diluted. Conditions prevailing in the late 1980's favor RO in this regard, even in the oil rich parts of the Middle East. The significance here is that membrane units will become commonly employed as replacements for aging MSF facilities, especially in an era or region of relatively expensive energy.

Silver (AE) also concluded that the market is becoming saturated. However, his asymptotic limit is at approximately 14.17 Mcm/day. He did caution that the saturation phenomenon really reflects the limited geography of the Middle East, and more specifically the Arabian Peninsula. Silver stated that desalination expansion will most likely occur via water re-use in the non-arid parts of the world. Silver's projections were that MSF will continue to predominate for very large-scale dual-purpose installations; RO will dominate the smaller dual purpose market and all single purpose water desalination stations; and, EDR will increase in brackish water treatment for inland sites where reject disposal is important.

The important comparison is the one between MSF and RO because the desalting world is totally dominated (approximately 90 percent of the worldwide installed capacity) by these technologies. The advantages usually ascribed to RO include energy efficiency, lower capital cost, shorter construction time, less corrosion problems, simpler construction, operation, and maintenance, and smaller space requirements (AJ). MSF on the other hand has reduced water pretreatment requirements, higher product quality, and a more constant production rate over time.

The increasing role of reverse osmosis in the study area is best viewed from the perspective of the Mekerot Water Company (AW). The plan for Israel is to increase the 1984 desalting capacity of 3 or 4 Mcm/yr to approximately 50 Mcm/yr by the early 1990s (AW) and perhaps to 100 Mcm/yr by the year 2000 (24). This increase is to be achieved through the installation of reverse osmosis plants at Eilat, Ein Boqeq, Nitzana, Mashabei Sade, and Nahal Taninum. The feed water will largely (93 percent) be brackish water in the TDS range of 2400-6000 mg/L, with the balance coming from seawater. It is also stated by Glueckstern (AW) that the longer term technological water fix for Israel will be predominately RO.

A similar posture is being taken by other key players in the Middle East. Historically, Kuwait has been a major user of MSF for the production of water. According to Al-Marafie and Darwish (BH), this dependence on MSF will change dramatically because the current economic situation favors RO. Consequently, the plans call for no new MSF facilities in Kuwait. Instead, new desalination plants will be RO installations built at electric power plant sites.

Regarding the future of desalination, it is important that countries use the cheapest and most manageable system available to them. It is concluded here that RO will grow in importance both due to the construction of new installations and the replacement of retiring ones. In distillation, the low temperature multi-effect process and the vapor compression system are very promising. These two processes will probably also become more important in the future.

## J. SUMMARY

Over the course of the decade of the 1980s, the relative economic picture among the competing desalination technologies has completely changed. Major advances in RO processing have occurred. These have resulted in higher operating pressures, lower energy demands, longer membrane life, and reduced chemical costs. The significance is that, at this juncture, RO is competitive under all conditions, and it is the process of choice much of the time. RO will clearly play a key role in the water picture of the study area over the coming decades. It is well positioned for both new installations and for replacing older plants which are being taken off-line.

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Figure 1. Cost of Seawater Desalination by Reverse Osmosis (2730). Costs shown as a function of membrane life (ML).

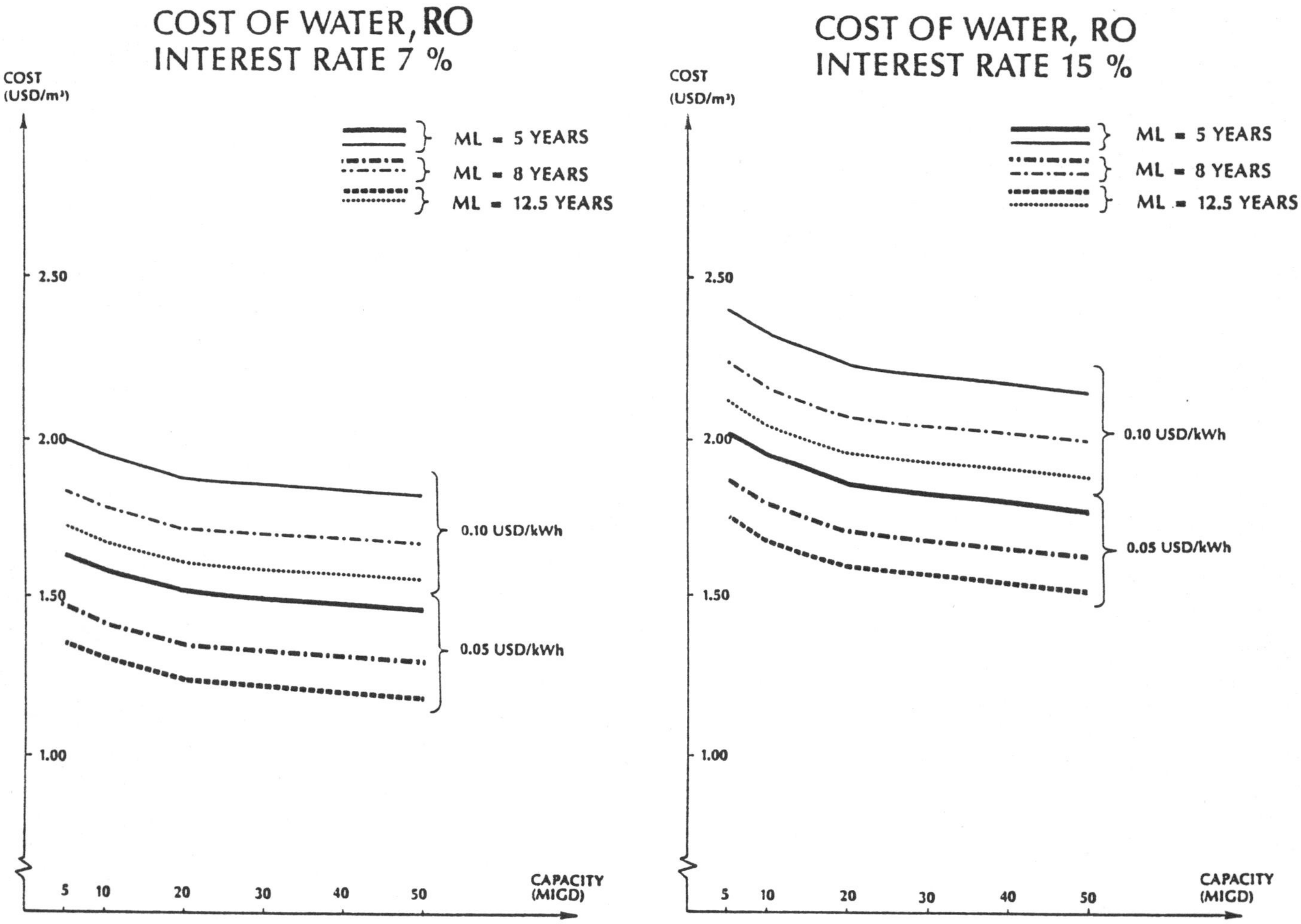
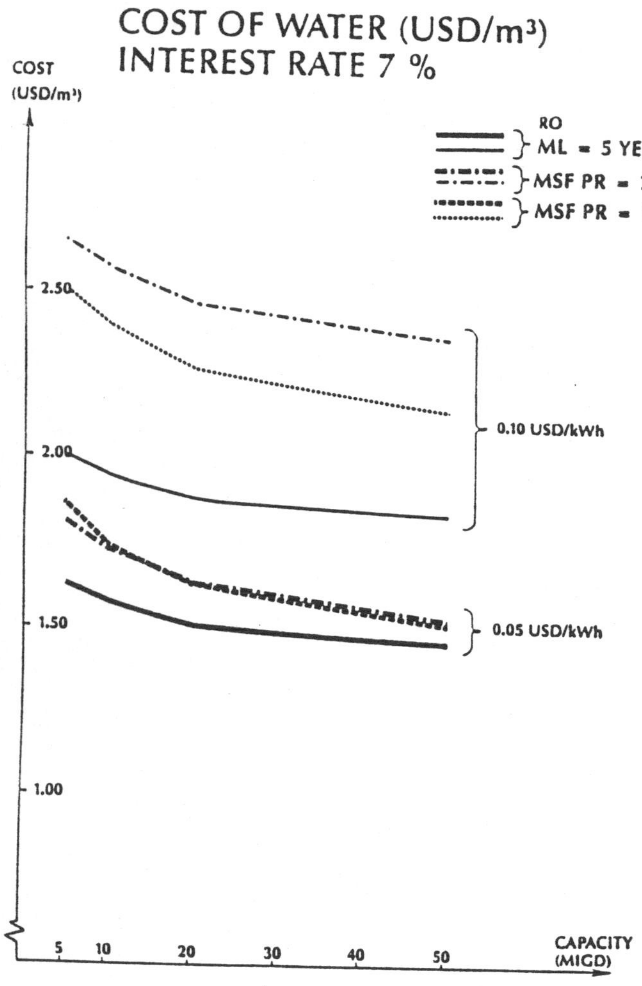


Figure 2. Cost of Seawater Desalination by Multi-stage Flash Distillation (2730). Costs shown as a function of performance ratio (PR) and, for comparison, RO membrane life of 5 years (ML).



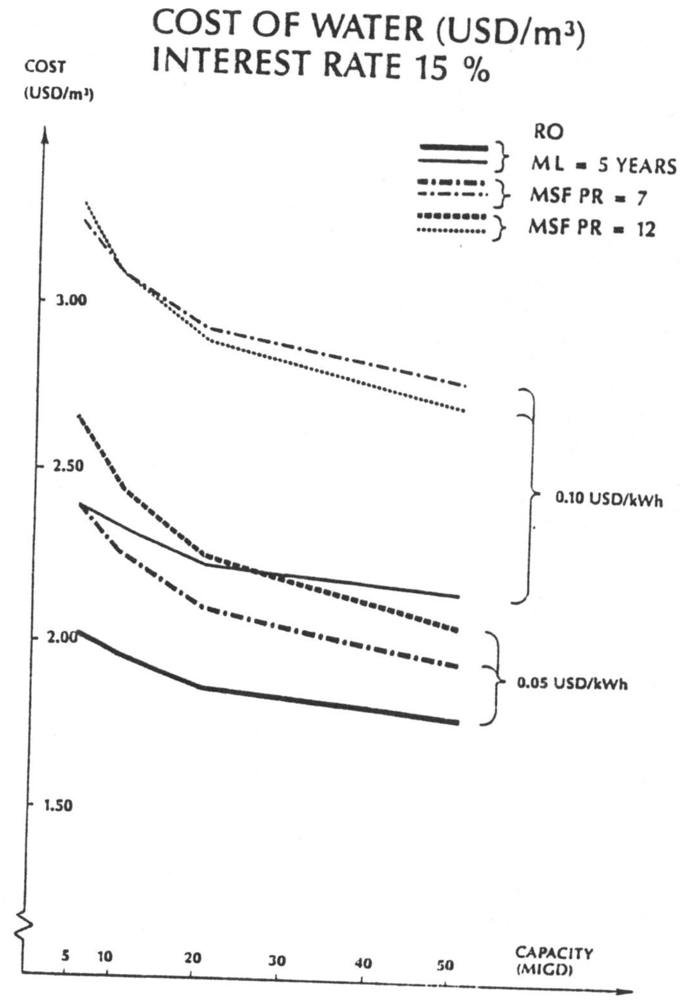



Table 1. Cost Comparison of Dual Purpose MSF with RO Desalination (AI). The costs are in units of 4th Quarter 1986 U. S. Dollars per cu m of product.

| | | | | |
|---|---|---|---|---|
| Plant capacity, 1000 cu m/d | 3.8 | 11.4 | 18.9 | 37.9 |
| RO Cost | 1.41 | 1.25 | 1.19 | 1.11 |
| MSF Cost | 1.65 | 1.32 | 1.25 | 1.15 |