Desalination at a glance

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Background and Introduction

Foreword

Since its formation, the International Desalination Association (IDA) has offered educational materials to interested non-specialists. The most popular example has been "The ABCs of Desalting", authored by Dr. O.K. (Kris) Buros and first published in 1990 and updated periodically through 2000. In 2010, the Publications Committee of IDA decided that enough changes had occurred in the technology and practice of desalination that "The ABCs" should be replaced by a new and separate publication rather than undergoing a simple revision. "Desalination at a Glance" focuses on the story of desalination to date and issues and trends into the future. While unsuccessful attempts to desalinate water are often a good story and hold valuable lessons, space is limited. The emphasis is on technologies that have been successfully commercialized. Emerging technologies are identified, but only time will determine their commercial success.

Introduction

By desalination, we will be referring to the production of a useful product water from a feed water that is too high in inorganic materials (salts) to be useful. The feed water may be seawater, brackish water, or other "impaired" water that cannot be used directly for potable or general industrial purposes. Notice that this definition includes the treatment of certain wastewaters for subsequent reuse.

The principal technologies used in desalination are based on concepts that are fairly easy to grasp by those with a modest amount of scientific training and/or technical experience. In practice, however, choices of technology and plant design are usually determined by factors that might appear minor to the inexperienced. Similarly, new technologies that show great promise in the laboratory frequently fail for reasons that were earlier overlooked or dismissed as trivial. Indeed, professional fascination with specific technical elegance has, in some cases, led researchers to remain oblivious to inherent limitations of a process. Nonetheless, attention to detail over the past five decades has resulted in dramatic reductions in capital and operating costs as well as greatly increased plant reliability and performance.

All desalination processes have certain things in common, including some terminology. This is a good place to start.

Water concentration – The concentration of salts in water is usually expressed as parts per million (ppm) of total dissolved solids (TDS). "Standard seawater" is about 35,000 ppm TDS or about 3.5% TDS. In the field, seawater may often vary from 20,000 to 55,000 ppm or even beyond. Brackish waters usually fall between 1,500 and 20,000 ppm. The World Health Organization recommends that drinking water contain no more than 500 ppm TDS. The best high quality municipal water can be as low as 50 ppm. Water for industrial purposes may need to be considerably more pure.

Recovery – This term is used to describe that portion of the input water to a desalination plant that is converted to product (fresh) water. For example, if a plant produces 100 units of fresh water for every 300 units of seawater input, it is said to have 33% recovery. High recovery minimizes feed water requirements and hence pumping and pretreatment costs. It is also important when the feed water source is limited.

Brine concentration factor – The plant described above produces (and must dispose of) 200 units (300 – 100 units) of a more concentrated stream (brine). This means that virtually all of the salts contained in 300 original units of feed water must now be packed into only 200 units of brine. The concentration of the brine must thus be 300/200 = 1.5 times the concentration of the feed water. A high recovery rate implies a high brine concentration factor. This may lead to problems with precipitation, scale formation, and disposal (see following sections).

Rejection – If the same plant takes in seawater at 35,000 ppm and produces a fresh water product of only 350 ppm, it is said to have a rejection of (35,000 – 350)/35,000 = 0.99 or 99%. That is to say that 99% of the TDS in the incoming feed water has been rejected and remains in the brine. (Obviously recovery, brine concentration factor and rejection are interrelated. If you know any two, you may easily calculate the third.)

It is also useful to note that desalination equipment is now commercially available in a range of capacities from 6 gallons/day (GPD)(0.022 m^3/day) to about 25 million GPD (95,000 m^3/day) per single operating unit. Obviously, it is dangerous to make too many generalizations over such a broad range of feed and product water qualities and equipment sizes.

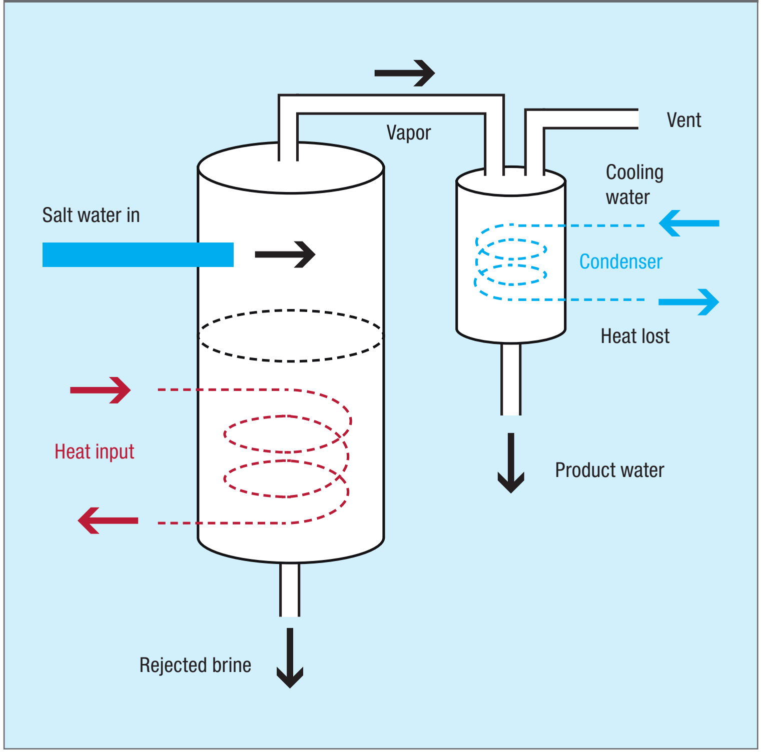
Chronological Introduction to the Core Technologies

Probably the best way to understand the basic desalination technologies is to treat them in the chronological order of their appearance. In that way, the logic behind their development is clear.

Simple Stills (SS

For many centuries, it had been known that fresh water could be produced from seawater by simple distillation in a device consisting basically of a boiler to generate steam and a condenser to produce water from that steam. Figure 1 indicates the features of such a system. Heat (often from steam) is added to the feed water to raise it to the boiling point. Then additional heat (the heat of vaporization) is added to convert the hot water to steam at the same temperature. (The heat of vaporization may be 6-7 times the heat needed just to raise the water to its boiling point.) This heat of vaporization is then lost to the cooling water (or air) used to condense the steam. High energy consumption limited the use of simple stills (SS) mostly to emergency situations.

Figure 1. A Simple Still (SS)

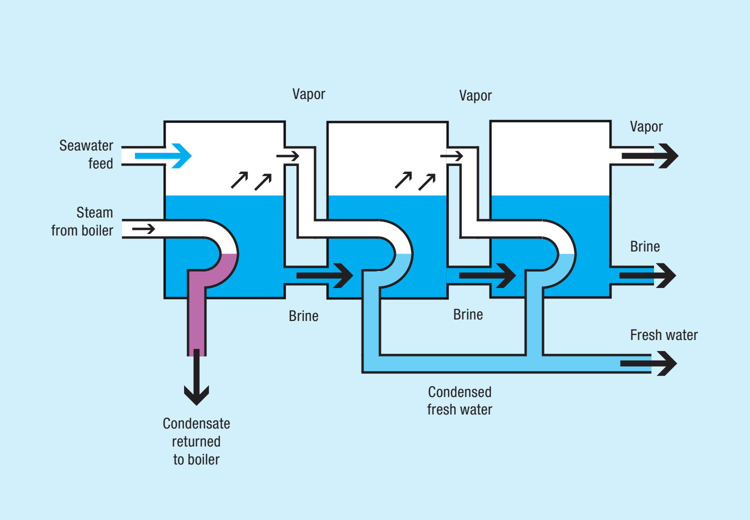


Multi-Effect Distillation (MED)

By the early 19th century, understanding of the nature of heat and steam had increased considerably. For example, it was now known that the boiling point of water was lower at reduced pressures. This led to the idea that in a modified still, the heat released during condensation of the steam could be utilized to evaporate additional vapor if the evaporating water were held at a reduced pressure. And this new vapor might, in turn, be condensed to evaporate more water at a further reduced pressure. In other words, although a unit (pound, kilogram) of steam only contained a unit (pound, kilogram) of water, it could contain enough energy to produce further units of water under the right operating conditions. This was a very big step and led to Multi-Effect Distillation (MED) as shown in Figure 2. MED caught on first in industries such as sugar and salt refining that benefited from improved evaporation efficiencies, but before the end of the 19th century, it was being used in land-based desalination plants.

The advent of MED also led to the concept of Gained Output Ratio or GOR. GOR is the ratio of the number of units of product water obtainable from a single unit of steam. In a simple still (one effect), the GOR cannot exceed unity. In MED, the GOR is directly related to the number of effects. Considering process inefficiencies, it is usually about 0.87 times the number of effects. We will refer to GOR again later in this booklet.

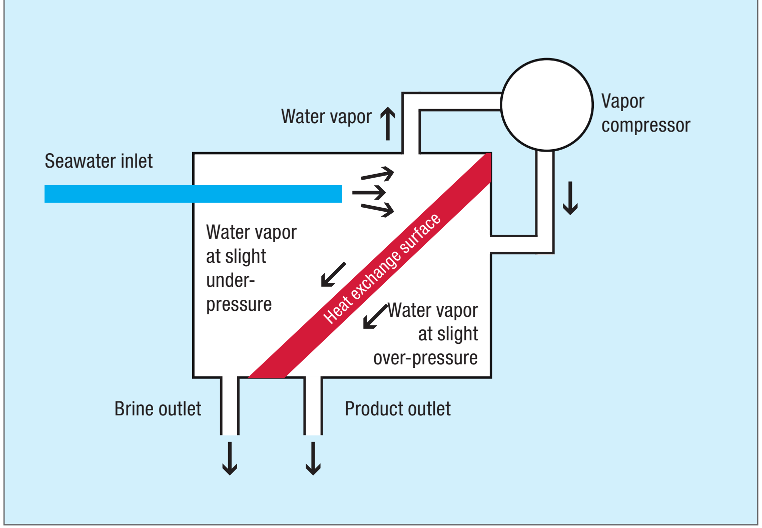
Figure 2. Multi-Effect Distillation



Mechanical Vapor Compression (MVC)

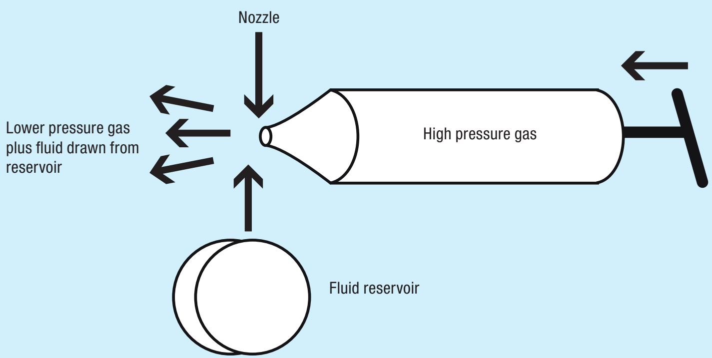
By the end of the 19th century, the age of steam was at its peak. Steam engines were converting thermal energy into shaft horsepower and industrial facilities everywhere were powered by rotating shafts via belts, pulleys and gears. It is perhaps not surprising that the question came up of desalting seawater with mechanical rather than thermal energy. If reduced pressure caused evaporation at a lower temperature, then compression should force condensation at a higher temperature. Could these phenomena be coupled in a useful way to yield desalination? The answer was yes, as shown in Figure 3.

Figure 3. Mechanical Vapor Compression (MVC)



In mechanical vapor compression (MVC), the feed water is sprayed against a heat exchange surface and a partial vacuum pulled by a pump against the vapor space. A portion of the water evaporates from the heat exchange surface, cooling it. The vapor (steam) passes through the inlet of the pump, is compressed to a higher pressure, and is applied to the back side of the original heat exchange surface. This vapor, now at a higher pressure, condenses on the heat exchange surface, re-warming it as it yields up its heat of vaporization (condensation). Thus the process may continue, the heat of vaporization being recycled within the system.

Figure 4. A simple ejector-compressor



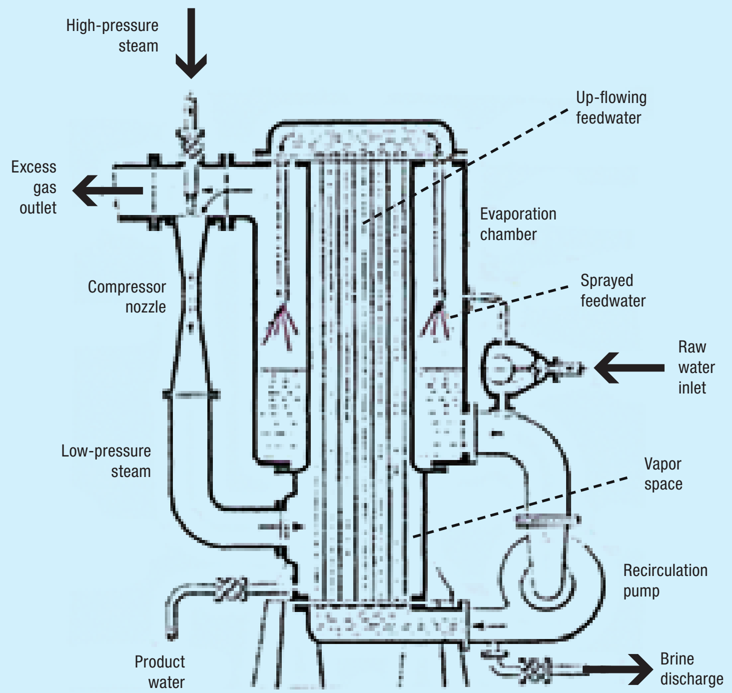
This process, in its original embodiment and time period, was never successful for desalination due to the unreliability and inefficiencies of the pumps available at that time. It did find some application, however, in salt mines and salt works. Nonetheless, the concept of MVC was demonstrated, and we will return to it later. (It is, in many ways, the same technology as used today in heat pumps and refrigeration.)

Thermal Vapor Compression (TVC)

It was soon recognized that the principal drawback of early MVC was the lack of reliable and efficient pumps to compress the water vapor. But could they be replaced by a thermally-driven no-moving-parts substitute? The answer was yes, and in 1908 such a substitute was introduced. It was based on a simple ejector-compressor or aspirator as shown in Figure 4.

Here, gas (usually air or steam) under high pressure is forced through a nozzle where it draws a vacuum on a reservoir and produces a medium pressure gas stream. When modified and integrated into a vapor compression system as shown in Figure 5, high pressure steam through an appropriate nozzle pulls a vacuum on the evaporating side of the system and introduces a medium pressure steam to the condensing side. Properly designed, the quantity of fresh water produced was several times the quantity of steam introduced at the jet nozzle (a GOR greater than 1). TVC was an immediate commercial success and by the 1920s, it was serving modest sized desalination applications.

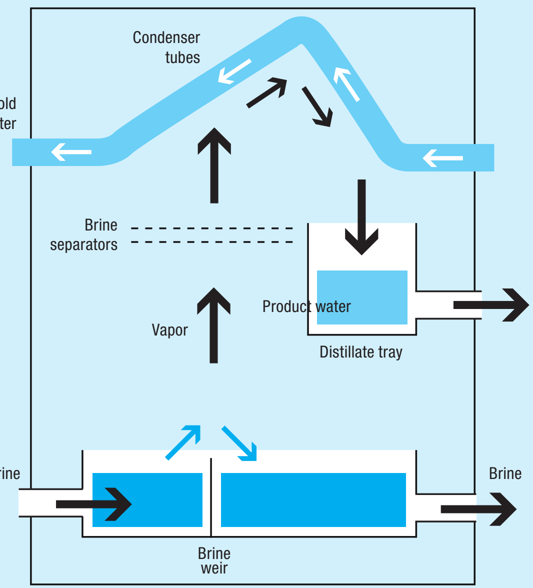
Figure 5. An early vapor compression system



Multi-Stage Flash Evaporation (MSF)

By the end of World War II, MED had become the technology of choice for large scale desalination applications. However it was plagued by the formation of inorganic scale (Mg(OH)2, CaCO3, CaSO4, etc.) on the heat exchange surfaces (tubes). This restricted flow paths, reduced heat transfer, and caused outages. It had long been known that water could be heated above its normal boiling point in a pressurized system. If the

Figure 6. A single flash chamber

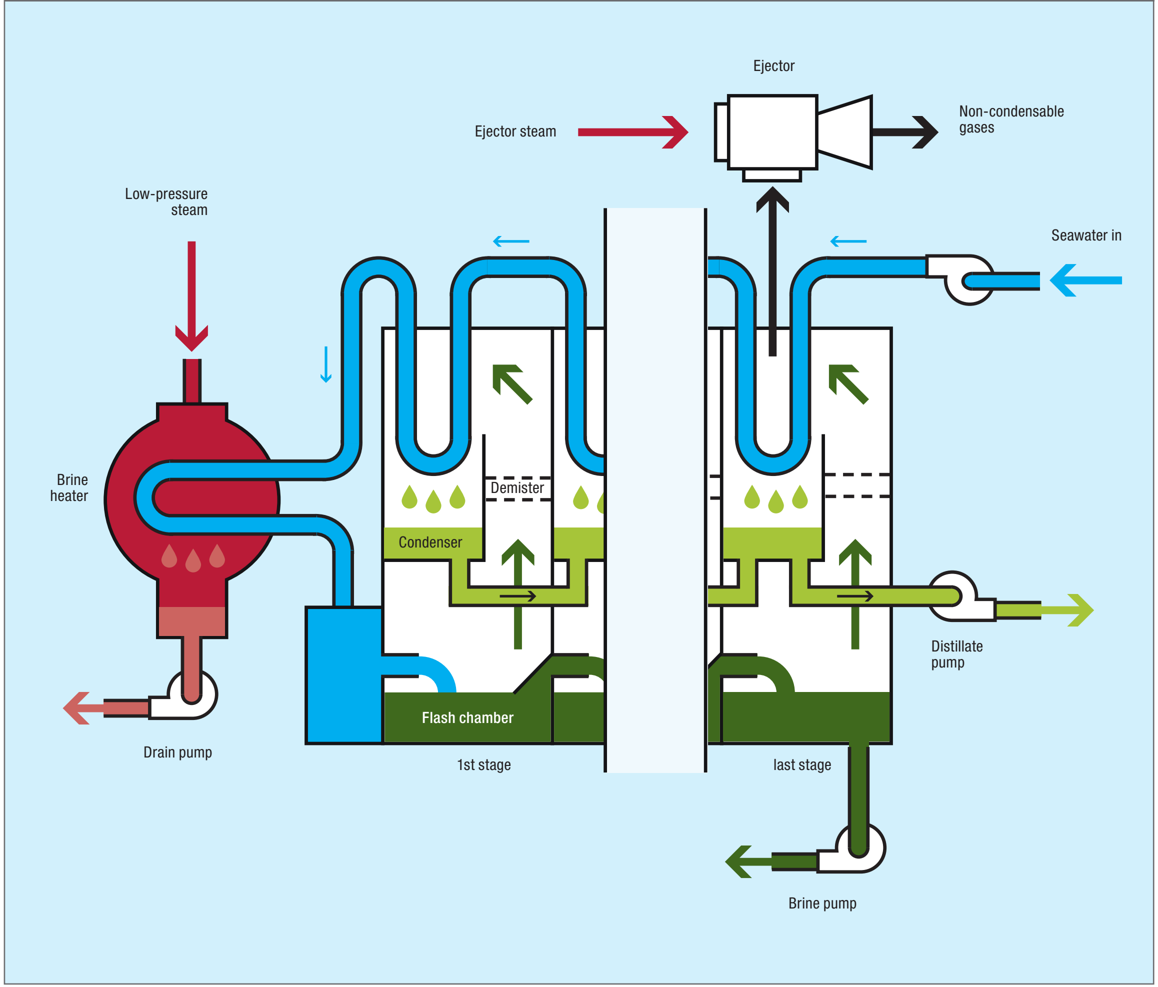


pressure were then suddenly released, a portion of this water would boil off or “flash”. As this boiling occurred from the bulk fluid rather from a hot heat exchange surface, opportunities for scale formation should be reduced. This is shown in Figure 6. The released vapor passes through a brine separator (demister) screen to remove entrained liquid droplets and is condensed on incoming seawater, which is, in turn, heated by the released heat of condensation.

A series of such flashing vessels (stages) could be linked together, each subsequent vessel operating at a lower temperature and pressure (Figure 7).

The seawater enters the heat exchange tubes in a direction counter to that of the brine flow through the various stages. After

Figure 7. Multi-Stage Flash (MSF) – simplest configuration



passing through the hottest stage, it enters the brine heater where it is further heated by a thermal source, usually steam. It then proceeds to the first and subsequent stage flash chambers, a portion evaporating in each.

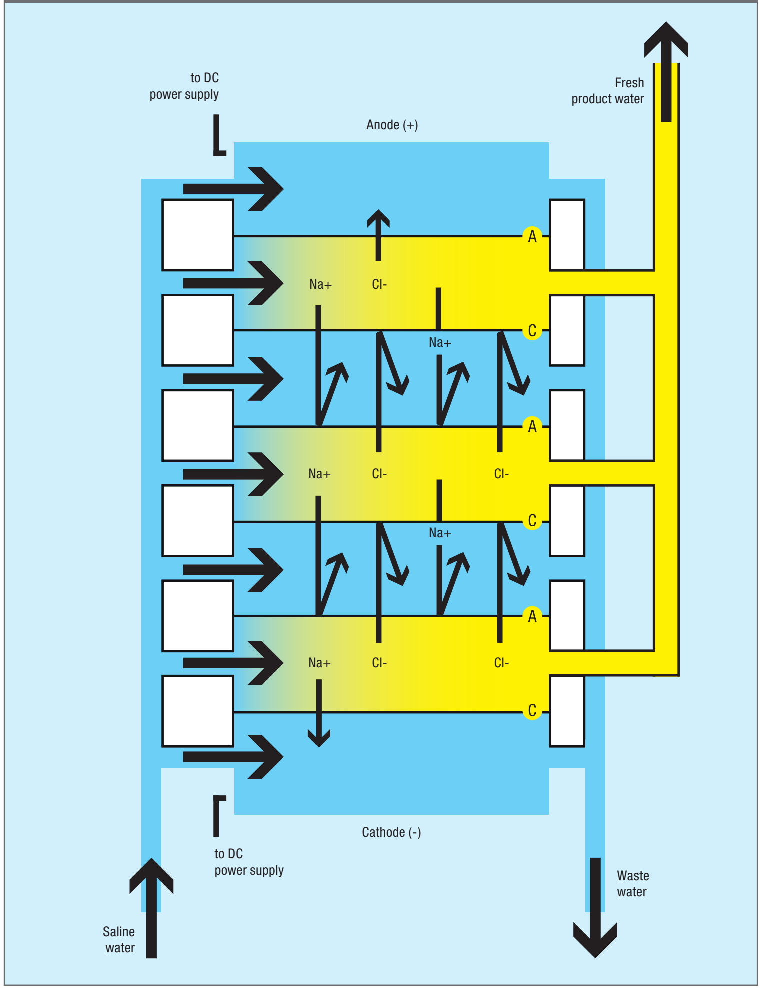
In practice, the energy efficiency (or GOR) is dictated primarily by the operating temperature range, not only by the number of stages as is the case with MED. The number of stages is dictated largely by the need to minimize total heat exchange area (a very important cost component). Perhaps counter-intuitively, it was found that this minimum heat exchange area was reached when the number of stages was about twice the GOR, or higher. In other words, it was more advantageous to use a larger number of smaller stages than to use a smaller number of larger ones. Thus the term Multi-Stage Flash (MSF) was born.

MSF evaporation was developed independently and simultaneously in Scotland, England and the United States in the 1950s and was an immediate success for seawater desalination. It could be scaled up to sizes beyond those attainable at that time with MED and enjoyed well-deserved popularity for large installations.

Electrodialysis (ED)

Despite the promise of MSF, there was a growing opinion that processes that did not involve phase change (liquid-to-vapor-to-liquid) might offer further energy savings. The first of these to achieve success was electrodialysis (ED). It utilized synthetic membranes that were selectively

Figure 8. Electrodialysis (ED)



permeable to positively or negatively charged ions, but not to water. The process was driven by an electric current and is shown in Figure 8. A "stack" is made up of alternating anion- and cation-permeable membranes with spacers between them to form flow channels. When a DC current was applied, the salt concentration of alternating channels was increased or decreased.

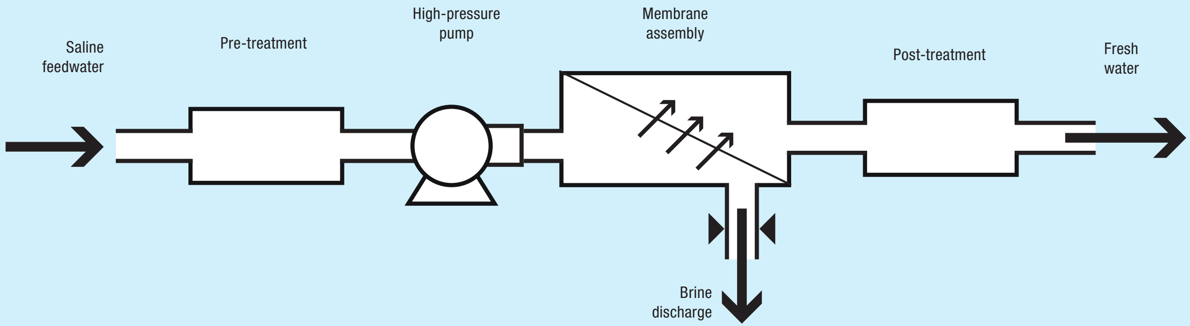
What MSF did for seawater desalination, ED did for brackish water desalination worldwide in the 1960s and 1970s. But ED was not energy efficient for treating seawater, as the energy consumed is too strong a function of the amount of salt that must be removed.

Reverse Osmosis (RO)

A decade or so after ED was commercialized, reverse osmosis (RO) appeared on the scene. Like ED, it depended on semi-permeable membranes, but in the case of RO, the membranes were permeable to water but not to dissolved salts. From a distant macroscopic view, it might appear to be just another filtration process involving exceedingly fine pores. However, at the microscopic or molecular level, it was more complex with the separation not as a result of physical pores, but rather of chemical interaction between water and the membrane material itself. Pressure was the driving force, but the pressure had to be sufficiently great to exceed the natural osmotic pressure of the saline feed water, which tended to drive the water in the opposite (wrong) direction.

In principle, it looked very simple; in practice there were many hurdles. Nonetheless, membranes would eventually be made in different physical forms and of different materials. They could be assembled into functional "elements" of different designs, and these elements combined in many ways into operating systems. This flexibility meant that RO could be customized to treat a variety of feed waters, including seawater. Figure 9 shows RO in its simplest and most basic form.

Figure 9. Reverse Osmosis (RO) –simplest configuration



Summary

One way to summarize the various technologies described above is list them by the type of energy that drives them:

Thermal Energy

- Simple Stills (SS)
- Multi-Effect Distillation (MED)
- Multi-Stage Flash Evaporation (MSF)
- Thermal Vapor Compression (TVC)

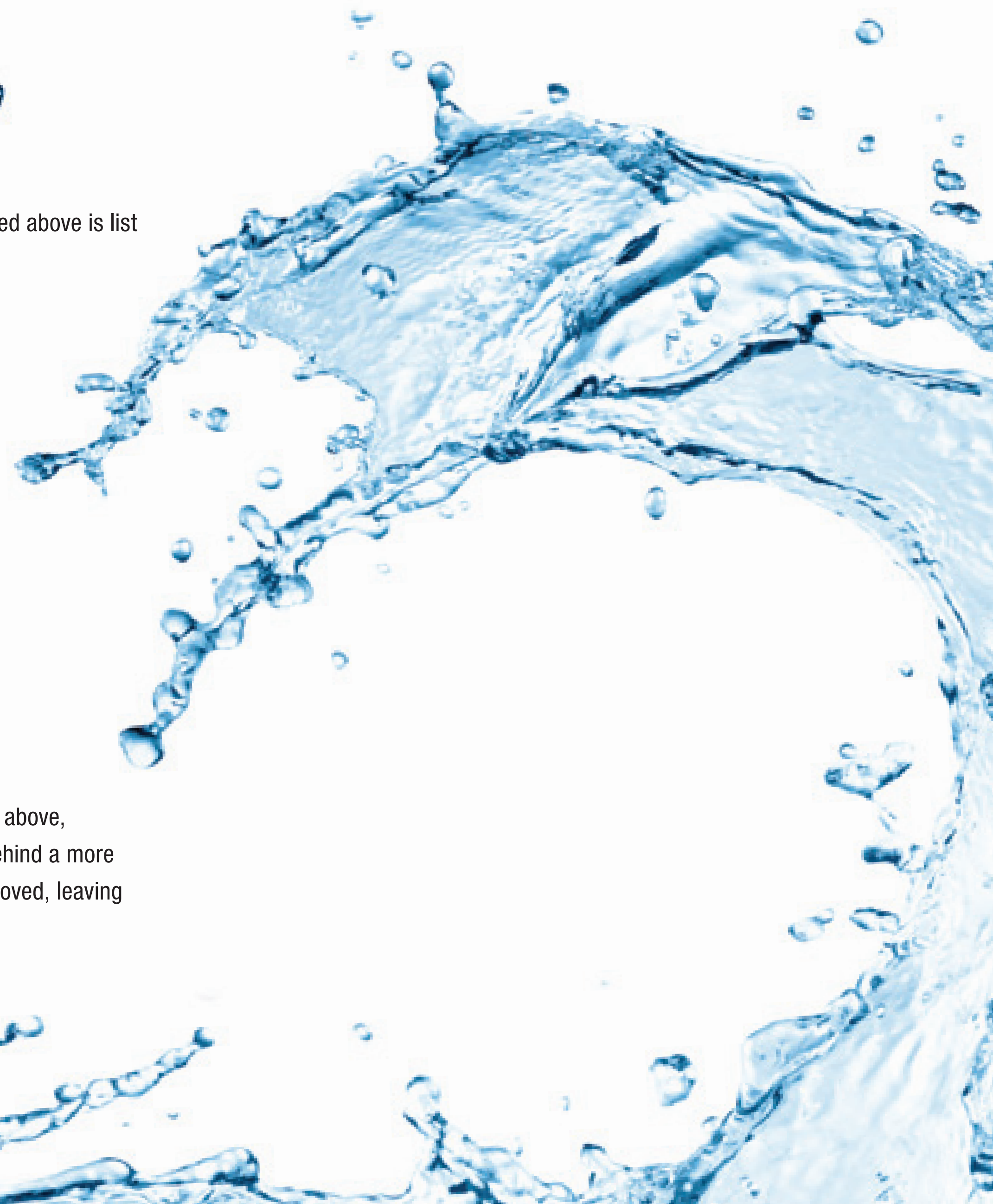
Mechanical Energy

- Mechanical Vapor Compression (MVC)
- Reverse Osmosis (RO)

Electrical Energy

- Electrodialysis (ED)

It is also worth noting that in six of the seven processes above, fresh water is removed from the feed stream, leaving behind a more concentrated brine. In only one case, ED, is the salt removed, leaving behind a purified feed stream.



The Magnitude of the Challenge

The salt burden

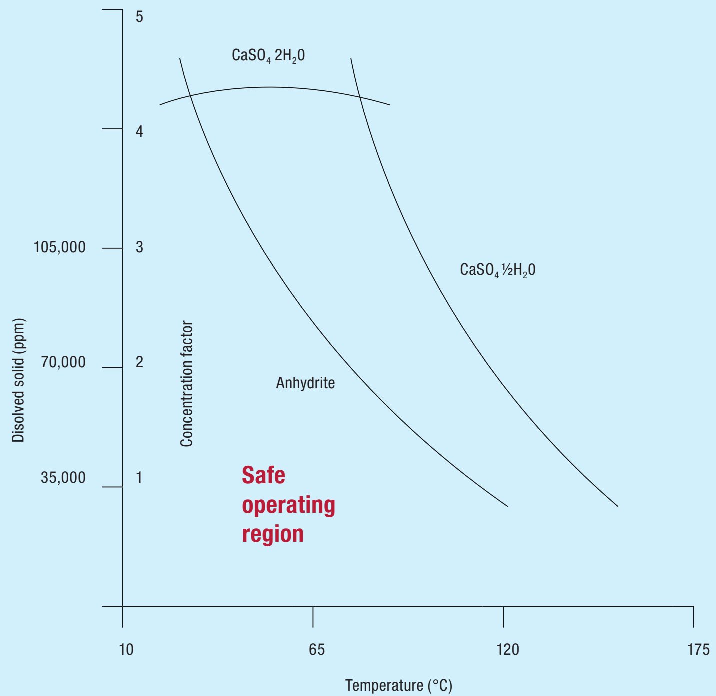
As mentioned earlier, a cubic meter (m^3) of seawater may contain some 20 to more than 50 kilograms (kg.) of dissolved solids. Based on recent contracts for the purchase of desalinated water, a competitive process today must be able to separate these constituents for well less than one dollar ($1.00) in total product water costs. This is a major challenge. The implications of this burden are often neglected by researchers seeking new separation methods. For example, methods based upon selective adsorption or absorption (e.g., ion exchange or surface adsorption/desorption) must utilize comparable quantities of adsorbents or absorbents. To minimize capital investment in such reagents, cycle times for salt loading and regeneration must be very short. But short cycle times require fast kinetics, often difficult if diffusion is relied upon for mass transfer. The trap that researchers often fall into is to focus narrowly upon what is likely to be the low energy consumption of a process proceeding eventually to thermodynamic equilibrium, rather than the kinetics of heat and mass transfer allowing the design of practical equipment of modest size and cost.

Minor constituents of feed waters

i. Inorganics

If feed waters consisted only of H_2O and NaCl, the desalter's assignment would be considerably simplified. Unfortunately, however, seawater and brackish waters as they are found in nature are contaminated by many other inorganic ions, with the result that many compounds are in solution at

Figure 10. Solubility limits of calcium sulfate



concentrations at or near their saturation levels. To worsen the situation, some of these (such as calcium sulfate) have solubilities that decrease with increasing temperature. Figure 10 indicates the solubility and temperature region in which calcium sulfate (and its hydrates) will remain in stable solution.

As temperature rises above about 50°C, solubility falls dramatically. As a result, local conditions within operating equipment frequently exceed these solubility levels. Therefore, evaporative systems have difficulty operating much above 100°C without scale formation, resulting in sub-optimal thermodynamic efficiencies. Elaborate precautions are very often needed to prevent these materials from depositing on surfaces where they retard the process by diminishing heat or mass transfer.

Such precautions can include:

- Screening and filtering to remove debris, dirt and suspended solids
- Pretreatment of feed water to remove certain critical species (e.g., softening)
- Alteration of chemical conditions to increase solubility (e.g., addition of acid)
- Modification of the morphology of the insoluble species to prevent formation and adherence of scale on critical surfaces (e.g., addition of a polyelectrolyte)

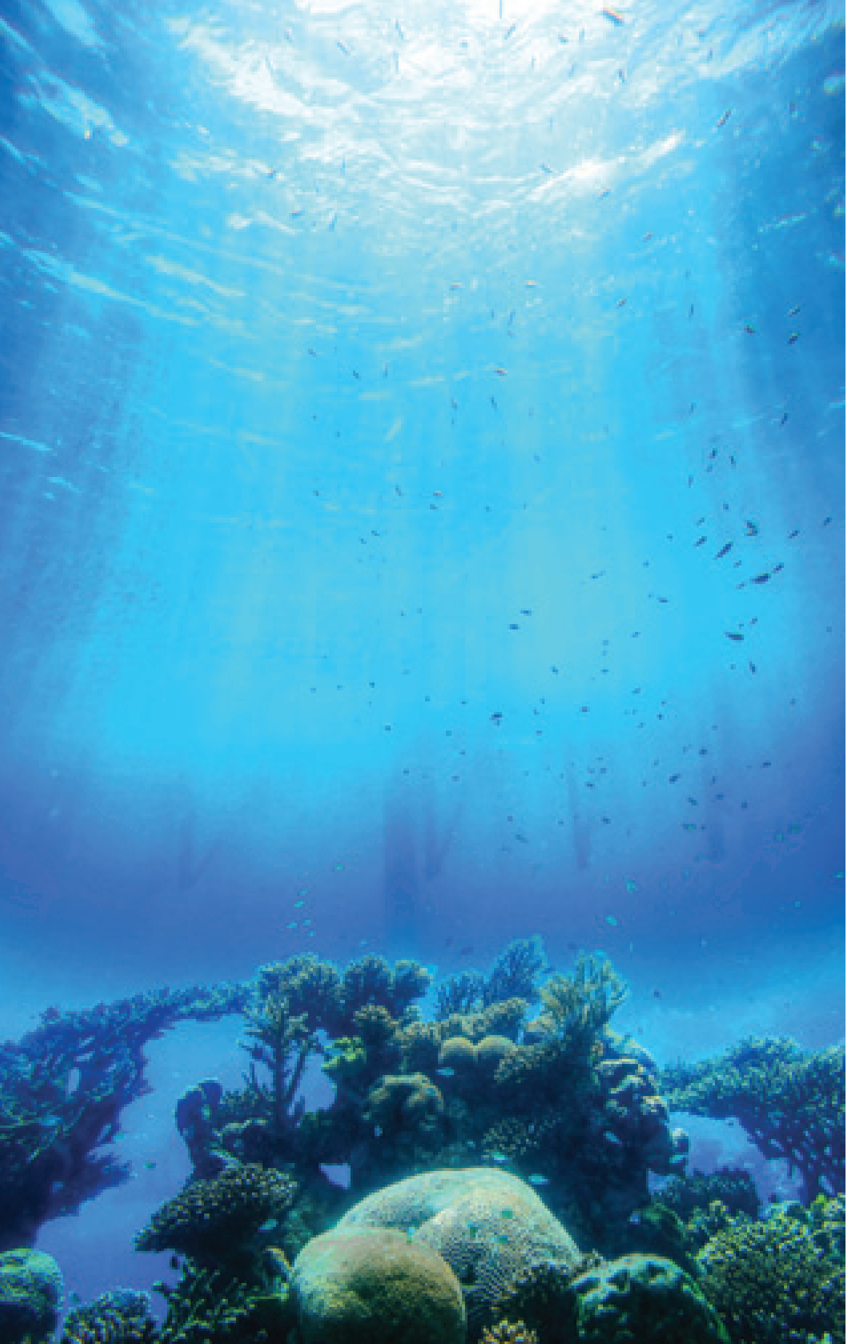
Such measures can be very successful but inherently add capital and operating costs to the system, as well as opportunities for malfunction. They must be incorporated into the very earliest planning and design phases of any successful system.

ii. Gases

Non-condensable gases such as nitrogen and oxygen that exist in solution may be released and form inert blanketing layers on surfaces where mass or heat transfer is expected to take place. In evaporative plants, they can accumulate in the vapor space and retard the condensation rates. They may also be introduced through ambient air leakage into systems operating at sub-atmospheric pressures and from the breakdown of chemical additives. One m^3 of seawater may release 15-20 liters of gas, and a very small quantity of non-condensable gas in water vapor can reduce heat transfer rates at the condensing surface considerably.

Chemically active gases such as oxygen, carbon dioxide, chlorine or hydrogen sulfide may lead to corrosion of metals, other oxidizing problems, odor problems, changes in acidity, and formation of insoluble species.

In evaporative systems, non-condensable gases are usually extracted by a vacuum system that continuously withdraws them (and a small amount of water vapor) from one or more carefully selected points in the vapor spaces of the equipment. There are associated capital and energy costs, but these are offset by the increased productivity in present day designs. However, proposed new evaporative systems frequently overlook these venting issues and costs or postpone their study until late in the development cycle when they may prove to be the undoing of the effort.



iii. Biological Activity

Living entities in raw feed waters can form surface films retarding heat and mass transfer and can grow to cause partial or complete blockage of flow paths. Such films can also provide sites conducive to increased corrosion or disturbances in the flow path leading to cavitation and pitting. Some species can degrade critical plastic materials such as cellulose, of which some membranes are made. Chemical and physical means of precluding these problems all bring with them attendant costs and "side effects". For example, biocides such as chlorine may do damage to membrane materials such as polyamides. Especially, they require careful operating control, as the window for reliable operation can be very narrow.

iv. Variability of Contamination

The challenges cited above are frequently exacerbated by large variations in their occurrence in seawater, over both time and location. Sampling and analyses of feed water chemistries used in plant design must anticipate not only tidal and seasonal variations, but also variations brought about by the effect of the plant itself on its local environment. Short term variations on an hourly, daily or state-of-tide basis can also lead to process upset and can best be coped with through the use of real time monitoring and feedback, where such instrumentation exists. Despite the best planning, unanticipated excursions in feed water chemistry (or operator attention) will occur, and therefore, any design must contain a realistic level of forgiveness.

Desalination as Practiced Today

As might be expected, in the 50 or so years since large scale desalination became common, service experience, research, development, and production engineering advances have led to significant design and operating improvements.

Simple Stills (SS)

Because of their high energy consumption, simple single effect stills are not used in medium or large scale desalination facilities. They persist only in very small high purity water applications or in home water purification appliances where energy consumption is not a major issue. We will not discuss them further here.

Multi-Effect Distillation (MED)

When multi-stage flash (MSF) was first introduced, interest in large scale MED waned for more than a decade. It was eventually revitalized by the realization that MED could be designed to operate efficiently (acceptable GOR) at lower temperatures than could MSF. This permitted the use of lower grade (cost) steam as heat input. The secret to this was the use of lower cost heat exchange materials (such as specialty aluminum alloys), which, in turn, permitted a larger number of effects, and hence higher GOR, at an acceptable capital cost. Perfecting all of this took time, and for years, MED lagged MSF in unit size and customer acceptance. It is currently, however, enjoying something of a rebirth, especially when coupled with thermal vapor compression (TVC) in a hybrid configuration.

Mechanical Vapor Compression (MVC)

Mechanical vapor compression remained a minor desalination technology until World War II, when military needs for fresh water at sea and in arid areas led to the development of portable units, often powered by dedicated gasoline or diesel engines. After the war, MVC found applications in the oil patch, on off-shore oil and gas platforms, and for the production of distilled water for industrial applications. Unit size was modest and limited by available compressors. In the 1980s, however, it received a boost with the development of a much improved compressor system, and units were successfully employed by island communities, industrial users and resort complexes. While unit sizes were increased to about 3,000 m^3/day, it eventually met competition from the newly introduced reverse osmosis technology, which offered significantly higher energy efficiencies. Today, MVC is a player in desalination only when the application requires a very high purity product or a very high percentage recovery.

Thermal Vapor Compression (TVC)

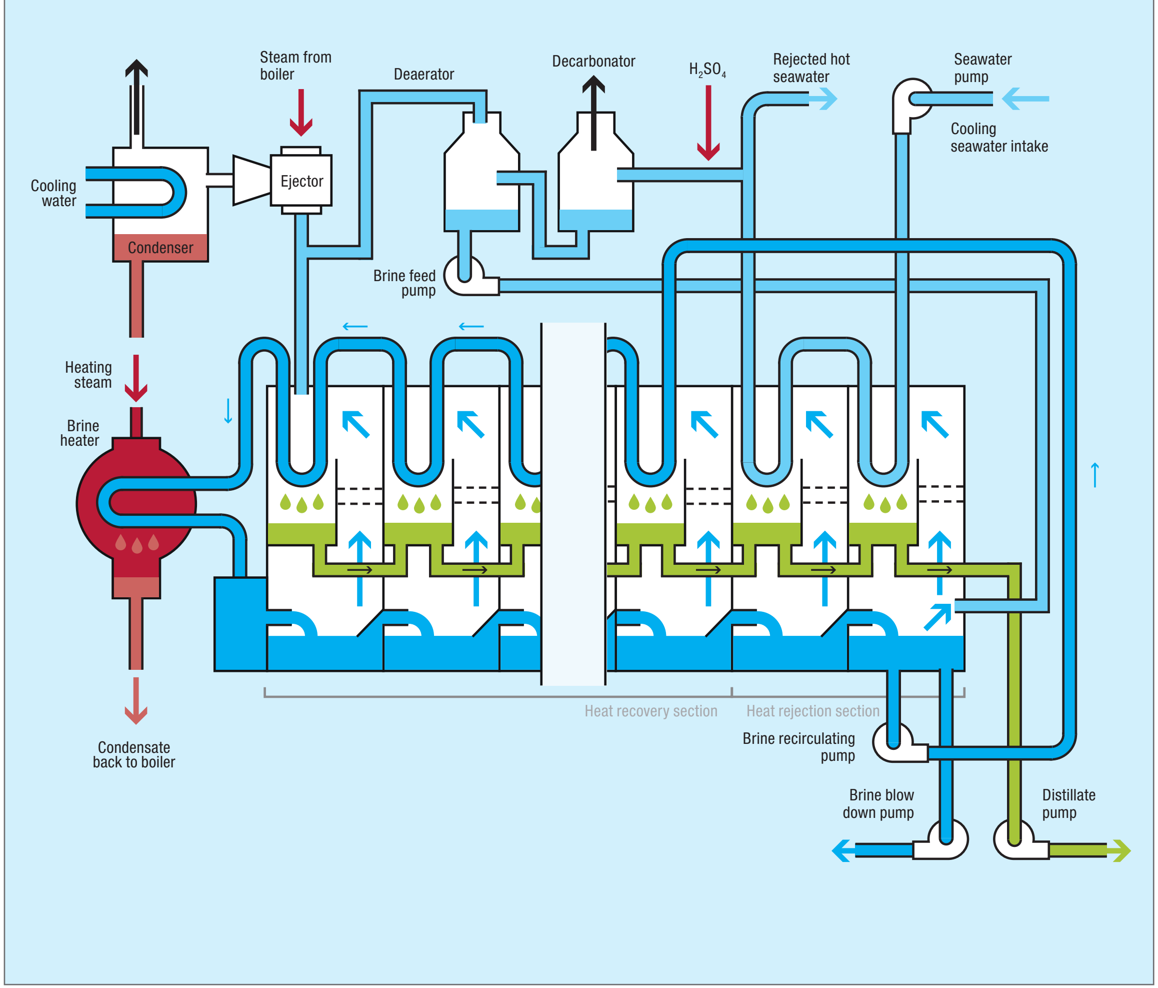
Although TVC has been commercialized for more than 100 years, it accounts for less than 10 percent of desalination capacity today. For years, it was available only in small unit capacities but today, coupled with MED in a hybrid configuration (see page 19), it is making a significant comeback in large installations. Unit sizes are now approaching 20 MGD (76,000 m^3/day).

Multi-Stage Flash Evaporation (MSF)

For decades, MSF has been the workhorse of seawater desalination, although it is currently feeling competitive pressure from RO and TVC/MED hybrids (see following sections). It long dominated markets in the Middle East and island communities where high seawater salinities placed serious burdens on RO. Individual unit sizes now exceed 98,000 m^3/day, with concomitant economies of scale. It is now offered almost exclusively in the "brine recirculation" configuration shown in Figure 11.

As Figure 11 shows, feed seawater is pumped through the heat exchange tubing of the two right-most stages (the heat reject section). Most of it is then discharged, but a small portion is diverted to a decarbonator,

Figure 11. Multi-Stage Flash (MSF) with brine recirculation



deaerator and such other pretreatment as may be required. It then is added to the recirculating brine flow to make up for the volume of brine discharged from the last stage (brine blow down). However, the bulk of the last stage brine is recirculated back to the coldest stage in the heat recovery section. Also in Figure 11, a steam jet ejector (upper left) is used to maintain appropriate vacuum in the flash chambers.

The recirculation modification reduces the volume of feed water that must be pretreated to avoid scale formation at high temperatures.

MSF is almost exclusively constructed in conjunction with a thermal electric power generating station. In such a "dual purpose" plant, high pressure steam from boilers is fed to high pressure turbine/generators to generate electric power. A portion of the steam subsequently drawn off at a lower pressure or back pressure steam exhausted from the turbine supplies the thermal energy needed in the MSF plant. It is fortuitous that in such a symbiotic relationship, the power/water production ratio at which the power and MSF plants may be efficiently coupled often approximates the power/water demand ratio in the communities being served.

MSF remains a highly reliable and mature option for large installations. (Two units were recently taken out of service in Qatar after 45 years of operation.) Its weakness is the high electrical energy load of peripherals (such as the brine recirculation pump). Nonetheless, reliability often carries the day, with conservative customers reluctant to commit to newer technologies. Figures 12 and 13 suggest the scale and layout of these plants.

Electrodialysis (ED, EDR)

What MSF did for seawater desalination in the 1960s and 70s, ED did for brackish water desalination during the same period. With a further refinement called electrodialysis reversal (EDR), wherein the current flow is periodically reversed for a few seconds, ED is made much more tolerant of

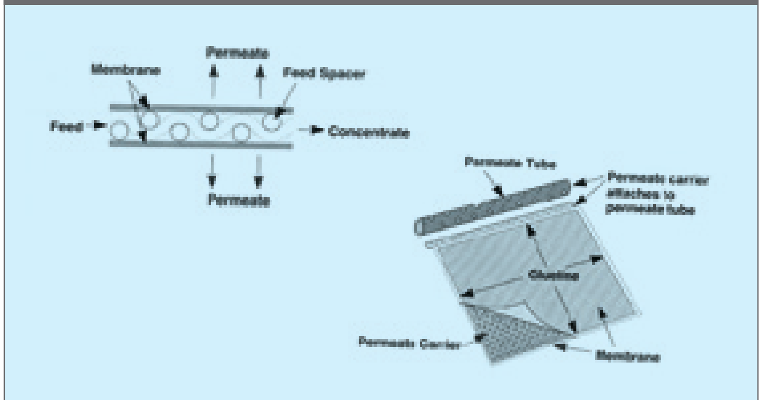
Figure 12. A few of the 40 units at Al-Jubail Phase 2, each 5 million GPD

Figure 13. A single MSF unit at Al-Jubail Phase 2

harsh scaling conditions. It can operate reliably without the need for highly skilled operators, tolerates high feed water temperatures, and can operate at high recovery ratios.

Its power consumption (P) is largely dictated by the applied current (I) and voltage (E) where P = I x E). Nearnst Law tells us that I will depend upon the quantity of ions removed (concentration change). Ohm's Law (E = I x R) reminds us that E will depend upon the internal resistance, R, of the system, as well as upon I. At higher concentrations, the proportionately higher value of I results in unattractively high power consumption (P = I2R). In more dilute solutions, the higher internal resistance of the system (R) dominates. Thus, in practice, ED and EDR have found most application with saline solutions of intermediate salinity (brackish waters) ranging from about 500 to 3,000 ppm.

Figure 14. Assembly of a spiral-wound RO element

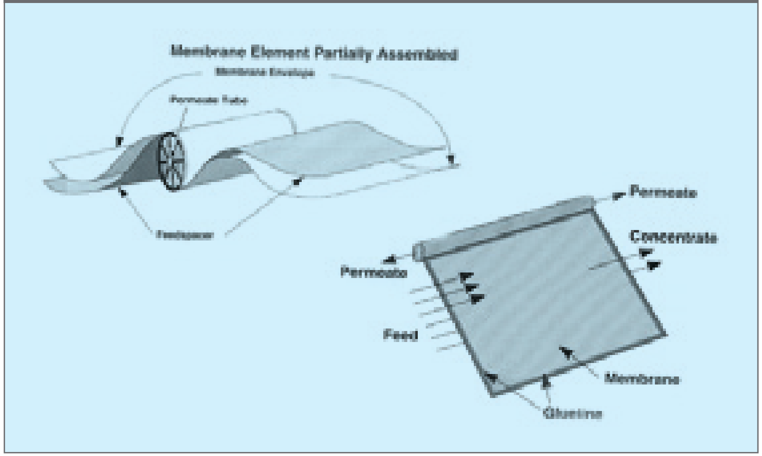


At present, fierce competition from more the energy efficient and versatile RO systems (see next section) has relegated ED/EDR to specialty applications. It is no longer a major player in desalination even for brackish water treatment, but finds use in post treatment for minimization of brine from RO plants. However, research continues to broaden its performance and markets.

Reverse Osmosis (RO)

Although RO had been anticipated for many years, no membranes existed with suitable water permeability, salt rejection and mechanical properties. This all changed in 1960 with the development of fabrication techniques to produce a cellulose acetate film having a graded or "asymmetric" pore structure. In such a membrane, the pore diameters are relatively large on the side away from the feed water, but taper down to a virtually continuous surface where they meet the feed stream. A solution-diffusion transport mechanism permits the passage of the more soluble water molecules across this active surface, while the tapered pore structure provides mechanical support against the applied pressure. Further research was required to develop the best physical configuration for such a membrane so that it could be successfully plumbed into an operating system. Flat sheet, tubular, hollow fine fiber, and spiral wound membrane elements have all been explored and commercialized in the past. Hollow fine fiber membrane elements enjoyed considerable popularity at one time, but are now used only for special feed water situations. By far the commonest configuration today is the spiral element shown in Figures 14 and 15.

Figure 15. Flow paths in a spiral-would RO element



Large sheets of membrane are assembled with spacing materials into flat envelopes (leaves), several of which are then wound around a perforated hollow mandrel or core. This unit is termed an element and is enclosed inside a cylindrical pressure vessel.

Feed water passes at high pressure across the outer surface of the leaves, and the product water is collected from the hollow core. Thus, a fairly high surface area of membrane per unit volume of the finished element is achieved in what is termed a spiral wound element.

In a subsequent development, it was found that a very thin and defect-free polyamide film could be formed on a microporous backing using an interfacial polymerization technique. Such “thin film composite” membranes offer higher permeability (flux) and salt rejection, and have replaced cellulosic membranes in most desalination applications.

A single installation may contain from a handful to several thousand membrane elements manifolded together in various configurations. It is common practice to have several (6-7) elements in series in a single long pressure vessel, feed and product water passing from one element to the next. Many of these vessels may be arrayed in parallel. In some cases, the product water may pass to a second stage (array) of elements to further purify it, the reject from this second stage being recirculated to the feed stream of the first array. Or the reject stream (brine) from the first stage may pass to a second stage of elements to further increase the total amount of water produced and reduce the volume to be rejected.

While the earliest elements were about 2 inches in diameter and a foot long, they have grown and evolved into standard sizes. For large installations, the 8 inch by 40 inch (20 cm x 100 cm) element became the standard. A number of suppliers offered pressure vessels to fit, and the elements themselves were relatively interchangeable among manufacturers. In the past few years, there has been a trend to even larger elements such as 16 inch (40 cm) by 60 inch (150 cm). By having fewer but larger elements, the number of connections is significantly reduced, as well as offering higher capacity per system volume and footprint. Figure 17 shows a typical large SWRO plant today.

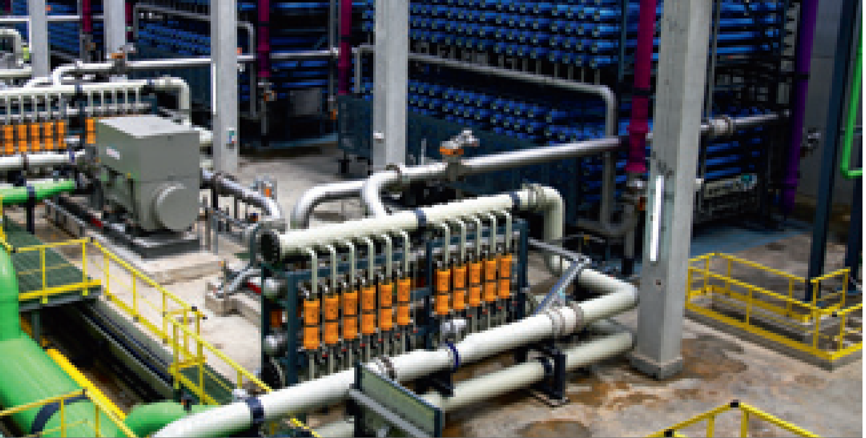
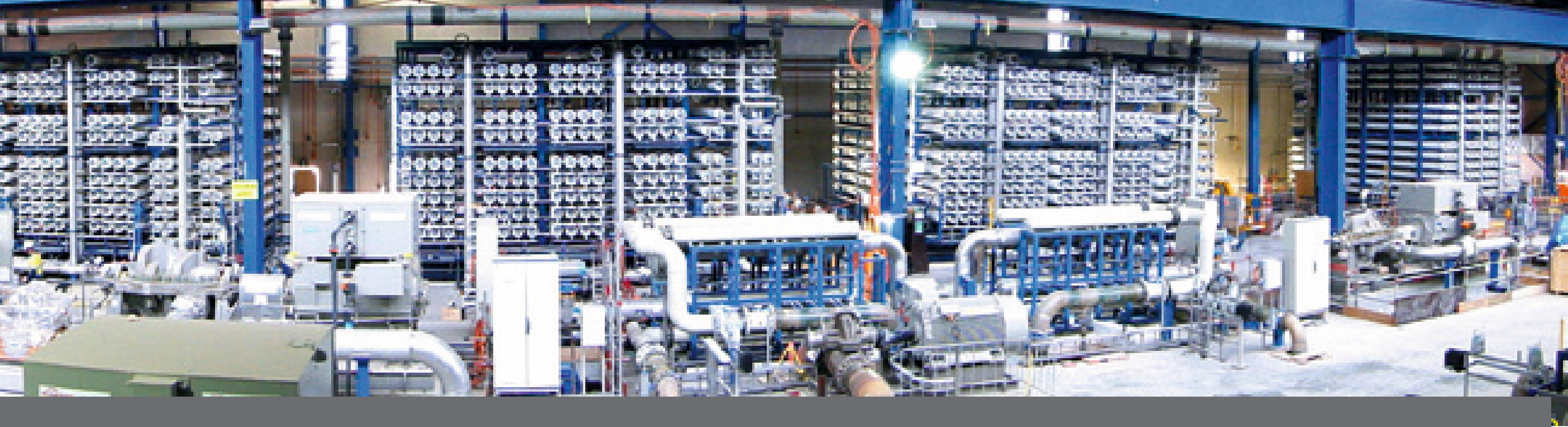


Figure 16. One example of energy recovery devices used in a SWRO plant

Figure 17. A typical large SWRO plant

Thirty years ago, the reject stream (brine or concentrate) exiting an RO system was customarily reduced to atmospheric pressure through an orifice or “cracked valve”. The energy represented by this flow and pressure drop, V times P, was considerable and was wasted. Today, through the use of energy recovery devices (ERDs), most of this energy may be returned to process. The ERDs take many forms, ranging from simple reverse running pumps to Pelton wheel and Francis turbines, to linear or rotating work or pressure exchangers or to other centrifugal devices (see Figure 16). In all cases, the energy recovered is used to help pressurize the feed stream or to take the load off the high pressure pumps. Today, virtually all seawater RO systems employ some form of ERD, and they are beginning to find their way into the lower pressure brackish water systems as well. As a result, energy consumption for seawater systems has fallen from about 8 kWhr/m^3 20 years ago to as low as 3 kWhr/m^3 today. Indications are that it may soon fall below this level, and this will be discussed below.

Advances in RO performance have not been limited to seawater systems. Parallel improvements in performance and cost have occurred with brackish systems and especially in the rather vague area of “other impaired waters”. That is to say, there are great quantities of surface waters and municipal, industrial, and agricultural waste streams that contain sufficiently high concentrations of dissolved inorganic materials (salts) that they cannot be treated effectively by conventional municipal water treatment methods (e.g., filtration, sedimentation, flocculation, etc.). Manufacturers have found that they can formulate RO membranes that have only a limited rejection (perhaps 50%) of monovalent species such as sodium or chloride ions, but reject divalent ions at a much higher level, say 90% or more. By sacrificing rejection, the membrane flux (throughput) (m^3/day/m^2) is greatly increased, even at low operating pressures. Such membranes, known now as nanofiltration (NF) or membrane softening (MS) membranes, are finding increasing usage in municipal water treatment, where they not only provide a softened product, but rejection of bacteria, viruses, suspended solids,



and disinfection byproduct precursors. Energy consumption is low and operating costs in line with conventional treatment methods. By exploiting their softening capabilities, they are also useful as pretreatment membranes upstream of RO systems.

Hybrids

There are several ways in which the above technologies might be linked to their advantage.

i. MSF/RO or MED/RO

Evaporative technologies (e.g., MSF or MED) and RO may be linked by designing the RO system to produce a product of somewhat less purity than desired in the final application. This reduces both the capital and operating costs of the RO. The RO product may then be blended with the very pure evaporative product, typically about 50 ppm TDS and thus more pure than required for municipal purposes, to yield an acceptable product.

A second RO/MSF configuration exploits the fact that the performance of an RO system varies with the temperature of the feed water, being more productive at higher temperatures. Seasonal variations in the feed temperature may be offset by designing the RO system to be optimized at the upper seasonal temperature. When the temperature of the feed falls below the design temperature, the feed may be blended with the heat reject stream from the MSF unit to maintain the optimal temperature level. Whether the design and operating complexity of any such hybrid system would counteract the advantages has yet to be determined.

ii. NF/MSF, NF/MED, NF/RO

As Nanofiltration (NF) emerged as a subset of RO, its potential use as a softening process gained attention in the desalination community. As cited earlier, the productivity and efficiency of evaporative systems are often limited by the top temperatures at which they can reliably operate without scale formation. As NF reduces concentration of divalent ions, then NF

pretreatment of feed water will permit higher top temperatures. Tests at both pilot and full scale facilities have demonstrated that this is so with MSF, and likely so with MED. Currently, the trade-offs are being weighed between increased first and operating cost of the NF component and the savings achieved.

Similarly, NF has potential as a pretreatment process for RO. Recovery ratios in RO are limited in part by scale formation in the concentrated brine. Softening with NF allows increased recovery, but the same trade-offs must be made as with evaporative plants.

iii. MED/TVC

The hybrid concept now achieving considerable success is the coupling of TVC with MED. The earliest TVC units were operated with only a single effect. They achieved GORs of 3 or 4. The earliest MED units operated with about 3-8 effects and at GORS of about 2.6-7.0. MED also usually employed steam jet ejectors to maintain the necessary low pressures in the cooler effects. Although it is a major oversimplification, a MED/TVC hybrid might be visualized as an oversized steam jet ejector recirculating its medium pressure exhaust steam to the first effect in a MED system as a heat source. This is essentially a MED/TVC hybrid where the oversized steam jet ejector is the TVC component. Large units are now in the field and commercial use. They can achieve GORs as high as 15 with peripheral electrical consumption of only 1-2 kWhr/m^3.

Future Trends and Issues

Energy Consumption

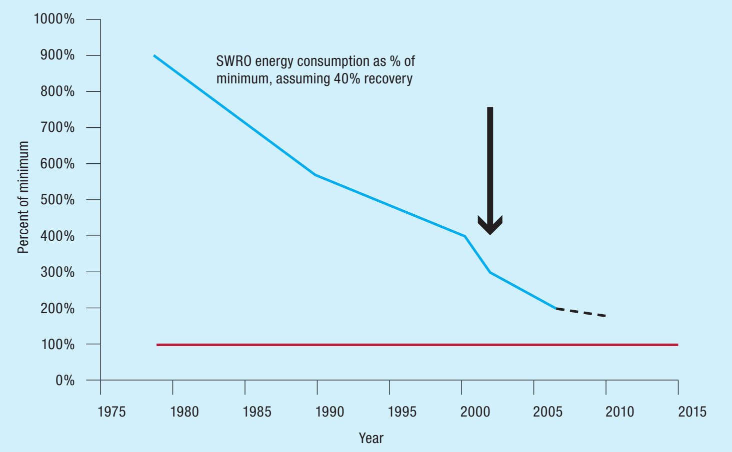
For more than 50 years, it has been known that there is a minimum separation energy for desalination processes, determined by chemical free energy considerations. It is a function of the concentrations of feed water, brine, product water, their temperatures, and the percent recovery. It is independent of the process of separation. For standard seawater at a typical recovery of 40%, minimum energy consumption is about 3.6 KWHr/1000 gallons (0.9 KWHr/m^3). If recovery were increased to 90%, minimum energy consumption would rise (roughly double) to about 8 KWHr/1000 gallons (2 KWHr/m^3). It should be remembered that in addition to the energy consumed in the separation step, there are other energy needs at the plant.

These include:

- Feed water pumping
- Pre-treatment, as may be required
- Post-treatment, as required
- Product water pumping to customer
- Brine disposal pumping
- Instrumentation and controls
- Other housekeeping requirements

These together may equal the energy requirements of the separation step alone. Thus an RO system with a net energy consumption of 6 kWhr/1000 gallons (1.5kWhr/m^3) for the separation step alone (including an ERD) may easily have a total plant consumption of about 12 kWhr/1000 gallons (3.0 kWhr/m^3). As Figure 18 indicates, the energy consumption for the separation step in seawater RO (SWRO) is rapidly approaching the theoretical limit. Future energy savings must come from minimizing it in other parts of the plant design.

Figure 18. Energy consumption of SWRO over time. Red line is theoretical limit.



For years, SWRO used more electrical energy than MSF. MSF represented a high degree of reliability with guaranteed performance on all feed waters. As SWRO electrical energy usage fell toward (or below) that of MSF, the competitive position of the latter softened. MED and TVC/MED also, sensing an opportunity, began to compete often and increasingly effectively with MSF for large plants with a thermal energy input option.

In the late 1970s, coincident with the development of high performance reverse osmosis membranes, the first large scale municipal seawater reverse osmosis (SWRO) plant was installed. Energy requirements for this plant were approximately 8 kWhr per cubic meter. Further advances in SWRO have continued to lower energy requirements. One of the major developments was the introduction of energy recovery devices in RO desalination plants. In the past 15 years, costs have been reduced by approximately 50% thanks to technological improvements, to the point where energy consumption in the core SWRO process of a demonstration plant in Southern California was measured at just 1.58 kWhr/m^3 (6.0 kWhr/kgal). Today's thermal MED/TVC plants use about 1 kWhr/m^3 in addition to the steam input required, very significantly less than the thermal plants built in the 1970s (Table 1).

Ultimately, the most important factor is not the absolute energy consumption of the desalination process. It is the relative energy consumption versus

Table 1. Typical energy requirements of major sea water desalination processes

Technology	GOR	kWhr/m^3
MSF	8 - 10	2.5 - 3
SWRO	N/A	2.5 - 3
MED/TVC	8 - 15	1.0 - 2

that of the other new water supply alternatives. Already we are at the point where the energy required for seawater desalination in Southern California is no greater than the energy currently being used to transport water from Northern California.

Alternative energy sources

Of course, to the plant owner, it is not just the consumption of energy that concerns him. It is also the cost of that energy. So he may consider substitution of energy sources. These include:

Low grade thermal energy

- Solar thermal
- Ocean thermal gradients
- Waste process heat

Other energy sources

- Solar photovoltaic
- Wind
- Ocean mechanical (waves, tides)
- Chemical concentration gradients
- Nuclear

All of the above have been explored, and work continues today. None have realized broad commercial acceptance with the exception of waste process heat. MED and MED/TVC have pushed the limits downward, but even then, they remain about 70°C (160°F) for top operating temperature. As bottom (lowest) temperature is usually fixed by the temperature of the feed water, low grade thermal implies smaller ΔT overall and probably per effect or stage and thus probably fewer effects. This reduces efficiency and increases heat exchange area. Higher grade energy yields higher efficiency and production. So a choice must be made:

- Operating more efficiently with higher cost energy, or
- Operating less efficiently with lower cost energy

Historically, when capital costs are factored in, the first option has usually been favored, but this can be very site- and time-specific.

Of all the alternative energy sources, low temperature solar thermal desalination has the longest history. The first conventional solar stills appeared in 1872 near Las Salinas (north of Chile). The plant was built to purify saline water to provide drinking water for mules working a mine. Other such early plants were constructed in Namibia and Australia near the beginning of the 20th century. During World War II, considerable work went into designing small solar stills for use on life rafts. This work continued after the war, with a variety of devices being made and tested, but none gained popularity.

These devices generally imitate a part of the natural hydrologic cycle in that the sun's rays heat the saline water so that the production of water vapor (humidification) increases. The water vapor is then condensed on a cool surface, and the condensate collected as fresh water product.

The greenhouse solar still, at first glance, appears to be a very simple device as shown in Figure 19. During operation, sunlight enters via the glass cover and passes through the water. It is absorbed by the blackened water basin and is subsequently transformed into heat. This heat warms the water with a consequent increase in vapor pressure. The warm water radiates in infrared, but since glass is opaque in relation to infrared, the heat is retained in the solar still and the temperature of the water contained in the still increases significantly above ambient temperature. However, despite its simple appearance, an analysis of heat and mass flows through the components of such a still shows it to be quite complex with many opportunities for inefficiencies.

Variations to this basic solar still (including incorporation of multi effect operation) have been made in an effort to increase efficiency, but they all share the following difficulties, which have thus far restricted the use of this technique for large-scale production:

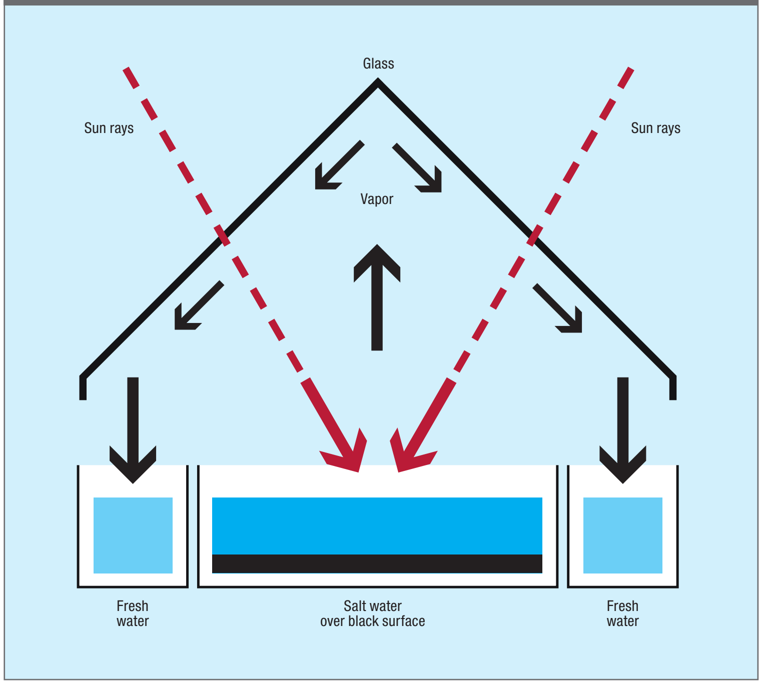
- Large solar collection area requirements
- High capital and maintenance costs
- Low energy efficiency
- Low recovery ratios
- Vulnerability to weather-related damage and vandalism
- Maintenance of clean surfaces
- Vulnerability to bad weather
- Variability of sun light

Although a properly constructed still can be quite robust, and some have operated successfully for 20 years or more, it is rare to achieve production of more than 3 – 5 liters/day/m^2 of surface.

When considering any alternative energy source, challenges include weighing energy cost savings versus cost of capital recovery. Continuous water production may require energy storage. Intermittent water production may require an over-sized desalination component plus water storage. It is always a matter of trade-offs:

- Energy efficiency vs.
- Capital cost, vs.
- Percent recovery, vs.
- Reliability, vs.
- Lifetime, vs.
- Size/area, vs.
- Other parameters

Figure 19. A typical "greenhouse" solar still



Capital Costs and Financing

The literature is full of data regarding the cost of desalted water. However, one must be careful in interpreting these data or comparing costs because these numbers often do not take into account local conditions, such as legislative or environmental issues or the cost of fuel. These factors can dramatically change the cost of water produced at two seemingly identical plants situated in different locations.

As a rule of thumb, one may say that total annual water costs are divided into three roughly equal shares: capital recovery, energy costs, and other operating costs. But there are always trade-offs among these three components. As major pieces of infrastructure, desalination plants are not inexpensive to build. In addition to construction labor and the cost of financing, materials costs comprise the significant portion of this overall capital expense. Over

the past few years, the financing component as well as some material costs (e.g., metals and speciality plastics) have experienced wide swings, thus impacting the cost of construction.
IDA is a strong proponent of making desalination as affordable as possible, while also taking the necessary steps to utilize desalination in an environmentally responsible manner. While cost is, of course, an important consideration, IDA believes that the fundamental issue is the value – not simply cost – of water. Access to clean, fresh water is vital for human life and health, and is also critical to the economy.

Over the past few years, one of the most significant emerging trends in financing and operation of desalination plants has been the increased involvement of the private sector. This represents a shift from the traditional model (which still plays a large role), where the financing, construction oversight, plant operation and facility maintenance are the province of governments. Today, the industry is witnessing a new model where the private sector is assuming responsibility for the financial and/or operational aspects of the plants, leaving governments free to focus on maintaining and policing regulatory frameworks regarding quality standard, service, protection of the health of their people, and sustainability.

As a result, there is today a rapid expansion of privately financed development of water projects around the world. In fact, 38% of desalination plant capacity constructed from 2002-2009 were privately financed.

These desalination projects come under the umbrella of such titles and models of contract as:

- Private Public Partnership (PPP)
- Concessions or Utility Outsourcing transactions
- Independent Water and Power Projects (IWPP), where water is produced usually through desalination alongside power generation
- Build Own Operate (BOO) schemes
- Build Own Operate schemes with a transfer component attached (BOOT)
- Alliances (Australia)

There is also evidence to indicate that transferring the responsibility to the private sector to finance, design, build, operate and maintain the necessary infrastructure is also leading to innovation, which, in turn, is delivering potable water at a more competitive price. This is particularly true when competitive tension is created through the use of transparent well-structured procurement processes to select and award the long duration water supply contracts.

Given that the total cost of each cubic meter of potable water will be directly impacted by the cost of construction, operation, maintenance and financing, in order to deliver the most competitive tariff ($/m^3 of water), the private sector entity has to select the most appropriate technical solution, considering the whole life cost of the asset thus optimizing capital and operating cost. The multiple objectives inherent in integrating design, construction, operation and maintenance with ownership and financing inevitably lead to conflicts. For example, the lowest cost of financing can only be attracted if risks are minimized – yet technological innovation means a higher level of risk.

The competitive tension introduced by a pre-qualified tender process encourages the evaluation of all technological options and process enhancement to select the least whole life cost solution. This is not only useful to encourage innovation, but is also essential to achieve the desalination industry's quest to continually lower the cost of potable water to reach the threshold of affordability by the public.

Environmental Issues

The desalination industry is serious in its commitment to environmental responsibility and, in fact, it has already done much to mitigate potential environmental impacts. The demand for desalinated water is growing at a pace of approximately 15% per year. In the meantime, care of the environment, sustainability considerations, and energy usage are playing an increasing role in the type, configuration, siting and power source for desalination plants.

Among the primary issues to be addressed in terms of environmental stewardship are strategies to reduce energy consumption, minimize the carbon footprint (both onsite and offsite), protect marine life, and manage the disposal of the brine (concentrate).

With seawater plants, protection of marine life is also a key consideration. Advanced seawater intake designs greatly reduce the threat of impingement or entrainment of marine species. Intake options include offshore environmentally friendly submerged intakes, sub-seabed intakes, co-located intakes, beach and coastal wells, and passive intakes. It is generally accepted that an intake velocity of less than 15 cm/second (0.5 fps) will significantly reduce impingement issues. Entrainment is generally not significantly impacted by velocity.

There are, likewise, a number of options that can be employed to reduce the impact of brine discharge, and new technologies offer the promise of further reductions. These options include multi-port diffusers; co-located, blended discharges of cooling water and wastewater effluent; deep well injection; evaporation and salt/mineral recovery. Mitigation measures to address potential impacts are common, and improvements are being implemented on a regular basis. Some of these mitigation methods include:

- Minimizing process chemicals allowed in the outfall and enforcement of discharge limits
- Implementing new technologies such as low pressure membrane pretreatment, to reduce the chemical load associated with coagulants and polymers in reverse osmosis desalination plants.

The desalination industry has also developed new methods for handling and disposal of backwash solids.

An important aspect of any desalination plant operation is the ongoing monitoring of the environment surrounding the facility. Improved monitoring technologies and practices allow for more accurate observation of potential impacts and enable the facility operator to change operating conditions to respond to environmental responses, if required. Recent surveys of activity in the neighborhood of brine discharge points in modern seawater facilities suggest clearly that they are lively habitats for marine life.

With brackish water plants, brine disposal likewise needs to be addressed. Sometimes it may be discharged without harm to an existing water body. It may be disposed of by deep well injection, or it may end up in an evaporation pond. In any case, safe disposal must be thought out in the original plant design and taken into account in projecting capital and operating costs.

Ultimately, what is important is not the absolute impact of a desalination project. Instead it is the relative impact of the project versus that of other new or existing water resources. For example, the construction of the SWRO plant in Tampa Bay, Florida, was driven in large part by the need to cease depleting the natural aquifers by over-pumping wells. The days are long gone when we can build a dam, a reservoir, a pipeline, or tap thoughtlessly into our aquifers without considering the consequences.

It is important also to include early public outreach in any planned desalination project, in order to educate the stakeholders regarding the facility and its relationship with the environment. Public education is

critical in providing accurate information, addressing misconceptions about desalination, and helping to alleviate potential concerns regarding the facility. Issues surrounding the environment can be addressed proactively and mitigation measures put in place early-on in the project development.

Ongoing Research and Development

A large number of other desalination processes have been investigated over the years. Most died an early death. Some advanced to the pilot plant stage. Some were commercialized but foundered when their promised advantages failed to deliver in practice. Only a small few (MED, MSF, MED/TVC, ED/EDR, and RO) achieved and maintained any level of commercial success. But that does not mean that there is not more that can be done. Desalination R & D today may be divided into three broad categories:

1. Attempting to resurrect previously unsuccessful technologies through the use of new science, experience, materials and application opportunities
2. Developing altogether new processes
3. Proceeding with largely incremental improvements to the existing technologies

Each or all of these categories may prove successful. Each has its proponents. It is not the position of IDA to favor one approach over another. Category 1 includes membrane distillation, freeze desalting, solvent extraction and refinement of ED/EDR for use on seawater or for brine reduction. Category 2 includes recent processes being introduced under such names as forward osmosis, capacitative deionisation, closed circuit desalination, membranes incorporating nano-technology, and various low-energy evaporative technologies. Category 3 appears unambitious but has its strengths. For example, a steady 10 % annual improvement in an existing process over less than seven years yields a 100 % improvement in performance. Should that occur all at once, it would be hailed as a breakthrough. And this is just what has happened in desalination over the past 20 years.

Any proposed new technology will promise lower costs, and today, lower energy consumption is rightly much in vogue. But perhaps we should take a broader look at inherent features required of new processes. First, we may grant that most of them will work to some extent. We may insult seawater in a variety of ways and achieve a measurable level of separation. So the question is not “Will it work?”, but “Can it compete?” This is what is important. We cannot predict what a successful new process will look like, but we may anticipate some characteristics:

- It will be simple. Dr. Robert Silver, one of the founders of MSF, coined the term “morphological simplicity”. It must be capable of high throughputs, perhaps with many (e. g., stages, effects, elements) in series, but all very much alike in design and construction.
- It will be fast. We are talking about veritable rivers of water pouring through the apparatus. There must be a short hydraulic residence time (HRT), the time the feed water remains in the system. Fifty years ago,

ED earned its early success with an HRT of 8 seconds in the simplest commercial units. Today, SWRO usually has an HRT also measurable in seconds. In MSF and MED, it may be single-digit minutes. Systems with longer HRTs must be physically larger to achieve the same through-puts. Larger means more tonnage of equipment, larger footprints, and ultimately, more capital cost. Technologies with more complexity, slower heat transfer rates, or sequential regeneration steps will be inherently slower. Processes dependent upon diffusion-limited mass transfer will be at a disadvantage.

- It will operate at a high recovery ratio. Low recovery means high feed water pumping costs, possible stress on a limited feed water supply, and a greater volume of spent brine to be disposed of.
- It will be reliable. This is important at two levels. Total water cost may be defined as total annual costs (including capital recovery) divided by total annual production. Annual production in turn is a function of:

  - Name-plate capacity
  - Deviations from name-plate capacity, and
  - On-stream time (plant factor)

An unreliable plant is a costly plant. Unscheduled down-time plays havoc with economics, and reliability is an under-appreciated factor in the basis of competition for most desalination plants. Can the customer count on the water being there? It is not the primary duty of the water utility to save money by doing something clever. Its duty is to guarantee that the water supply is safe and secure.

Desalination in the 21st Century

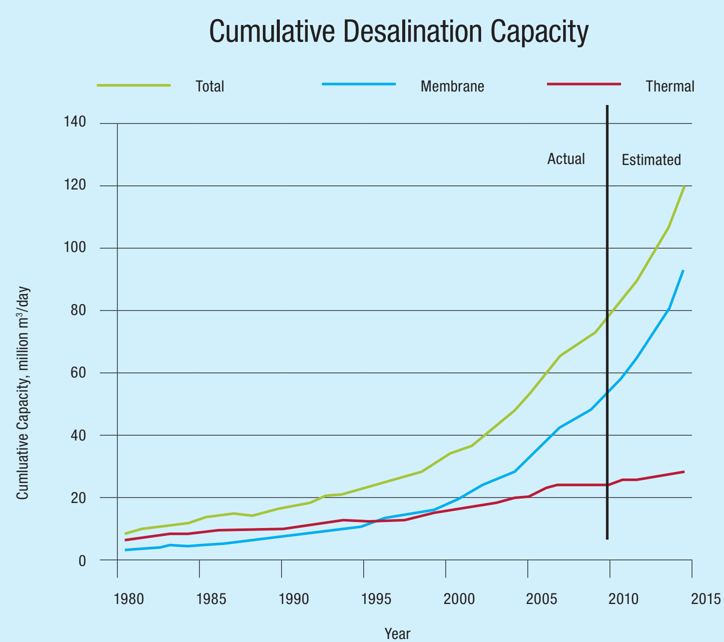
With its ability to deliver a new, sustainable supply of water to growing populations at decreasing unitary costs, desalination is a critical component of today's water management strategies. Technological improvements have significantly lowered the cost of producing desalinated water, and efforts continue to further reduce energy consumption and all other operational costs. The industry's focus on addressing environmental concerns also enables desalination to be used in an environmentally responsible manner.

Today, desalinated water is used as a main source of municipal supply in many areas of the world. There has been an explosion of demand in the Middle East and North Africa region due to population growth and high oil prices. At the same time, desalination is widely employed in many other countries such as Spain, the Caribbean, and Australia, and new markets are opening in China, India, Singapore, Chile and the USA.

The greatest growth has been in seawater desalination, and this trend is expected to continue. Reasons include over-exploitation of non-renewable groundwater resources and the increasing demand for water. Seawater desalination provides a guaranteed, sustainable supply of water, and it has become more affordable in comparison with the alternatives. Figure 20 shows the growth in installed capacity world wide over the past three decades, plus projected future values.

Present (2011) desalination expenditures worldwide are estimated by Global Water Intelligence to be about $7.6 billion in capital expenditures and $6.8 billion in operating expenditures.

Figure 20, Past and projected growth in installed capacity, in millions of m3/day



Source: Global Water Intelligence

Desalination also offers outstanding career opportunities for professionals engaged in the water industry, science or engineering. Initiatives such as IDA's Young Leaders Program are aimed at promoting opportunities for young professionals in the industry, supporting career advancement, and providing a forum for communication, networking and exchange of ideas among these emerging leaders and the industry at large.

While the current technological trend has been increased use of reverse osmosis, especially outside the Middle East, there is no “best” method of desalination. The selection of a process should be made according to a careful study of site conditions and the application at hand. Local circumstances will always play a significant role in determining the most appropriate process for a given area.

Fresh desalination technologies continue to emerge. Combining desalination with sustainable and renewable power is also developing as a green solution to water supply in arid regions. Research in desalination is ongoing in more than 30 countries, searching and developing lower-cost and environmentally sustainable desalination technologies and practices.

At its 2011 World Congress on Desalination and Water Reuse in Perth, Australia, IDA introduced the theme of “Desalination – Sustainable Solutions for a Thirsty Planet”. As our thirsty planet searches for solutions to global water issues, desalination – with its proven ability to provide a new and sustainable source of clean water – is already fulfilling this promise every day to millions of people around the world and looks confidently toward the future.

Acknowledgements

I have borrowed heavily from those IDA directors who submitted contributions to this effort. In some cases, I have edited their material so that it is barely recognizable; in other cases I have inserted whole blocks of text which are not mine. I would thank each of them individually but often do not even know who they are. Much the same may be said for the illustrations, many of which have been gleaned over the years from various sources, including product literature. At the end of the day, I take responsibility for those factual errors which have inevitably slipped through.

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