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Desalination: *Present and Future*

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Abstract: *The need for high-quality water significantly increased during the second half of the last century. While heading towards the third millennium, an important problem is about to be solved at a near-affordable cost. The cost of desalinated water is decreasing, and this trend is continuing. Pure, high-quality drinking water is essential for day to day living, food production, better industry, and a better standard of living. The article summarizes the techniques, trends, economy, environment, energy aspects, and other significant parameters associated with the state of the art of modern desalination. Directions are shown for future research and development work for further reduction in water costs.*

Keywords: *Desalination, evaporators, membranes, reverse-osmosis, nanofiltration, multi-stage flash, multi-effect distillation, vapor compression.*

Introduction

During the preparation of this article, the radio announced that a baby born in August 1999 would bring the current world population to six billion. The need for water is rapidly increasing, and current freshwater resources will not be able to meet all requirements. Water cannot be considered now as a natural, self-renewable, low-cost resource, easily accessible to all. Many years of drought at various locations, followed by desertification and movement of the population towards this essential resource calls for different considerations in terms of economic and social effects.

Desalination of sea (or saline) water has been practiced regularly for over 50 years (Wagnick, 1996, 1998) and is a well-established means of water supply in many countries. It is now feasible, technically and economically, to produce large quantities of water of excellent quality from desalination processes. Challenges, however, still exist – to produce desalinated water for relatively large communities, for their continuous growth, development, and health, and for modern efficient agriculture, at affordable costs.

Two main directions survived the crucial evolution of desalination technology, namely evaporation and membrane techniques. The cost barrier broke during the last few years and is now down to the level of 50 to 80 cents/m^3 of desalinated seawater, and the decreasing cost tendency continues. Desalination of brackish water is even cheaper, at costs ranging from 20 to 35 cents/m^3. Membrane techniques penetrate deep in water treatment technology wherever possible. Wastewater also is treated with membranes, though rarely. Many countries are now considering desalination as an important source of water supply.

Main Desalination Techniques

The mult-stage flash (MSF) procedure is the most common technique for desalination, found mostly in the Persian Gulf (Awerbuch, 1997b). The technique's worldwide capacity adds up to about 48 percent of the total number of bigger plants having a capacity greater than 4,000 m^3/day.

Among other evaporation techniques, the multi-effect distillation (MED) may be mentioned here, either with vertical or horizontal smooth tubes or doubly fluted tubes (see the tower desalination process, Pepp et al., 1997). The vapor compression course is very popular for remote locations, resort areas, islands, etc. These two techniques, though not widely used, are promising as far as good water quality, simple application, reliability, and efficiency are concerned.

Membrane processes, mainly reverse osmosis (RO), are currently the fastest-growing techniques in water desalination. Other types of membranes, described below, are used for water quality improvement.

Membranes

The RO membrane technique is considered the most promising for brackish and seawater desalination (Furukawa, 1997). The RO uses dynamic pressure to overcome the osmotic pressure of the salt solution, hence causing water-selective permeation from the saline side of a membrane to the freshwater side (Faller, 1999). Salts are rejected from the membrane, and hence, the separation is accomplished. The RO membranes used are semi-permeable polymeric thin layers, adhering to a thick support layer. Membranes are usually made of cellulose acetates, polyamides, polyimides, and polysulfones. They differ as symmetric, asymmetric, and thin film composite membranes. Membranes are sensitive to changes in pH, small concentrations of oxidized substances like chlorine and chlorine oxides, a wide range of organic materials, and the presence of algae and bacteria. Therefore, careful pretreatment is needed in order to prevent membrane contamination and fouling: pre-filtration to remove suspended solids from feed water; dosage of acid (hydrochloric or sulfuric) to remove bicarbonate ions, followed by aeration to remove carbon dioxide; and filtration by active carbon to remove dissolved organic materials and chlorine compounds. Different anti-scalants are used in order to prevent precipitation of dissolved salts due to increased concentration. These are efficient against precipitation of $CaCO_3$, $CaSO_4$, $SrSO_4$, $BaCO_3$, but are less effective in the case of silica precipitation.

In order to allow the best ratio of the membrane area to operation volumes, two most convenient designs are made to fit the pressure vessels: spiral-wound and hollow-fibers membranes. Figure 1 shows a schematic presentation of an RO desalination plant. The process takes place in ambient temperature. The only electrical energy required is for pumping the water to a relatively high operating pressure. The use of special turbines may reclaim part of the energy. Operating pressures vary between 10–25 bars for brackish water and 50–80 bars for seawater.

High pressure is needed to allow sufficient permeation at relatively high concentrations of the concentrating brine along the membrane axis located in the pressure vessel. Water conversion can go as high as 90–95 percent in the case of light brackish water, down to 35 to 50 percent recovery in the case of seawater. Low recovery is obtained especially in a relatively closed sea, like the Red Sea or the Persian Gulf.

Increased water temperature, up to the membrane limitation, also increases flux through the membranes. This calls for increased efficiency by using hot seawater flowing from the cooling system of a large power plant. The water quality depends on membrane rejection properties, the degree of water recovery, and proper system design. Some relatively small molecules like carbon dioxide, hydrogen sulfide, silica, and boric acid may penetrate and pollute the water product. These problems can be solved either by aerating, using ion-exchanger and/or mixing the water to change the content, and dilute concentration. Small organic compounds dissolved in the feed water may also find their way to the product water. Product quality is fair. It depends on feed quality (brackish or seawater); salt content may vary between 100 to 600 ppm of total dissolved solids (TDS). This can be improved by using a secondary stage, which will increase the cost significantly, but is useful in cases where ultra-pure water is needed.

The RO technique is used usually for small and large plants, amounting to about 22 percent of the world's larger plants of capacity above 4,000m^3/day (Wangnick, 1996). RO systems can easily be integrated within other thermal desalination technologies, namely hybrid systems for efficient water production.

Electro-Dialysis (ED), or the more modern Reversible Electro-Dialysis (EDR), in which ions are forced to pass by means of DC electrical power through semi-permeable membranes into concentrated streams leaving behind dilute salt solutions, were considered to be a promising technique. This was mainly attributed to the relative insensitivity of the membranes for fouling, and due to the thermodynamic transfer properties of this technique. Unfortunately, the technique did not succeed in taking the naturally expected position among other processes. Currently, the technique is in use mainly for brackish water desalination and water purification (Thampy et al., 1999).

Nano-filtration (NF) membranes are used to partly remove heavy salts from water (Hassan et al., 1998). Ultra-filtration (UF) is the modern solution for removing bacteria and viruses from water. Micro-filtration (MF) membranes are used for removal of suspended particles and may provide good protection against *Giardia* and

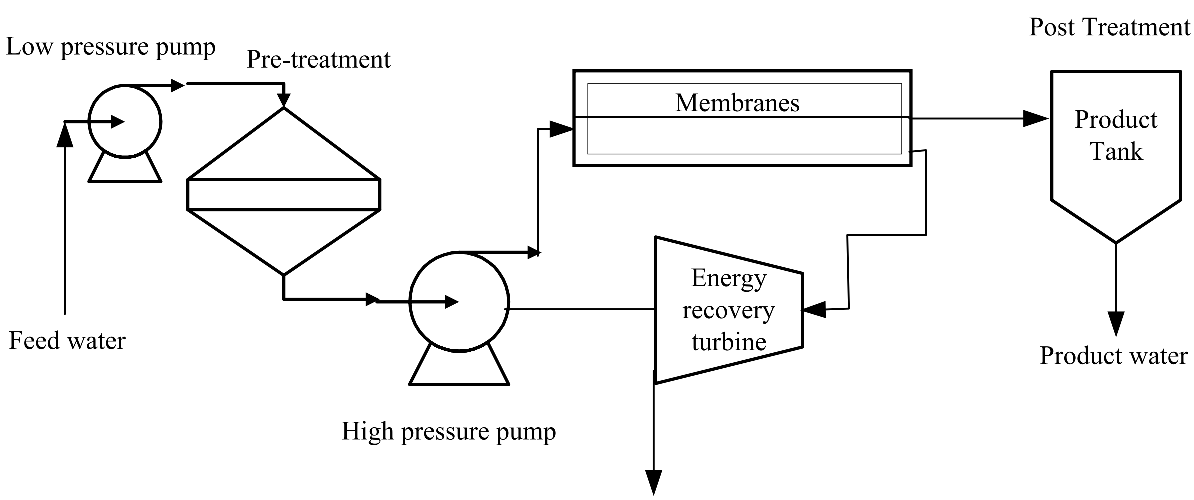

Figure 1. Schematic presentation of a reverse osmosis desalination plant.

Cryptosporidium as well as most viruses. EDR membranes are usually used to remove special salts like nitrates from waters. Some of the above mentioned membranes are used for pretreatment of polluted waters before RO desalination. Membrane processes gradually take their position in water quality, wastewater reclamation, cleaning of industrial waste solutions, etc. (Gagliardo et al., 1998; Johnson et al., 1997).

Thermal Desalination

Multi-Stage Flash

The MSF distillation is currently the most common and simple technique in use. It has operated commercially for more than 30 years (Awerbuch, 1997b). Figure 2 shows a schematic presentation of an MSF desalination plant. Pressurized sea water flows through closed pipes where it exchanges heat, with vapor condensing in the upper sections of the flash chambers. Water is then heated to a certain initial high temperature, using burnt fuel or external steam, and this allows flashing along the lower part of the chambers, from chamber to chamber under reduced pressure conditions. Vapor generated is allowed to flow through a mist eliminator to meet the condensing tubes, where heat is transferred to the heating feed seawater. The condensate drips into collectors and is pumped out as the plant product. Exhausted brine, concentrated in salt, is pumped out and rejected to the sea.

Part of the brine is recirculated with the feed in order to increase water recovery. The technique consumes high energy, as sensible heat and pumping. Increasing energy efficiency is a function of the number of stages involved, highest temperature of the preheated feed seawater, better heat transfer at the condensing vapor, better utilization of the heat rejected with the product and the rejected brine, controlling and preventing scale formation, prevention of accumulated non-condensable gases, etc. Corrosion is associated with the highest temperatures, existence of dissolved oxygen in the water, and the choice of materials for heat transfer surfaces.

The process is not very sensitive to the initial concentration of seawater. It is also not sensitive to suspended particles, and a simple straining-filtration technique is suitable. Acid and/or anti-scalants may be added to feed water for controlling scale precipitation. This is also an important advantage of the process over other distillation processes, since scale does not precipitate on heat transfer surfaces but within the chambers. Biocides are also used as a pretreatment to prevent microbiological activity. De-aeration is needed to remove oxygen and to reduce the possibility of non-condensing gas accumulation. The described pre-treatments are also suitable for most of the other evaporative desalination techniques.

The product of this technique has the common advantage of most evaporation techniques – water produced with about 50 ppm of TDS, due to drops carried by vapor. It is possible to produce better quality water, down to 10 ppm TDS. The by-product is aggressive and can cause corrosion. It is usually mixed with another source of wa-

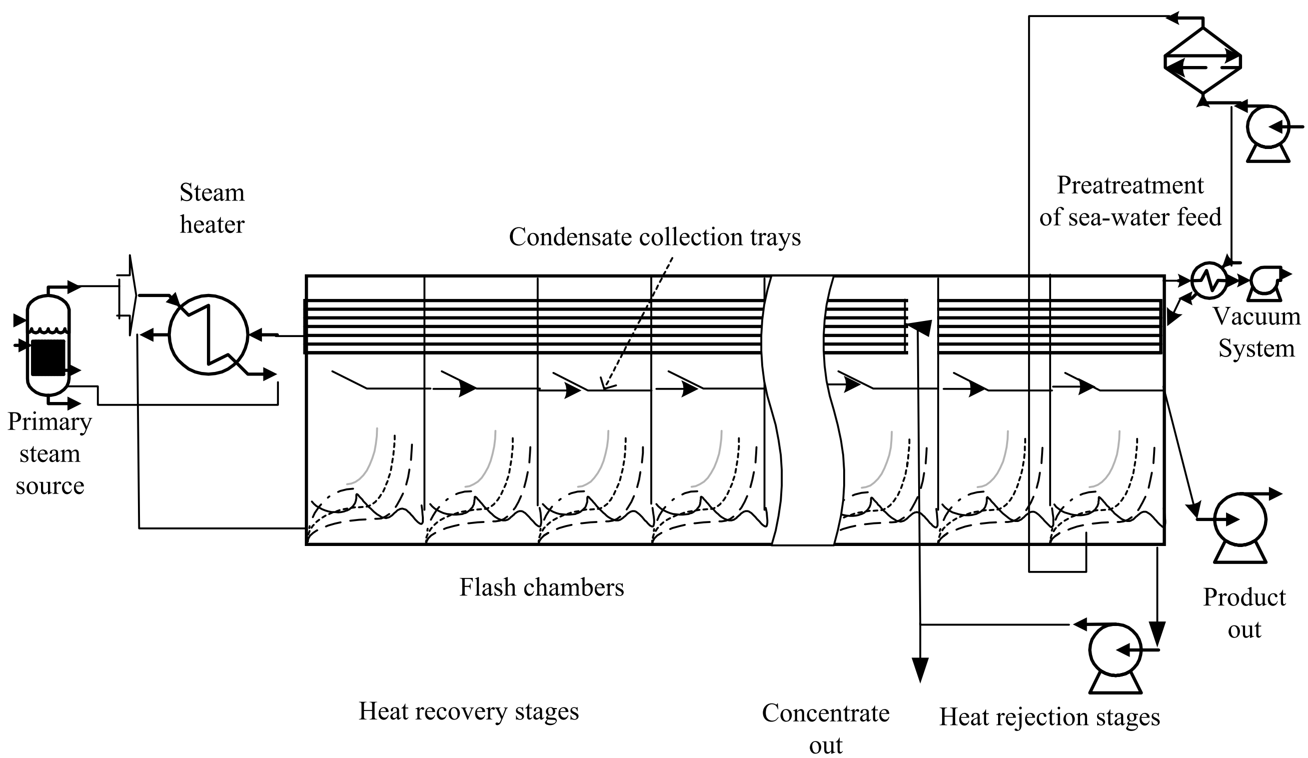

Figure 2. Schematic presentation of a Multi-Stage Flash desalination plant.

ter to control salt concentration and prevent corrosion.

Multi-Effect Distillation

MED is one of the most promising evaporation techniques existing today (Awerbuch, 1997b; Ophir and Weinberg, 1997). The concept of multi-stage evaporation is common in the chemical industry. It has been used for many years for solution concentration, crystallization, solution purification, etc. The process has been used for seawater desalination for the last 25 years. Basically, the method can use low-temperature, low-pressure steam as the main energy source. Steam from burnt coal or fuel can be used, as well as spent steam emerging at the outlet of a steam-operated power station.

The primary steam is used to evaporate heated seawater and to generate more steam at a lower pressure, while the primary steam condensate is taken back to the generation chamber, or to the steam generator of the power station. The secondary steam generated goes into a second stage to condense while transferring the latent heat to low-temperature seawater, flowing in falling film. The process is repeated as many times as the design permits, between the upper possible temperature and the lower possible cooling temperature, which depends on seawater temperature. The condensate is accumulated stagewise as the product water. A vacuum pump takes the remaining vapor after the last condensation stage, to maintain the gradual pressure gradient inside the vessel. Figure 3 describes the schematics of Horizontal Tubes MED unit.

MED operates usually on horizontal or vertical pipes where steam condenses on one side of the heat transfer surface while seawater evaporates on the other. This uses a double film condensing-evaporating heat transfer mechanism that is highly effective. Usually, eight to 16 stages are common in such operations. This allows a good performance ratio, namely the ratio of tons of water produced per ton of initial steam. The ratio in MED can go up to 15, while the corresponding ratio for MSF unit is limited to 10. Recently, a new design was proposed based on the vertical tower, initiated by the South California Water District, in cooperation with IDE Technologies LTD, Parsons and Reynolds Metals (Dean et al., 1995a, 1995b; Pepp et al., 1997; Weinberg and Ophir, 1997). The design is based on 30 stages of vertical fluted tubes, located in a tall concrete tower. Seawater evaporates on the inside surfaces of the tubes; as water falls down, the steam condenses on the outer side of the tubes. Feed water flows upward, using a single pump, in a different section between the tubes where part of the vapor is used to heat the water while rising. The higher temperature is obtained as in the MSF system, by using external heat. Using the right combination of tube materials for high and low temperatures, combining low cost aluminum as doubly fluted tubes, may reduce the area needed for heat transfer with low corrosion problems. The schematics of this design are shown in Figure 4. The designers claim to be able to produce freshwater at a cost of \$0.5/m^3, maintaining a performance ratio as high as 24.

The number of stages is essential for returning better energy utilization. In cases where low-cost heat at lower temperature is available, optimization of operation conditions may lead to a lower number of stages. A low temperature operation yields the ability to use low-cost materials without exposure to severe corrosion problems, while improving plant reliability. The efficiency of the process is also bound by high values of boiling point elevation at high concentrations.

Unlike the MSF technique where water is produced mainly by turning sensible heat into latent heat of evaporation, the MED technique uses latent heat to produce secondary latent heat in each section. The efficiency of production that may be obtained from a unit of feed water is essentially higher than that in the case of MSF distillation.

Different designs like a co-current or counter-current flow of seawater against the direction of the produced steam, can be found. These designs are also different in the path of the circulating brine in connection with the curves of calcium sulfate hydrates saturation vs. temperature. Co-current operation is convenient since the satura-

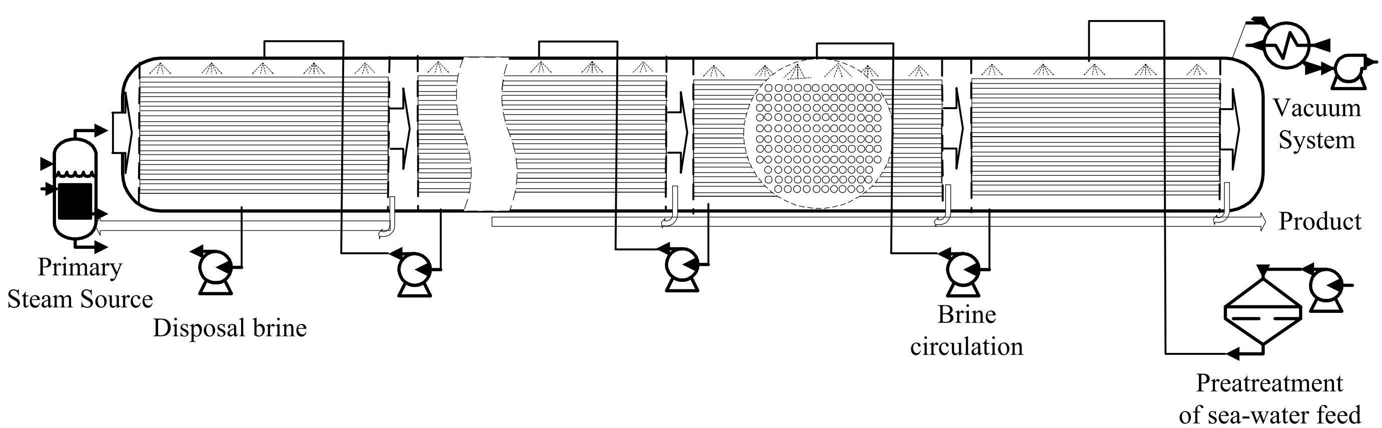

Figure 3. Schematics of a Horizontal Tubes Multi-Effect Distillation plant.

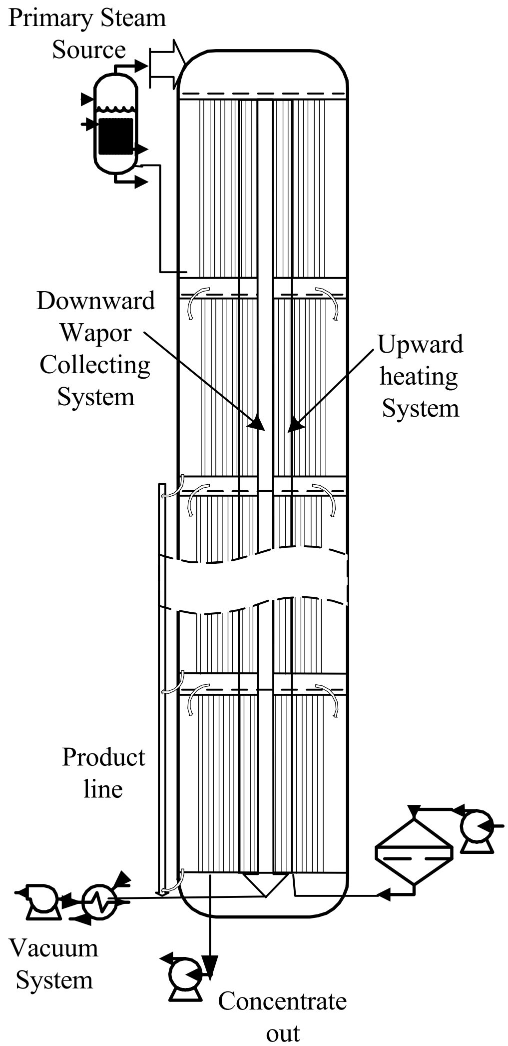

Figure 4. Schematic presentation of the new concept, tower multi-stage vertical tubes desalination plant.

tion level increases while water temperature reduces. In the countercurrent operation, the highest saturation is obtained at the highest temperature. This is an important question of scale control, and is also important in the case of water circulation and pumping expenses. The problem of water flow distribution on the heat transfer surfaces is also essential for fouling control. Co-current operation takes place in the MED-MWD tower design, where the highest temperature is obtained at the lowest concentration. In this design, the brine temperature-concentration curve along the tower is closed, almost parallel to the CaSO4 saturation-temperature curve.

Vapor Compression

The VC operates mainly at a small scale, on small locations (Awerbach, 1997b). The main mechanism is similar to MED except that it is based on compression of the vapor generated by evaporating water to a higher pressure, which allows reuse of the vapor for supplying heat for the evaporating process. Compression of the vapor may be carried out by using a mechanical compressor (the most common way), or by mixing with small amounts of high pressure steam (Thermal Compression).

Feed water is preheated against brine and the product leaving the system. Heat transfer usually takes place in the form of a double falling film, which is an effective heat transfer mechanism. The latent heat of the condensing vapor is used to make more vapor on the other side of the heat transfer surface, basically a "heat pump" process, so that the main need for energy is for elevating the pressure to provide the driving force by temperature difference.

The process takes place usually from one to three stages, thus the operating temperature may be chosen for the best optimization of the process. No external heat is needed for the mechanical compressor, so basically the technique relies on the electric power supply. Part of the water circulates to increase the water recovery. Figure 5 presents a schematic view of a mechanical VC unit. VC is considered to be the most efficient evaporation desalination process. The ability to operate at low temperatures makes it possible to use simple metals like aluminum, with almost no corrosion attack and safety from scale formation. The largest units available on the market can produce up to 5,000 m^3/day. The use of electricity makes the technique compatible for use in parallel with other desalination techniques, as hybrid operation for optimization of the energy consumption. A modern compressor presents efficiency of up to 80 percent. The quality of the product is similar to other evaporation techniques. The technique may also be used for part removal of salts that are at the saturation level, in case of low boiling point elevation.

Other Techniques

Significant efforts were invested in many techniques that did not survive the tough evolutionary path. It is important to mention at least some of them, as some are

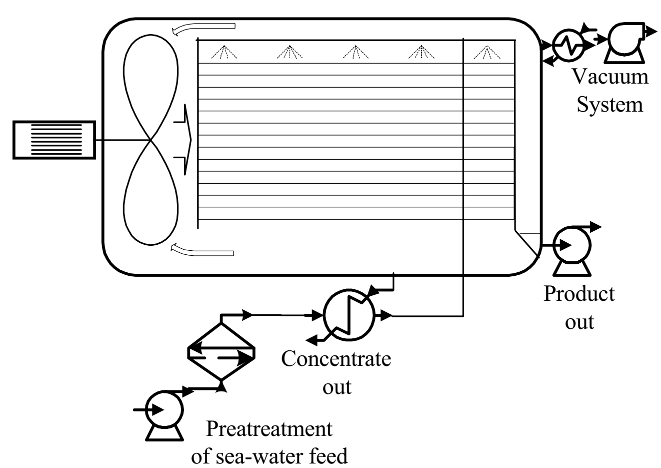

Figure 5. Schematic presentation of a horizontal tube, Vapor Compression desalination unit.

used small scales, and mainly because people tend to forget the old proposals and re-invent the wheel. The solar desalination still is not completely under this category, namely, the use of a transparent cover to allow sun radiation to heat directly a layer of water at the bottom of the still. Water evaporates and the vapor rises to condense on the cover. Condensing vapor accumulates as the product. One of the serious disadvantages of the solar still is that it needs about 250 m^2 to produce 1 m^3 of freshwater per day. This makes it inefficient even for the deserted arid zones, as this form of energy is available only one-third or one-fourth of the time. Different techniques are in use to enhance evaporation in order to reduce the ground area needed. Another form of solar energy that has been checked in the recent past is the solar pond, which may provide heat at a level of 90°C, or close. This method, based on a highly concentrated salt solution at the bottom of the pond that absorbs sunlight and does not mix with the upper layer of the diluted water solution, suffers from many technical problems as well as from low heat efficiency.

Solar cells can be used to supply electricity to run a VC or RO unit. There are different types of energy collectors, viz steam-producing parabolic mirrors, hot oil collectors, or chemical storage furnaces. Solar energy is expensive and therefore not normally used for electricity production. This is the main reason why it was not used in water desalination techniques. Without major improvements, solar techniques can only survive at low production scales in rare conditions, such as for desert communities, where no access to electricity increases the cost of water production or transportation.

Another promising technique is the freezing method, referred to for producing water by precipitation of ice from solution, usually by extraction vapor. The ice formed is free of salts, remaining in the mother liquor. The process can take place close to the triple point where vapor, liquid, and ice may coexist. This was implemented with water vapor as well as with low vapor pressure organic solvents at low temperatures. The freezing technique was proven recently as an adequate technique for a high-capacity ice machine for large cooling and air-conditioning systems.

Different techniques of water extraction using organic solvents, low vapor pressure solvents for freezing, production of clathrates, removal of water from humid air, etc., did not make it either.

Energy Aspects

Optimization of a stand-alone desalination plant yields a relative cost of energy in the range of 30 to 50 percent of the produced water cost. This depends on the cost of energy on the spot, either as electricity or as heat. At a regular cost of electricity, for example, processes using mainly electrical power will consume the lowest available energy cost, like energy from fossil fuel. This is why a single commercial desalination plant was not based on any other source of energy.

Many researchers and organizations try to relate desalination to renewable energy sources, nuclear energy, solar energy, wind, etc. This tendency increases due to the current trend to reduce atmosphere emission of CO_2 from burnt fuel, in a goodwill to minimize the greenhouse effect. This is also an important issue that needs to be examined, but not at the expense of the desalination processes. The combination of the search for new forms of energy and desalination is fatal for the latter and will cause many delays in utilizing the proper techniques.

No doubt more effort should be devoted towards the use of renewable sources of energy. The real test, however, for any new source of energy is its acceptance of electricity production or other common use of energy. Saving on CO_2 emissions needs to be made on other forms of energy uses and not on such a delicate issue as desalination for freshwater production. Using nuclear energy, which is currently more expensive than fossil energy, is dangerous in areas where political instabilities exist. It is also problematic where technology is not accessible and must relayed to imported, trained, and sophisticated manpower. Photo-voltaic cells need not only a large investment but also a large collecting area.

There is a claim to benefit from the day-night, summer-winter electricity production cycle, namely to produce desalinated water during the night when lower power is consumed. The main disadvantage is that the desalination equipment will be idle a large percentage of the time. This is wrong, since as in any modern plant, production costs are higher if the equipment is not in full use. In other words, an efficient desalination plant needs to be operated around the clock, 24 hours a day, 365 days a year, with exceptions for maintenance only. During this time, it needs a full supply of energy, at the lowest cost.

Since energy is so important in desalination, a few directions on possible energy usage may significantly reduce desalination costs.

Use of spent energy from large steam power plants: the dual cycle. Every steam cycle power station purges large amount of energy at the condensing stage right after the turbine. This heat may be combined with a thermal desalination technique in order to supply the primary steam, as in MSF and MED (Awerbuch, 1997b). The problem is that efficient power stations release the exhausted steam at around 35–40°C, which is too low for the proper operation of the desalination plant. Instead, it is possible to release the steam at elevated pressure and temperature, using back-pressure turbines, that will fit the desalination plant needs. This will cause some loss of production on the power generation side. This calls for integration and optimization of the two processes together, which are very difficult to perform if two different authorities are involved for power and water production (El-Nashar, 1997). This type of hybridization was successfully employed in for

Persian Gulf countries when the same authority controlled the two industries.

Desalination dedicated power plants. In order to best utilize the energy, it is better to operate a dedicated power station that can produce electricity and heat. The heat, either in the form of rejected steam or hot gases, can be used for thermal desalination, while electricity production can serve either large RO units or several VC units (Awerbuch, 1997a). This mix of such processes in desalination is called the hybrid process, and it is common in the chemical industry. Such a dedicated power station can produce electricity at lower, reliable costs. The total water production cost will be reduced significantly.

Increase production scale and maintain the best energy utilization schemes. This is always true, yet needs to be emphasized.

Environmental Aspects

Desalination processes may be characterized by their effluent to the environment, the air, the nearby land, and to the seas. Desalination is dependent on energy and usually uses fossil energy. All types of air pollution associated with energy production, namely emission of NO_x, SO_2, volatile compounds, particulate, CO_2 and water exist here as well, either by using electricity produced by a conventional power station or by using a dedicated power station.

Effluents of desalination plants contain relatively highly concentrated water, which depends on the water recovery from the feed brine. In the case of seawater desalination, rejected brine is concentrated close to twice the original sea water solution. The concentrate also contains chemicals used in the pretreatment of the feed water. The latter may contain low concentrations of anti-scalants, surfactants, and acid. To this may be added occasional washing solutions or rejected backwash slurries from feed water. In small operation scales, the problem is mild and no serious damage may affect the marine life. In large scales of water production, the problem is a little more severe; however, dilution and spreading of effluents may solve the problem. Natural chemicals that do not harm the environment will probably replace the added chemicals in the future.

The more serious problems are those concentrates produced inland, in cases of brackish water desalination. The concentrate composition in these is not similar to seawater composition. In most cases the solution contains more calcium and magnesium, and sometimes other components are involved, depending on the composition at the source. The problem is less severe when the solutions are purged into the open sea. Where no access to the sea is possible, the concentrate may increase groundwater salinity if allowed to penetrate the earth. A possible solution to that problem includes zero discharge treatment, namely evaporative separation between solids and water, so solids may be stored properly inland. This solution may be performed by solar ponds or by forced evaporation using available heat sources. The process is expensive, but the basis for comparison is the cost of brine transportation to the nearest possible authorized area, taking into account the influence of this treatment on the product cost.

Quality of Water Produced

Water produced by the different techniques mentioned varies significantly in quality. Thermal processes may produce water containing five to 50 ppm of TDS, similar in composition to the feed seawater. The RO product may contain 300 to 500 ppm of TDS, basically NaCl and a smaller portion of other salts. Some minor constituents as boric acid, hydrogen sulfide, and CO_2 can also be present in the product, depending on the composition of the feed water, but may be removed by adequate post-treatment. It is important to mention that feed water containing dissolved volatile organic compounds will generate water contaminated with the same components, unless special care is taken. This is true for RO and evaporation techniques.

The product water is aggressive, tends to corrode iron pipes, and dissolves protective layers containing calcium and other salts on the inner sides of the mains. The water needs, therefore, post-treatment that usually includes an increase in the pH level, addition of Ca (to the level of about 100 ppm as $CaCO_3$) and alkalinity, namely HCO_3^- (also to a level of about 100 ppm as $CaCO_3$), according to local water regulations.

Desalination Techniques for Water Quality

The development of membrane modules gave a boost to the use of membranes in water purification and treatment. Wilbert et al. (1998) described various treatments available for surface water and other sources. Nano-filtration membranes are used for the removal of hardness from drinking water (Bergman, 1995; Hassan et al., 1998a, 1998b). They can also be used to remove some other unwanted dissolved species, even partial removal of nitrates from ground water. Ultra-filtration and micro-filtration can be back-washed occasionally to remove accumulated solids from the membranes. While MF can be used to remove micron size and upper suspended particles, namely bacteria, algae, etc., UF membranes can also be used to remove most of the viruses found in surface water. In fact, the solid layer, the "cake" that adheres to the membranes in the last two techniques, acts like a dynamic membrane and removes smaller particles even at a level of colloids and viruses. The use of MF membranes might be cheaper than sand filtration in the treatment of surface water. Lyonnaise Des Eaux, the international water company, uses UF membranes combined with active coal and sedimentation stages to purify polluted Seine water for drinking purposes (Baudin et al., 1997).

The use of membranes penetrates into the process industry, where better water quality is needed. Power stations and petrochemical and high-tech production plants seek better quality water and use different types of membranes to meet their needs.

Uses for Sewage Treatment

Membranes penetrate also into wastewater treatment. Many projects at a pilot stage use membranes to treat the water (Gagliardo et al., 1998). In some cases MF membranes are directly used on strained wastewater to remove suspended particles that are too large for the gap between two membranes (Johnson et al., 1997). The treated water is transferred directly to RO membranes to remove salts. Permeate is usually allowed to pass across active coal in order to remove remaining dissolved organic materials. In other cases RO membranes are used to treat effluent after secondary treatment, just to remove most of the remaining dissolved solids.

Economy of Modern Desalination Projects

Awerbuch (1997b) reports that in 1971, the total worldwide desalination capacity was 1.5 million m^3/day. Wangnick (1996) reports that 24 years later, namely at the end of 1995, the worldwide total capacity went up to 20.3 million m^3/day, in about 11,000 installations spread in 120 countries all over the world. The Persian Gulf Cooperation Council States have installed about 50 percent of world capacity, and they have arrived at a saturation level, so not many new units are currently built in this region.

The Kingdom of Saudi Arabia has the largest world capacity, about 30 percent of the total (Awerbuch, 1997b). The world's largest plant is located in the Al Jubail Phase II complex, which has produced since 1982 close to one million m^3/day using the MSF technique. This is followed by the production of 1,300 MW of electric power. About 1,900 units are installed in the USA, having a capacity of over 15 percent of the world's production. In the USA, most of the production is based on RO systems, to treat mainly brackish and surface water.

Figure 6 represents the trend in cost reduction in this industry. The relative cost of spiral-wound membranes since 1980 is shown to decline by more than 60 percent. The membrane industries have grown in the last decade by more than 20 percent per year. The decline in the production cost of spiral-wound membranes occurs despite the fact that the use of membranes is constantly increased (Wangnick, 1998; Furukawa, 1997) and membrane performance continues to improve. The membranes will be significantly improved in the future, and their price probably will continue to decline.

Figure 7 presents a different aspect than Figure 6, but

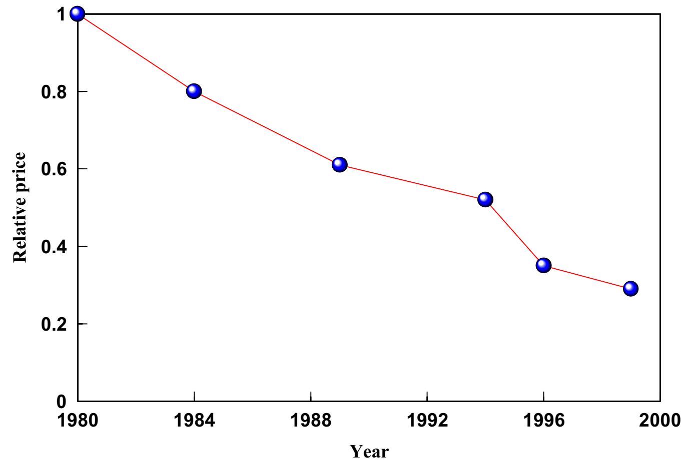

Figure 6. Cost trend of spiral-wound membranes modules.

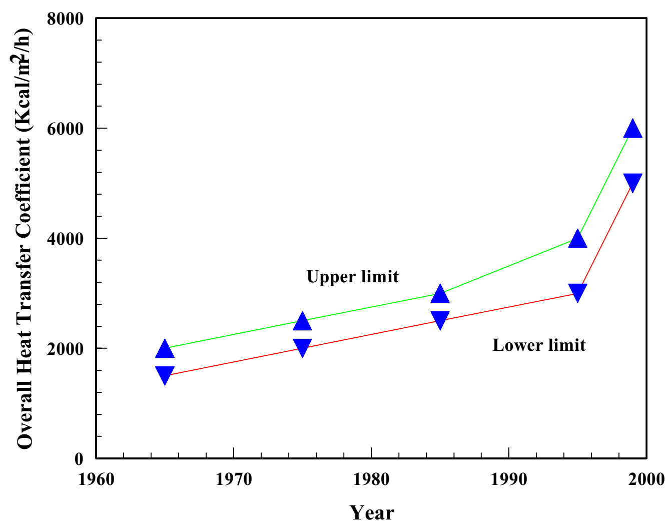

Figure 7. Trend of heat transfer improvements in Horizontal Tubes Multi-Effect Distillation (recent points refer to experimental pilot unit with verticle double fluted tubes).

the significance is similar. The values of the heat transfer coefficient in commercial units of MED systems are improving with time (Ophir and Weinberg, 1997). The significance of this trend is related to further developments and improvements of the flow and heat transfer mechanisms, with more attention to effects of non-condensable gases within the vapor streams, etc. Alfa Laval Technologies announced their recent development based on plate heat exchangers, to improve heat transfer for MED and VC plants. This brings a significant reduction in the heat transfer area needed per unit of water produced, smaller vacuum operated vessels that, in turn, lead to lower water production costs.

The cost differences between the techniques are well illustrated in Table 1. The common production costs together with specific installation costs are shown in the table. The three columns marked by an asterisk represent recent reported numbers from the latest development re-

Table 1. Cost Comparison for Different Desalination Techniques

		MSF	*MSF (Singapore)**	*MED*	*MED-MWD**	*VC*	*RO*	*RO-Tampa Bay**
Installation costs	$/m^3/day	1,200-1,500	2,300	900-1,000	660	950-1,000	700-900	1,000-1,350
Product costs	Cents/m^3	110-125	150	75-85	46	87-95	68-92	45-56

*Estimation, based on publications or recent proposals.

ported: RO in Tampa Bay, Florida (Leitner, 1999), MSF in Singapore (Leitner, 1998d), and the MED tower of the MWD (Dean et al., 1995b). The differences are quite significant and self-explanatory. The cost of the MSF project is high and so is the product. RO and MED present similar production and specific investment costs. The specific investment of the MED-MWD tower is significantly lower. Among the reasons for low costs of the Tampa Bay project are the convenient financing terms – (30 years and low interest) and low cost of electricity. The MED-MWD tower is based on known, but never used, technologies and on 65 percent recovery from seawater – this was never accomplished.

Different companies presented calculations of the Tampa Bay project, and their results are similar (Leitner, 1998a,b,c). Table 2 presents the cost of water produced in the project, from the viewpoint of different bidders. Again, the main point is that with proper attention, water cost can be significantly reduced.

Figure 8 presents a typical picture of the expenses for RO. As stated before, energy takes about 40 percent of the total cost. Regularly, electrical energy is considered at a cost of six to seven cents/kW. The cost of a regular power station takes into account the daily and seasonal changes in production. A dedicated power station for desalination will produce electricity at a significantly lower cost, say about four cents/kW. This is known and occasionally used in the process industry when large electrical consumption is needed. The use of a dedicated power station is possible only in large installations, again, a benefit for plant scale. Figure 9 presents similar cost-share for the MED-MWD tower desalination technique (Dean et al., 1995b). The energy analysis is similar, since in this particular design, the energy comes from spent power-plant steam. Similarity exists also in the other parameters, as can be seen below.

The second large portion of the cost is the part of the equipment. In the case of an RO unit, this may be divided between the cost of membranes, pressure vessels, low and high-pressure pumps, energy recovery turbine, and pre-treatment stages, including large area media filtration. In the case of evaporation techniques the items are heat transfer surfaces, vacuum vessels, pumps and vacuum pumps, piping, etc. As the list is large, no significant cost reduction of any of the mentioned parts will significantly affect the total cost. However, improvement of the pre-treatment stages, the membrane performance in flux and salt rejection, the pump and turbine efficiency, and the heat transfer surfaces in evaporation techniques will definitely reduce the total cost of the produced water.

Feed waters to a desalination plant pass a certain pre-treatment before the actual process takes place. In most techniques, the main constraint of the energy used is independent of the recovery ratio. This is the most important point to understand; namely, after treating the feed and recovering the water, the plant still rejects concen-

Table 2. Developers' Nominal Costs for Desalinated Water, Tampa Bay Project (using tax exempt financing), 94,625 m^3/d.

Developer	*First Year Cost $/m^3*	*30 Years Average Cost $/m^3*
Florida Seawater Desalination Company	0.54	0.65
Florida Water Partners (Parsons & IDE Technologies)	0.53	0.60
Progress Energy Corp. Ionics Partnership	0.56	0.67
Stone & Webster - TIC - Citizens Utiliies	0.45	0.55

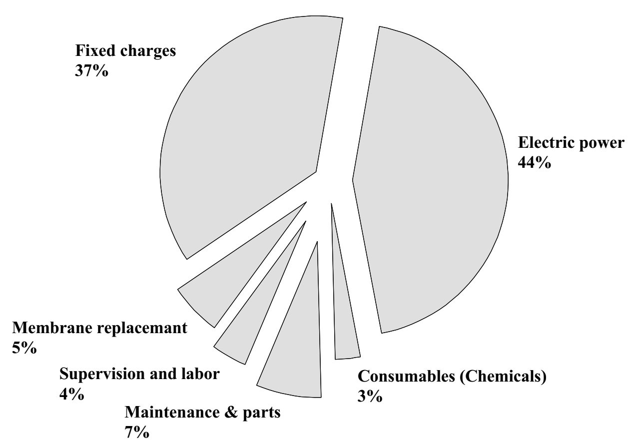

Figure 8. Typical Sea Water Reverse Osmosis water cost.

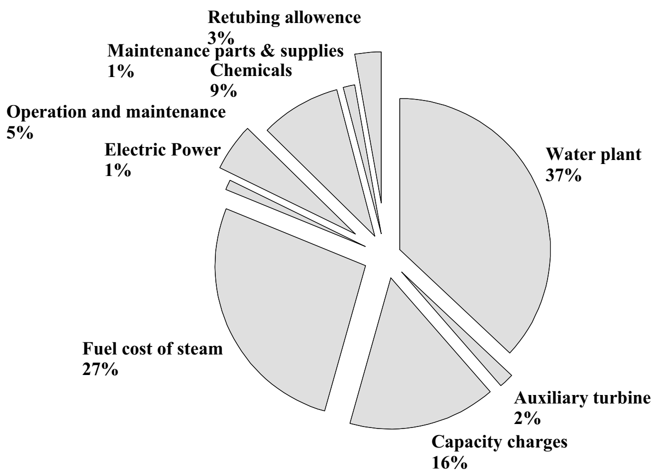

Figure 9. Cost parameters of the MWD tower MED desalination design.

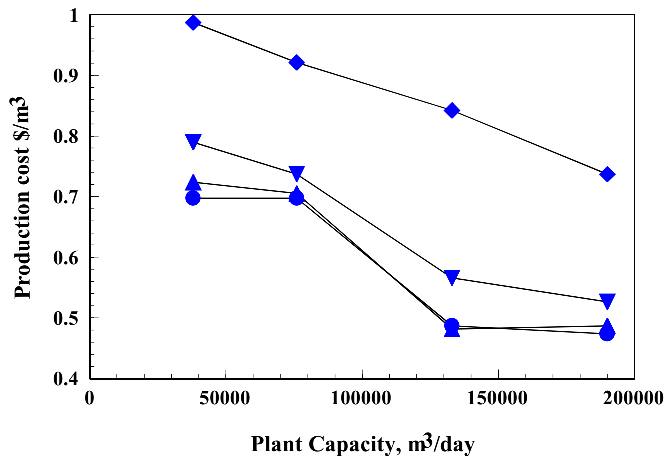

Figure 10. Water cost dependence on plant production. Cost calculation for the four runners-up bidder at the Tampa Bay project. RO seawater desalination.

trated brine that contains usable water. In other words, increasing the efficiency of the process by increasing the recovery ratio is a key factor in major cost reduction.

The analysis of a desalination performance is complicated due to the many parameters involved. Examination of operated systems (Leitner, 1995) can make the best and accurate analyses. However, most producers are not willing to release this information. A good estimation may also be obtained from open contests on large projects. Figure 10 presents an analysis made by the four runner-up bidders at the Tampa-Bay project (Leitner, 1998b). This is a good demonstration of the effect of plant size on the production costs. It is clear that the larger the plant size, the lower will be the price the consumer will have to pay.

Future Directions

There is no doubt that desalination techniques even now being matured to produce water on a commercial basis are still climbing on the learning curve. Each new development reduces the cost and takes a further step. It is important to continue the investment efforts in Research and Development (R&D) programs in order to continue and reduce the cost of water production. The key is to invest in new plants, increase the free competitions between producers, and cooperate with research institutes. A few possible directions for future R&D are listed below.

The mechanism of water transfer and salt rejection in RO membranes is not clearly understood. Better understanding at the molecular level will lead to new membranes that may show higher fluxes and better salt rejection.

It is evident that the most expensive steps in membrane operations are independent of water recovery. Increasing water recovery is therefore a key for reducing water production costs. Operation of systems with untrained, inexperienced workers increases the need for expensive safety factors, like extra pre-treatments. Better-trained operators and more sophisticated automation and control may result in lower cost of water production.

The VC and MED techniques produce better water quality than the RO process. The two techniques need further development, to improve heat transfer surfaces, reduce equipment size, and improve energy efficiency. Again, more research work is needed.

The energy question is very important, not only for desalination but also for future general energy needs, and in terms of environmental problems. It is necessary, therefore, to continue with international efforts toward revolutionary new renewable sources of energy, which in due time will also be used for desalination.

The implementation of water desalination in existing water systems is a complicated issue that needs strong, intelligent policies. Needs for new water resources are severe in many locations on earth on one hand, but the cost is still high in comparison with common water supplies. It is easier to introduce desalinated water into developed cities where people pay almost threefold or more than the cost of desalination for their water uses. Usually those locations do not suffer from water scarcity. Water is needed in locations where agriculture is still the basis for life, and simple agriculture cannot afford the costs described here. It is a global question of the same type as the usage of energy resources and solutions for environmental problems. The future of mankind depends on proper answers related to those questions, together with the questions of global peace and human wealth on earth. At the moment, without international acts, only local solutions may be given for the water problems.

In the meantime, to summarize and induce a general framework for possible research directions in different desalination directions, a methodical evaluation of R&D needs for achieving meaningful desalinated water cost reductions is presented below.

Reduction of Desalination Energy Requirements

- Develop concepts and schemes for optimal integration, by cogeneration or otherwise, of various energy sources and desalination technologies.
    (a) Hybrid systems.
    (b) Solar energy integration.
    (c) Desalination dedicated power plants.
- Identify novel schemes for improving desalination processes and/or energy recuperation.

Improvements in Current Thermal Technologies

- Develop improved designs and manufacturing technologies for heat transfer bundles and containment vessels that reduce investment costs.
- Develop improved pretreatment methods for controlling scaling, fouling, and bio fouling.
- Consider proposals for increasing heat transfer coefficients to reduce heat transfer areas.
- Improve plant performance through advanced control tools.

Improvements in Current Membrane Technologies

- Develop membranes achieving better performance at reduced permeation pressures.
- Develop an improved methodology for achieving optimal pretreatment.
- Improve the resistance of membranes to oxidizing agents.
- Enhance possibilities of integrating micro and ultrafiltration in feed pretreatment.
- Extend membrane lifetime.
- Improve membrane salt rejection.
- Reduce membrane compaction.
- Develop higher efficiency pumps and energy recovery turbines.

Integration of Desalination Into the Overall Water System

- Widen the scope of water reuse through membrane technologies.
- Focus on processes enabling exploitation of polluted streams.
- Investigate supply and demand curves for water of different qualities by various consumer groups or industries.
- Investigate the effect, of integrating desalination, in varying degrees, in national and/or regional water systems on the supply and demand for water.
- Develop new concepts for optimal desalination-oriented water supply systems.
- Integration of desalinated water into modern agriculture.

Reduction of Environmental Problems Associated with Brine Disposal

- Development of the zero-discharge concept.
- Development of natural pre-treatments additives.

Conclusion

It is clear that the water desalination industry is currently at an important stage, where the need for water availability and quality is increased in many places. The production cost is declining due to healthy competition, while performance is improving along with production efficiency. No arguments are needed with respect to the quality of the water; the main struggle is still the cost of the production. It is clear, however, that the cost of water is steadily declining so that more people can afford desalination. A small barrier must still be broken in order to facilitate the use of desalinated water in modern agriculture. This too is close to being achieved in the near future.

In order to achieve these targets, significant international research and development efforts are needed. A few international organizations exist that are devoted to these tasks; however, more effort is needed, especially along production lines, for building operating plants, water factories, producing freshwater, and further reducing the cost of water. Future developments do not need to concentrate only on technical aspects. Looking at the global picture, it is important to pay attention to the environment, namely to produce fresh and clear water without causing harm to the surroundings. Therefore, new developments in renewable energies are needed, independently with current and near-future desalinated water production. New techniques are needed to overcome the current pollution-causing aspect of the processes. Desalination techniques will also serve as important tools in the reduction of pollution from waste industrial solutions.

Finally, it is time for an international act to achieve direction and means to benefit from all new developments, together with acts that have already started in relation to energy use and environmental issues to ease the implementation of new sources of water, including desalination, for improving life on earth and reducing fights and wars.

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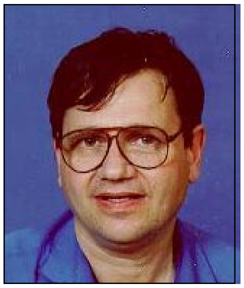
About the Author



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References

Awerbuch, L. 1997a. "Dual Purpose Power Desalination/Hybrid Systems/Energy and Economics." IDA Desalination Seminar, Cairo, Egypt, September.

Awerbuch, L. 1997b. "Current Status of Seawater Desalination Technologies." IDA Desalination Seminar, Cairo, Egypt, September.

Bergman, R.A. 1995. "Florida – A Cost Comparison Update, Membrane Softening Vs Lime Softening." *International Desalination and Water Reuse* 5, No. 3: 35–43.

Baudin, I., M.R. Chevalier, C. Anselme, S. Cornu, and J.M. Laine. 1997. "L'Apie and Vigneux Case Studies: First Months of Operation." *Desalination* 113: 273–275.

Dean, D., R.P. Hammond, D.M. Eissenberg, D.K. Emmermann, J.E. Jones, H.H. Sephton, F.C. Standiford, R.E. Scott, and W.J. Rider. 1995a. "Seawater Desalination Plant for Southern California: Part 1." *International Desalination and Water Reuse* 5, No. 1: 10–16.

Dean, D., R.P. Hammond, D.M. Eissenberg, D.K. Emmermann, J.E. Jones, H.H. Sephton, F.C. Standiford, R.E. Scott, and W.J. Rider. 1995b. "Seawater Desalination Plant for Southern California: Part 2." *International Desalination and Water Reuse* 5, No. 2: 19–24.

El-Nashar, A.M. 1997. "Energy and Economic Aspects of Cogeneration Plants for Power and Fresh Water Production." IDA Desalination Seminar, Cairo, Egypt, September.

Faller, K.A. 1999. "Reverse Osmosis and Nanofiltration." *AWWA Manual of Water Supply Practice*, M46.

Furukawa, D.H. 1997. "A Review of Seawater Reverse Osmosis." IDA Desalination Seminar, Cairo, Egypt, September.

Gagliardo, P., S. Adham, R. Trussel, and A. Olivieri. 1998. "Water Purification via Reverse Osmosis." *Desalination* 117: 73–78.

Hassan, A.M., M. AK. Al-Sofi, A. Al-Amoudi, T.M. Jamaluddin, A.G.I. Dalvi, N.M. Kitner, G.M. Mustafa, and I.A. Al-Tisan.1998a. "A New Approach to Membranes and Thermal Seawater Desalination Processes Using Nanofiltration Membranes: Part 1." *International Desalination and Water Reuse* 8, No. 1: 53–59.

Hassan, A.M., M. AK. Al-Sofi, A. Al-Amoudi, T.M. Jamaluddin, A.G.I. Dalvi, N.M. Kitner, G.M. Mustafa, and I.A. Al-Tisan.1998b. "A New Approach to Membranes and Thermal Seawater Desalination Processes Using Nanofiltration Membranes: Part 2." *International Desalination and Water Reuse* 8, No. 2: 39–45.

Johnson, W.T., R.W. Phelps, P.J. Beatson. 1997. "Wastewater Reuse Using Membranes." IDA World Congress on Desalination and Water Science, Madrid, October.

Leitner, G. 1999. "Developer Selected for 25MGD (94,625m3/d) Florida West Coast Seawater Desalting Plant." *Desalination and Water Reuse* 9, No. 1: 11–16.

Leitner, G.F. 1998a. "Updates on the Tampa Bay Projects*." International Desalination and Water Reuse* 7, No. 5: 14–20.

Leitner, G.F. 1998b. "Updates on the Tampa Bay Projects*." International Desalination and Water Reuse* 8*,* No 2: 58–60.

Leitner, G.F. 1998c. "Updates on the Tampa Bay Projects*." International Desalination and Water Reuse* 8*,* No 3: 12–13.

Leitner, G. F. 1998d. "Vibrant, Prosperous, Singapore, Time for Seawater Desalination?" *International Desalination and Water Reuse* 7, No. 4: 10–21.

Leitner, G.F. 1995. "Water Cost Analysis… We Need To Do Better*." International Desalination and Water Reuse* 5, No. 1: 24–27.

Ophir, A. and J.Weinberg. 1997. "MED (Multi-Effect Distillation) Desalination Plants: A Solution to the Water Problem in the Middle East." IDA World Congress on Desalination and Water Science, Madrid.

Pepp, F., L. Weinberg, D. Lee, A. Ophir, and C. Holtyn. 1997."The Vertical MWD-MED (Multi-Effect Distillation) Process." IDA World Congress on Desalination and Water Sciences, Madrid, October.

Thampy, S.K., R. Rangarajan, and V.K. Indusekhar. 1999. "25 Years of Eletrodialysis Experience at Central Salt and Marine Chemicals Research Institute Bhavnagar, India." *International Desalination and Water Reuse* 9, No. 2: 45–49.

Wangnick, K. 1996. "1996 IDA Worldwide Desalting Plants Inventory Report No. 14. Privately published.

Wangnick, K. 1998. "New IDA Worldwide Desalting Plants Inventory Report No. 15 – 55% Higher Sales and Dramatic Changes in Market." *International Desalination and Water Reuse* 8, No. 2: 11–12.

Weinberg, J. and A. Ophir. 1997. "Ashdod Experience and Other Dual Purpose Desalination Plants Based on Multi-Effect Desalination with Aluminum Tubes." Symposium of Desalination of Seawater with Nuclear Energy, Taejon, Korea, May.

Wilbert M.C., F. Leitz, E. Abart, B. Boegli, and K. Linton. 1998. "The Desalting and Water Treatment Membrane Manual: A Guide to Membranes for Municipal Water Treatment." 2^{nd} Edition. *Water Treatment Technology Program Report No. 29*. Bureau of Reclamation, United States Department of Interior.