Integrated Hybrid Desalination Systems

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It is great opportunity to take part in discussions on Innovations and Applications of Sea-Water Desalination particularly in the context of developing new solutions to balance the significant increase in fuel-energy and material cost which has a dramatic impact on capital and operational cost of Desalination and Power plants. Impact of US$ 60-75 per barrel oil and high demand for raw materials, steel, copper, nickel and concrete has dramatically increased pressure to develop novel solutions which can minimize energy consumption and reduce volume and weight of desalination plants.

The integration of energy –power and water becomes of even more important today in coping with the increased costs. The desalination technology has to adapt to the new conditions and find solutions to produce plants with higher efficiency, performance ratios and minimizing the use of materials.

Desalination is an energy and capital intensive process. All seawater desalting processes, multi-stage flash (MSF), multi-effect distillation (MED), and seawater reverse osmosis (SWRO) consume significant amounts of energy and materials. In view of the rising fuel costs, the amount and cost of fuel consumed to desalinate seawater becomes one of the main factors determining the operational cost of desalted water cost. Similarly the materials selected and the increased cost of materials for desalination has significant impact on capital cost. These raising costs in turn become a major factor in choosing the method and technology to be used.

The future of water demands creative solutions. It requires effective innovations and integration of energy resources to generate power and to economically create and store desalinated water. Confronting the water challenge is essential to a country’s sustainable development and to the security of its communities. Desalination is the only realistic hope to create new water resources in the midst of water crisis and water pollution.

We need to innovate and integrate energy, power, and water. We have to look for new ideas on hybridization, energy recovery, and more effective materials and chemicals. We have to learn how to extend the life of existing plants and upgrade existing desalination facilities. The integration and Innovation approach is of critical interests to the water and power sector in the Middle East region and World Community. In an era of high energy and material cost, technology an integrated use can compensate the impact on rising cost. As desalination and water reuse expansion in the Middle East and the World continues at a rapid pace, these innovations must be integrated into the next generation of water facilities.

Introduction

The hybrid desalting concept is the combination of two or more processes in order to provide a better and lower cost product than either alone can provide. In desalination, there are distillation and membrane processes which under hybrid conditions can be combined to produce a more economic process. Thus, two or three elements that are integrated to make hybrid desalination are:
- distillation: multi-stage flash (MSF), multi-effect distillation (MED), vapor compression (VC)
- membrane desalination: reverse osmosis (RO), nanofiltration (NF)
- power: steam power plants, combined cycle power plants

Large dual-purpose power-desalination plants are built to reduce the cost of production of electricity and water. Over 30,000 MW of power is combined with desalination plants in the largest use of cogeneration concepts. In many countries, particularly in the Middle East, peak power demand occurs in summer and then drops dramatically to 30–40%. In contrast the demand for desalinated water is almost constant around the year.

The focus of this paper is on examination of hybrid systems and hybrid technology in order to take full advantage of both thermal and electrical energy as well as membrane processes.

This article is based and updated from Awerbuch hybrid chapter contribution to book by M. Wilf The Guidebook to Membrane Desalination Technology (1).

Two comprehensive studies were carried out on hybrid desalination systems by Daniel Hoffman and Amnon Zfati (1) and by Sherman May (2), and full review by Awerbuch (3).

**Description of hybrid systems**

*Simple hybrid.* In the simple hybrid MSF/RO desalination power process, a seawater RO plant is combined with either a new or existing dual-purpose MSF/power plant to offer some advantages. Several plants currently installed are using some of these advantages. Examples are in Jeddah RO, Jubail and Madina-Yanbu II in Saudi Arabia and Fujairah in UAE.

*Integrated hybrid.* The fully integrated MSF/RO desalination power process, which is particularly suitable for new seawater desalting complexes, takes additional advantage of integration features.

*Power/water hybrid.* Integration of the power and water cycle aims to obtain the optimum cost for both water and power. Important parameters in the design of these systems include:
- seasonal demands for electricity and water
- power-to-water ratio
- minimization of fuel consumption and increase in the power plant efficiency
- minimization of the environmental impact of carbon dioxide including potential consideration of CO2 tax credit.

Some of the earlier analyses in the references showed that when seasonal and daily variations occur; electrically driven technology can provide an excellent choice for hybridization with more conventional dual-purpose plants. The hybrid approach could achieve the lowest cost of total investment, flexibility in production and the lowest cost of power and water production. Water can be stored while electricity storage is not practical. In this case excess electricity can be diverted to water production incorporating electrically driven seawater reverse osmosis (SWRO) and/or vapor compression (VC) and combined with low pressure steam driven technology of MSF or MED, making it advantageous to design an integrated hybrid plant. One method of making use of idle power capacity is the use of electrically driven RO or VC plants in combination with Desalination Aquifer Storage Recovery (DASR) both for averaging the desalination capacity, for strategic fresh ground water storage or improving quality of the basin.
The increase in the unit size of MSF, MED, VC and RO will lead to reduction of capital costs, but combined with unique application of hybrid ideas will offer reduction in water cost. Effective integration of membrane/thermal desalination and power technology can reduce the cost of desalination and electrical power production (hybrid desalination).

Early suggestions for hybrid desalination were based upon elimination of the requirement for a second pass to the RO process so that the higher-salinity RO product could be combined with the better quality product from an MSF plant. This is the simplest application of hybrid desalination. Since then, other concepts have been proposed for hybrid desalination. Today although RO can produce product of potable TDS in one pass, blending allows reducing the requirements for second and third partial pass to solve the critical boron issue.

The dual purpose power-desalination plants make use of thermal energy extracted or exhausted from power plants in the form of low pressure steam to provide heat input to thermal desalination plants for MSF or MED distillation processes. The electrical energy can be also effectively used in the electrically driven desalination processes like RO and VC processes.

In the simple hybrid MSF/RO desalination power process, a SWRO plant is combined with either a new or existing dual-purpose MSF/power plant with the following advantages:

- A common, considerably smaller seawater intake can be used.
- Product waters from the RO and MSF plants are blended to obtain suitable water quality.
- Product waters from the RO and MSF plants are blended, therefore allowing higher temperature of distillate.
- A single pass RO process can be used.
- Blending distillation with membrane products reduces strict requirements on boron removal by RO.
- The useful RO membrane life can be extended.
- Excess power production from the desalting complex can be reduced significantly, or power to water ratio can be significantly reduced.
The fully integrated MSF/RO desalination power process which is particularly suitable for new seawater desalting complexes, takes additional advantage of integration features, such as:

- The feedwater temperature to the RO plant is optimized and controlled by using cooling water from the heat-reject section of the MSF/MED or power plant condenser.
- The low-pressure steam from the MSF/MED plant is used to de-aerate or use de-aerated brine as a feedwater to the RO plant to minimize corrosion and reduce residual chlorine.
- Some components of seawater pretreatment process can be integrated.
- One post-treatment system is used for the product water from both plants.
- The brine discharged-reject from the RO plant is combined with the brine recycle in the MSF or is used as a feed to MED.
- The hybridization of nanofiltration as softening membrane process of the feed to distillation plants MSF and MED could lead to significant improvement in productivity of desalination plants.
- The hybridization of MSF with MED can offer many improvements in energy utilization between two thermal processes operating at two different temperature regimes.

The energy conservation using a hybrid system

In view of dramatic rise in fuel prices in excess of US$ 60/barrel which is equivalent to US$10.3/MMBTU hybrid (RO + distillation) system offers significant saving in fuel cost in comparison with only distillation option (Fig. 2). This well demonstrated by simple presentation provided by Dr. Corrado Sommariva in his course on Thermal Desalination Processes and Economics.

**Fig. 2** A case study of a hybrid system. The thermal plant configuration 400 MW power + 100 MIGD: PWR = 4 (courtesy of Dr. Corrado Sommariva)

In this case (Fig.3) for 100 MIGD (455,000 m$^3$/d) MSF desalination and 400 MW of electric power generation plant the annual fuel cost requirement will exceed 86 million US $ based on historic fuel cost of only 1.1 US$/GJ. By comparison a hybrid 100 MIGD (455,000 m3/d) desalination plant based on 60% thermal and 40 % RO will operate at reduced fuel consumption of only 55 million US$ per year (Fig. 3). This annual fuel cost difference of over 30 million US$ per year is based on 1.1 $/GJ, considering the impact of today’s fuel price of 10. $/GJ the annual cost differential will exceed 300 million dollars and will pay back for the total Capex in less then 3 years. Of course in base case we produce more power and to some extent this compensates the additional cost, but this assumes that we need the power.
A full review of the impact of the high energy and material cost on desalination technology is described by Awerbuch (4).

There are unique conditions in the Gulf countries where peak demand for electricity rises significantly during summer mainly because of the use of air-conditioning, and than drops dramatically to 30–40% of summer capacity. This creates situation that over 50% of power generation is idled. In contrast, the demand for desalinated water is almost constant. This inequality of demand between electricity and water can be corrected by diverting excess of available electricity to water production incorporating electrical driven technology of SWRO and/or VC and combined with low pressure steam driven technology of MSF or MED, making it advantageous to design an integrated hybrid plant.

**Hybrid—the new alternative**

The idea of combining electrical power, MSF, and SWRO has been reported in a number of publications. Initial publications were in the early 1980s. The Hybrid Desalting Systems idea of combining power, MSF distillation plant and a membrane SWRO plant was previously reported to offer significant advantages (5-9).

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- Product waters from the RO and MSF plants are blended, therefore allowing higher temperature of distillate.
- A single pass RO process can be used.
- Blending distillation with membrane products reduces strict requirements on boron removal by RO.
- The useful RO membrane life can be extended.
- Excess power production from the desalting complex can be reduced significantly, or power to water ratio can be significantly reduced.

The fully integrated MSF/RO desalination power process which is particularly suitable for new seawater desalting complexes, takes additional advantage of integration features, such as:

- The feedwater temperature to the RO plant is optimized and controlled by using cooling water from the heat-reject section of the MSF/MED or power plant condenser.
- The low-pressure steam from the MSF/MED plant is used to de-aerate or use de-aerated brine as a feedwater to the RO plant to minimize corrosion and reduce residual chlorine.
• Some components of seawater pretreatment process can be integrated.
• One post-treatment system is used for the product water from both plants.
• The brine discharged-reject from the RO plant is combined with the brine recycle in the MSF or is used as a feed to MED.
• The hybridization of nanofiltration as softening membrane process for feed of distillation plants MSF and MED could lead to significant improvement in productivity of desalination plants.

The classic scheme
This is the most common and straightforward hybrid plant scheme (Fig. 4). It has been adopted in Jeddah to blend higher TDS RO permeate with distillate from existing MSF plants, and is described in detail by Awerbuch et al. (5,10) and by many other papers. In general in this scheme part of the MSF plant’s heated coolant reject is de-aerated, using low-pressure steam from the MSF plant (to reduce corrosion and residual chlorine), and used as the feed to the SWRO plant. The higher temperature of the feed improves membrane performance (flux, at constant pressure, increases by 1.5–3% for each °C). This is particularly important during the winter, when seawater temperatures can drop to as low as 15°C (59°F). The MSF plant’s distillate, at less than 20 ppm TDS, is blended with the SWRO plant’s product, making it possible to meet potable water standards for maximum TDS and chloride concentrations with higher SWRO plant product salinity. This, in turn, means that the SWRO plants can be operated at higher conversion ratios, thereby reducing consumption of energy and chemicals and extending membrane useful life.

The classic scheme variant
In one variant of the classic scheme, the SWRO plant’s reject brine becomes integrated into the feed to the MSF plant, utilizing its high pressure, with a special turbocharger, to boost the MSF plant’s recirculation pump (Fig. 5).

The once-through MSF scheme
In this scheme, described by Kamal et al. (9) Al-Sofi et al. (5), Awerbuch et al. (6,7,8) and others, a once-through MSF plant is specified, and it’s preheated and de-aerated reject, at about 47,000 ppm TDS (with Gulf 42,000 ppm TDS seawater), is used as SWRO plant feed. This scheme has the same advantages as the “classic scheme”, but benefits also from the continued de-aeration of the feed by the Non Condensable Gases (NCG) removal system, as the seawater flows through the MSF plant’s heat recovery section, and from the reduction of the seawater’s bio-fouling potential due to the high temperature sterilization effect at the MSF plant’s heat input section.

Fig. 4 The basic classic scheme hybrid system configuration.
The conversion ratio of the SWRO plant is then limited by the maximum brine recirculation concentration possible. With a once-through MSF plant this limitation is avoided.

*The duo-cycle ROMED scheme*

This is Hornburg’s duo-cycle ROMED hybrid system (11). The main feature of this scheme is the use of a high-GOR TVC (or MVC) plant in lieu of an MSF plant, but the flow scheme is also different from that of the above variant schemes. The seawater is first fed to the SWRO plant, i.e., without preheating and de-aeration in the distillation plant (TVC plants normally do not include feed de-aerators). The SWRO plant’s reject is directed, after passing through an energy recovery turbine, into the TVC plant’s heat discharge section, serving as its coolant (TVC plants’ heat rejection sections normally utilize falling-film, heat-transfer surfaces, whereas MSF plants utilize pressurized, forced circulation-flow shell and tube condensers). Part or all of this coolant is then used as the feed to the TVC plant’s heat recovery section.

*The direct-drive steam turbine scheme*

The fifth scheme was is the one proposed by Hazen E. Nelson in US Patent 3,632,505 “Evaporation-Reverse Osmosis Water Desalination System” assigned to Stone and Webster Engineering Corporation as early as 1972. It is based on an MSF-SWRO plant combination; with motive steam directed first to back-pressure steam turbines that drive directly the SWRO plant’s high-pressure pumps. The steam exhausted from the turbines is then fed to the MSF plant’s brine heater. The SWRO plant’s brine discharge energy-recovery turbines generate the electric power required for all other pumps and the system’s auxiliaries.

**R&D related to improving hybrid systems**

The R&D activities pursued today that are most relevant to cogeneration and/or hybrid systems are those relating to the creation of a wider range of nanofiltration and SWRO membranes and the pilot-plant testing and prototype plant designing of low-cost high-GOR high-temperature MED plants. As Awerbuch (6) suggested, an optimal hybrid system would benefit from SWRO membranes with higher fluxes and lower rejections than currently being offered commercially. The minimal accepted membrane rejection will be that which will give permeate with a salinity sufficient to provide, after dilution with the MSF plant’s distillate and permeate post-treatment, a combined product salinity of 500 ppm TDS. Some membrane manufacturers have been investigating the potential performance and markets for such high-
flux SWRO membranes. The ongoing work on nanofiltration membrane softening technology combined with distillation and hybrid options of NF-MSF-RO or NF-MED-RO offer new potential for improving hybrid systems.

**Fig. 6** Effect of distillation to RO capacity ratio on combined system cost.

**Quantifying the benefits of the hybrid SWRO/thermal plant scheme in cogeneration stations.**

The magnitudes of these potential savings are a function of the relative outputs of the SWRO and distillation plants Fig. 6. They are quantified below for preferred hybrid scheme developed by Hoffman et al. (2)

**Savings due to reduced seawater requirements**

The use of distillation plant coolant reject as feed to a SWRO plant within selected hybrid plant scheme reduces both seawater supply and brine and coolant rejection requirements vis-à-vis non-hybrid, separate and independent (stand-alone) thermal and SWRO plants. The cost savings are derived from four sources:

- reduced investment in the seawater intake and supply system
- reduced investment in the brine and cooling water discharge system
- reduced seawater pretreatment costs
- reduced seawater-pumping energy

**RO membrane life**

For all membranes, water permeability (i.e., permeate production) declines with operating time while product salinity and chloride concentration increases. The drop in production with time can be compensated by installing extra membrane rack space and installing additional membranes as required. The increase in product salinity cannot be compensated for except with large scale membrane replacement. Therefore, to maintain the product water quality within WHO standards, the designer of stand alone seawater RO plants has the option to replace membranes more frequently or install a two pass (seawater RO and brackish water RO) system. In the case of hybrid systems (RO + distillation), a single pass RO system can be specified while maintaining a long membrane life. This is made possible by blending the RO product water with the high purity distilled water produced by the thermal desalination unit.

**Membrane performance as a function of seawater temperature**

The use of all or some of the preheated cooling water discharge from a thermal desalination plant as feed to a SWRO plant enables elevating and controlling the SWRO plant’s operating
temperature at its optimal or any other higher desired value. Feed water temperature affects the two main performance characteristics of a membrane: flux and salt rejection. Higher feed water temperatures increase not only flux but also salt passage. Operation at higher temperature may also reduce membrane life (due to membrane compaction), but, as there are no definite quantitative figures relating to this effect, we will not include it in our considerations.

For all membranes, water production is a function of temperature, at constant feed pressure. Production will go up with temperature increasing by 1.5% to 3% per degree Celsius for nearly all membranes, thereby enabling reduction of the number of RO membrane modules required for a given permeate capacity.

This is of course condition to that feed water quality is sufficiently good that membrane fouling rate will not increase during operation at higher flux. For the fully integrated hybrid process, the above advantage can be utilized by operating the RO plant at optimum temperature and pressure conditions by using cooling water from the reject section of the MSF plant. El-Sayed et al. (12) conducted pilot study of MSF/RO hybrid systems in Kuwait and observed a significant increase in RO product water flow rate. It was demonstrated on basis of experimental data that 42–48% gain in the product water flow could be achieved for a temperature of 33°C (91.4°F), over that of an isolated RO plant operating at 15°C (59°F) during winter season. The results imply that the energy consumption of RO can be reduced without involving any form of energy recovery, to the level of 5.2 kWh/m3 (19.7 kWh/kgal) using a simple integration of MSF/RO hybrid arrangement in which the RO plant is fed the preheated seawater rejected from the MSF heat rejection section. A very interesting study was conducted recently by Nisan et al. (13). It summarizes an investigation on conceptual studies with preheating of feedwater, which is expected to lead to lower specific power consumption, higher water production, thus further reducing the cost of desalination. The results were based on Dow- FilmTec ROSA software and performance of membrane SW 30 HR 380.

The results obtained by the author based on simulation work with the ROSA program are presented for feed TDS values of 28,127, 32,163, 39,086 and 47,400 mg/l. The feed temperature was varied from 10°C to 44°C (50–111°F). The results included in these figures show the variation of the permeate production and recovery ratio as a function of feed temperature at different feed TDS values and at constant design parameters of feed flow, number elements and pressure vessels and at a constant feed pressure.

Fig. 7 indicates the possibility of increased desalted water production with increased feed water temperature applying constant feed pressure. The rate of capacity increase levels off at the higher end of the temperature range evaluated. The calculation was based on a constant feed flow rate to reflect the usual design conditions of RO pumping and pretreatment equipment. Therefore, higher permeate flows with increased temperature are associated with increased recovery rate (Fig. 8). It is quite obvious that higher recovery can be obtained with lower salinity feed, which has clear process implication when we consider Nanofiltration in front of RO system or use of blending seawater feed with lower salinity water (concentrate of brackish RO for example) to lower the feed salinity to RO system.

Higher membrane permeability at elevated temperature may also result in higher recovery rate. However, higher feed water temperature and recovery rate is associated with an increase of osmotic pressure (Fig. 9).
The permeate TDS systematically increases as the feed temperature and recovery rate are increased (Fig. 10). Fortunately, this salinity increase can be easily compensated in hybrid systems (RO + thermal desalination unit) where the ratio of distilled water to membrane permeate can be controlled to achieve required product TDS.

The increase of recovery rate at constant feed pressure at increased temperature in a RO hybrid system leads to reduction of specific power consumption (Fig. 11).

A direct consequence is the reduction of the desalination costs with increased feed temperature as shown in the Fig. 12.
Naturally, for given temperature the desalination cost increases with higher feed TDS. The economics of RO operation was calculated using DOW EVA Elements Value Analysis program. All computer runs included as input values the same feed flow rate, number of elements and feed pressure, which gave good approximation of impact of temperature and feed salinity on a life cycle cost. The above calculations illustrate the potential for improved economics of operation of RO at elevated feed water temperature in hybrid systems (RO + thermal desalination unit). The full economic benefits of increased membrane permeability can be realized if it would be possible to operate RO membranes at much higher permeate flux rate than is custom today. Operation at high flux rate will require feed water of high quality. It is very likely that it will require incorporation of membrane pretreatment seawater RO process to achieve sufficiently improved feed water quality. Some of the critics of higher temperature of operation of RO and NF membranes suggest higher rate of fouling due to increased biological activities. If this is the case an
effective method of biological control would have to be developed for high temperature operation. The increase of seawater temperature which is happening inside the condenser or rejects section of the distillation plant is being achieved in a matter of seconds. The assumption is that these rapid rates of temperature increase my act as a thermal shock, possibly reducing biological activity in seawater feed to the membrane unit. Another issue of concern is the compaction of membrane material (permeability decline) during long term operation at high feed pressure and elevated temperature. Both of these issues will have to be tested in field conditions and their effect evaluated against economic benefits of operation of RO unit at elevated temperature in a hybrid system configuration.

**Performance of nanofiltration membranes as a function of temperature**

In nanofiltration systems the increase of temperature of seawater feed could result in higher rate of water permeability increase than it is expected in RO unit. This was one of conclusions of theoretical evaluation work by Agashichev published recently (14). According to author concentration polarization is a significant factor in reduction of available net driving pressure (NDP). In nanofiltration membranes concentration polarization increase with temperature is lower then in RO membranes due to significantly higher salt transport through NF membranes. In hybrid systems use of Nanofiltration membranes operating also at higher temperatures, due to available heat from power plant condenser or reject section of distillation plants in combination with RO and MSF/MED, has some additional opportunities to reduce desalination costs.

![Fig. 13 Membrane flux vs. temperature at constant feed pressure.](image)

This is shown in the data from the joint research on the new LET NF process conducted by DOW FilmTec and Toray under the direction of LET. As shown in Fig. 13 the improvement in productivity is from 2.5 to 3 times at 55°C vs. 25°C (131°F vs. 77°F) for specific Nanofiltration membrane SR 90. For other Toray NF membrane the dependence on temperature of operation is shown in Figs. 14 and 15.

![Fig. 14 Passage of ions and flux as a function of temperature.](image)
Specifically by using feed comprising variable proportions of softened seawater and water containing a higher concentration of hardness ions than the softened stream, concentration of hardness is sufficiently reduced, thereby allowing a beneficial increase in the TBT of the distillation desalination process.

Higher operating temperatures provide an increase in productivity, recovery and performance at lower energy and chemical consumption. As a result, the cost of desalinated water production, including operation and maintenance could be significantly reduced.

Savings due to control of SWRO plant feed temperature

The feed water temperature elevation in any hybrid plant will be a function of the mix ratio of seawater and reject cooling water forming the feed. This mix, in turn, depends on the amount of cooling water available (i.e., the GOR and design temperature rise in the heat rejection condenser of the distillation plant) and the ratio of the outputs of the SWRO and the thermal plants.

The main results are:

1. Hybrid plants have the potential to increase the average annual membrane permeate flow through increased flux rate and reduce the required membrane surface in the SWRO plants from 10.5%, when only thermal plant cooling water is used as SWRO plant feed, to 4.6%, when the ratio of the outputs of the SWRO and thermal plants is 6:1.

2. The corresponding increases in salt passage and SWRO plant product salinity will range from 4% to 9%. The US $0.6/m³ ($2.3/kgal) membrane cost saving figure will be compounded by the savings due to the reduced investment in a range of other items of equipment related to the number of membranes in the plant. These include the membrane pressure vessels, the stainless steel high-pressure connection pipes and fittings, membrane racks, etc. Hoffman estimated the investments in these items as US $90–100/m³/d, or about 10% of total plant investment.

Savings due to blending SWRO and distillation plants’ products

The blending of SWRO and thermal plants’ products makes it possible to use the low-salinity (less than 20 ppm TDS) distillation plant product to compensate for higher salinity SWRO plant product. Based on past operating parameters of low recovery rate with current SWRO membranes performance (initial salt rejections of 99.6–99.8%), it is possible to obtain a lower than 500 ppm TDS product water in only one pass operation, even with high-salinity Gulf and Red Sea seawater (rather than with two passes, as required ten years ago).
ago, when membrane salt rejections were only 99.2%). However, if the plants are designed to operate at the high conversion ratios used today in most modern SWRO plants, 45–50%, it is projected that product salinity will exceed 500 ppm TDS after about four years of operation, as a result of membrane performance degradation. In fact, the maximum operating pressure allowed for the selected membrane turned out to be the critical factor limiting membrane lifetime. This limit was 12 years, an extension of seven years to the guaranteed five-year lifetime and eight years above the four-year limit, corresponding to operation without any blending (i.e., the expected lifetime in non-hybrid SWRO plant). Thermal desalination plant product salinity was assumed to be constant, at 20 ppm TDS.

The membrane replacement cost savings due to the blending of products within a 150,000 m3/d hybrid plant, within the above range of SWRO and thermal plants’ output ratios, are shown at the optimal output ratio of 2:1. The savings in membrane replacement costs in the corresponding 100,000 m3/d (26.4 MGD) hybrid SWRO plant, compared with its equivalent 100,000 m3/d non-hybrid plant, are about US $1,172,000 per year, or about US ¢3.6/ m3 (¢13.6/kgal).

**Increased recovery ratio**

Recovery ratio (conversion) is one of the key RO design parameters. It determines the size of the feedwater handling system (e.g., intake, pretreatment, high pressure pumping) for a given plant size. Higher recoveries decrease the cost of the feedwater handling system and the required electrical and chemical consumption while increasing the initial and replacement costs of the membrane system. Some of the reasons why higher recovery ratios have not been used in the past are related to the performance characteristics of the membranes and the product water quality specifications. Higher recovery ratio increases required feed pressure due to increase of the average osmotic pressure in the RO system. Also, due to the salt rejection property of available membranes, product water specifications (typically 500 ppm TDS and/or 250 ppm chloride) could not be easily met at higher recovery ratios. In a hybrid system, higher recovery ratios of RO unit can be incorporated into the plant design. Operation at increased feed water temperature requires lower NDP therefore provides some compensation for increased osmotic pressure. Blending of RO permeate with very low salinity distillate enables attaining the overall product water quality specifications.

**Feedwater deaeration**

Most aromatic composite membranes require dechlorination of the feedwater as they are very sensitive to even very small concentrations of residual chlorine and/or bromine. If feed water to an RO system is being chlorinated then addition of large quantities of sodium bisulphite is required to reduce free chlorine in the feed water. As an alternative, free chlorine removal can also be accomplished by use of a deareator, followed by significantly reduced quantities of sodium bisulphite. Deaeration of the feed water also reduces corrosion significantly. In the case of hybrid systems, low pressure steam suitable to operate the deareator is readily available from the MSF plant at low cost. Deaeration can reduce the specification for high pressure piping from SMO-254, SS-317L to lower grades and more economical SS 316L.

**Examples of existing hybrids**

**Jeddah hybrid**

The results of conceptual and design work (5, 6) led to construction of the simple hybrid project at Jeddah 1, phase I and II plants. The Jeddah 1RO plant is 30 mgd (113,600 m3/d) combining Phase I which has been operated since 1989 and Phase II has been operated since March 1994. The plant is owned by the Saline Water Conversion Corporation (SWCC),
design by Bechtel, constructed by Mitsubishi Heavy Industries, Ltd., under the supervision of SWCC technical committee. Al-Badawi et al. (15) reports the operation and analysis of the plant which utilized Toyobo Hollosep double element type hollow fiber RO modules. The Jeddah complex in addition to 30 mgd RO permeate, produces 80 mgd distillate from Jeddah II, III and IV and 924 MW electricity. Jeddah I RO plant adopted successfully an Intermittent Chlorine Injection method (ICI) in order to prevent membrane degradation by oxidation reaction and bio-fouling.

Yanbu – Medina hybrid

Objective to minimize power to water ratio lead to construction of Madina and Yanbu Phase II. Nada et al. (16) describes the design features of the largest SWRO plant in the Saudi Kingdom of 130,000 m3/d (33.8 mgd) in Madina and Yanbu. The plant is able to produce power 164 MW electricity and 288,000 m3/day (76 mgd) of desalinated water. Two 82 MW back pressure steam turbine (BTG) provides steam to four 36,000 m3/d (9.5 mgd) MSF distillation units and the electricity to fifteen RO units of 8,500 m3/day (2.25 mgd), each. Although the plant was not design as an integrated hybrid it provided very good example of significant reduction of the power to water ratio (PWR).

Fujairah hybrid

This seawater desalination and power plant is the largest in the world hybrid configuration of thermal processes and reverse osmosis to be implemented up to now. The paper presented by Ludwig (17) describes in the design considerations for this hybrid plant. The latest excellent description of the Fujairah Hybrid is contained in a paper presented by Doosan (18) describing the design and two years of operation. The Fujairah plant due to hybridization generates only 500 MW net electricity for export to the grid, and 662 MW gross for water production capacity amounts to 455,000 m3/d (100 MIGD) shown in Fig 16. Otherwise similar MSF only plant in Shuweihat required 1500 MW for the same 455,000 m3/d (100 MIGD) capacity.

The Fujairah desalination plant is split into 284,000 m3/d (62.5 MIGD) from the thermal part and 170,000 m3/d (37.5 MIGD) from the membrane process. The power plant is configured as a combined cycle with supplementary firing. It comprises four gas turbines each rated 109

![Fig. 16](image)
MW (oil- or gas-fired) and four heat recovery steam generators each of 380 t/hr at steam parameters of 68 bars/537°C that supply the two steam turbine generators. The expanded steam from the turbines serves as process steam for the MSF units.

The Fujairah Project uses gas that is currently imported from the Sultanate of Oman, and will soon be imported from Qatar, when the Dolphin project is completed at a fuel cost of $1.6 per million Btu. At a rather low power-to-water ratio of 500 MW-to-100 MIGD, a hybrid MSF/RO technical solution was extremely attractive for the Fujairah project. Doosan Heavy Industry and Construction Company were selected as the EPC contractor through an open and competitive bidding process. The main contract was awarded in June 2001. Doosan selected Degremont as a subcontractor to receive the basic design and major equipment supply of the SWRO Plant. During the design stage an extensive pilot plant testing of the RO process was conducted to confirm the performance of the technical solution selected for pretreatment and to determine the impact of dosing of various pretreatment chemicals.

The 100 MIGD (455,000 m3/d) water productions started on June 31, 2003, with a total construction, commissioning, and startup time of less than two years. The Total Dissolved Solids (TDS) of the product water from MSF units was specified as 25 mg/liter, whereas, that from RO plant was not specified in Request for Proposal (RFP) documents from the client. However, the TDS of potable water after remineralization was specified as less than 200 mg/l. In order to meet the potable water quality of the MSF/RO hybrid process, RO plant should produce desalinated water having less than 180 mg/l of total dissolved solids at the end of fifth year to make blended product water having 60 mg/liter of TDS. The RO plant is designed as a two-pass system, specifically to obtain the low chloride and TDS contents of the drinking water required for corrosion suppression.

The seawater desalination processes are designed for seawater TDS of 40,000 ppm and a seawater temperature design range of 22–35°C. Specified for the drinking water product is a maximum TDS of 200 mg/l and its chloride content should not exceed ~85 mg/l.

The blended product from MSF and SWRO is treated in a joint potabilization facility, supplied by CO2 from the MSF vent gases.

To compensate for the conditions that one of the MSF units being taken out of service or for enhanced hardening of the water, the CO2 demand can be met by an additional CO2 generation plant.

Seawater intake. The seawater intake is located at 320 meters from the seashore at 6 m above the seabed and 6 m below the surface of the mean sea level. The seawater intake system consists of three submerged pipes 1200 mm diameter, and 500 meters long. Minimum depth at intake point is 9–10 meters. The seawater intake serves RO Plant, MSF Plant and as well as Power Plant. Two of the pipes are dedicated to the MSF Plant for which seawater is chlorinated continuously. The third pipe is allocated to the SWRO Plant only. This to allow intermittent shock chlorination of the seawater used for RO to be carried out rather then continuous chlorine dosing applied to MSF feed. Two of the ten raw seawater pumps are assigned to the RO Plant. For this plant a design decision was made to separate intake for the RO plant, through which the specific chlorination requirements for SWRO can be maintained. It was chosen over the use of a common seawater extraction system. Feeding of preheated cooling water from the MSF reject section to the RO plant was also rejected because, here too, only water that had been chlorinated continuously, and in part shock dosed, was available.

In my opinion this decisions are controversial and in the future more considerations could be given to take clear advantage of common intake and feed temperature control. A study of
shock chlorination on top of residual chlorine or de-aeration/dechlorination of RO feed could allow the benefits of hybrid integration.

**SWRO plant.** The RO Plant consists of two independent identical lines, called Line A and Line B. Each Line includes nine First Pass RO trains and four Second Pass RO trains. The First Pass RO train is designed to produce desalinated permeate water with a TDS of maximum 590 ppm at design condition at the end of fifth year. However, if the permeate water with a TDS of 590 ppm, set as design salinity limit from a single pass of RO plant, is blended with 25 ppm of desalinated water from MSF plant, the specified potable water quality target of 200 ppm could not be accomplished. Should the required quality (TDS) of potable water were above 300 ppm, which is still far better than WHO recommendation, only single pass of RO plant could have been enough for the hybrid plant. Then, this would have resulted in a more attractive economics of the MSF/RO hybrid water plant. The first pass is design for a recovery rate of 43% and consists of 18 trains, with 17 normally being in operation and one on standby. The second pass that consists of eight trains has a capacity of 74% of the maximum total output of the SWRO, and is designed for a recovery rate of 90%.

**MSF plant.** The MSF plant consists of five MSF units, each producing 57,000 m3/d (12.5 MIGD). The evaporators containing sixteen heat recovery stages and three heat rejection stages. It have been manufactured as a single module in South Korea and transported to the site on a barge. The thermal desalination segment of the facility comprises five MSF units each of 57,000 m3/d (12.5 MIGD) capacity, with a performance ratio of 8 and a top brine temperature (TBT) range of 107–109°C (224.6–228.2°F). Fujairah plant-MSF area overview is shown in Fig.17.

![Fig. 17 Arial view of the Fujairah MSF desalination plant.](image)

**Performance of the Fujairah hybrid plant**

Fujairah hybrid performance as reported by Sung W. Woo et al. (18) of Doosan deserves a more detailed review but is briefly summarized.

**MSF plant performance.** The performance of each MSF unit in terms of distillate flow rate and distillate conductivity is much better than the design and guaranteed values. The average performance ratio of the MSF units was in the range of 9.1~9.5, which was higher than guarantee value of 8.0 at design condition. During the reliability and performance test, specific power consumption of MSF plant including potable water plant was about 4.4 kWh/m3 (16.7 kWh/kgal) of product water which is less than guaranteed value 5.1 kWh/m3 (19.3 kWh/kgal).
Plant performance (SWRO). The SWRO plant commenced operation on June 31, 2003. The plant has performed satisfactorily, complying with all contract obligations as regards to water quantity and quality in accordance with performance specification defined in tender document. The RO plant is shown in Fig. 18.

Performance of pretreatment section

During the last year, the Silt Density Index (SDI) remained between 3 and 4, which is much below the SDI limit value of 5.0, as specified by the membrane manufacturers. Backwash frequency of media filters also remained at design frequency, one backwash per 24 hours.

Fig. 18 Fujairah plant SWRO racks and feed pump/ER turbine

RO membrane performance

Normalized permeate flow rate and salt passage. The normalized permeate product flow rates are higher than the projected initial permeate flow rates and the initial normalized salt passages are less than that of the projected salt passages until the beginning of October 2004. Therefore, since their loading on April 2003, the membranes need not be cleaned nor replaced. All trains showed a trend of improving conductivity with time when operated continuously. Projected pressure is 67.6 bar (972 psi) while the actual pressure ranges between 67 and 67.5 bar (971–972 psi). Based on this comparison of projections with trains in Line B, the membranes are performing as expected, even though the operation of the trains was intermittent and for short periods of time. Performance trend indicates that continuous operation of the trains will produce permeate conductivities equivalent to or below the projected values. The performance of SWRO membranes is good enough up to now even without chemical cleaning or membranes replacement. Boron concentration was not of RO permeate quality specifications. Therefore, no particular equipment such as pH control or ion exchange bed, etc. has been installed. However, RO plant provided eighty percent (80%) of boron rejection, resulting in 0.7 ppm content in desalinated permeate water. When the permeate water from the SWRO plant was blended with the product water from MSF plant, the boron content in the mixed water was 0.3 ppm, which is less than WHO recommendation (0.5 ppm). In conclusion, the overall membranes performance is good till today.

Overall Fujairah conclusions

The combined power consumption of the Fujairah hybrid (SWRO + MSF) plant is lower than would be required by an MSF plant of the same capacity. The possibility of blending of RO permeate with MSF distillate enables reliable production of potable water of very low salinity in respect of every constituent, including boron. A proper combination of MSF/RO hybrid
desalination plant to reduce capital and water cost depends on various parameters such as power-to water ratio, potable water quality, system configuration, etc. Up to now, the potable water quality (TDS) from MSF plants in Middle East has been specified as less than 150 ppm. However, if the potable water TDS of an MSF/RO hybrid desalination plant is specified to be around 250–300 ppm, which is still quite less than WHO recommendations, then MSF/RO hybrid plant water will become much more competitive against MSF plant only, resulting in lower water cost.

Hybrid variations

As the concepts and applications of hybridization are accepted between distillation processes and RO, we believe that membrane manufactures will develop a new generation of membranes. This new generation of membrane (7,19, 20) is characterized by a very high specific flux about double the flux of the current generation with small reduction in salt rejection. The current high flux membranes, developed for brackish water desalting demonstrated the ability to significantly reduce the cost of desalting and will be ideal for hybrid plants that include distillation units.

Hybrid system using multi-effect distillation

Multi-effect distillation (MED) is in our opinion the most important large scale evaporative process offering significant potential for water cost reduction.

The major potential advantage of MED process is the ability to produce significantly higher Performance Ratio (PR) in excess of 15 pounds of the product per pound of steam where MSF practical limits PR to 10. The size of MED units is growing rapidly. In Sharjah SEW operated for last two years the largest commercial MED units of 22,700–36,4000 m3/d (5–8 MIGD). Similar capacity unit is under construction in SEWA Layyah Station, and the design and demonstration module already exist for 45,500 m3/d (10-migd) unit. MED recently received a lot of attention, as a result of numerous commercial successes of Thermocompression like MED for Al Taweelah A1 a 53 MIGD (240,000 m3/d) capacity plant. In general MED capital cost today varies from US$ 1000–1300/m3-d (US$ 4.5–6.00/igpd) capacity. The future calls for increasing top operating temperature, finding new ways to improve heat transfer performance to reduce heat exchange area, search for an increase in heat transfer performance by tube enhancement, and use of very thin wall in tubular materials. The critical challenge is to adopt Nanofiltration as means to dramatically increase output and increase efficiency of MED plants.

Hybrid using nanofiltration-membrane softening

Membrane softening technology adapted to hybrid with distillation processes could lead to significant increase in productivity of existing and future distillation plants as well as resulting in better process economics. Similar to reverse osmosis, nanofiltration (NF) is based on solution-diffusion as major transport mechanism; however, nanofiltration membranes contained fixed (negatively) charged functional groups on the membrane surface. As a result, the selectivity of NF membranes for monovalent and bivalent anions is significantly different as compared to regular RO membranes. Specially designed NF membranes have capability of high rejection for divalent ions (Ca, Mg and SO4), while allowing relatively high passage of monovalent ions (Cl, Na and K).

Nanofiltration hybrid background

The basic idea of use of ion selective membranes as a presoftening process for seawater distillation goes back to early publication in 1980 by Wensley et.al. (21) and Furukawa
communication (22). Today pioneering work on Nanofiltration membrane NF softening technology as applied to desalination processes and specifically to seawater desalination is under active development by two groups the Leading Edge Technologies Ltd (LET) based on granted patents Awerbuch (23) and the Saline Water Conversion Corporation (SWCC) of Saudi Arabia based on Hassan patent (24). Numerous publications described the concept Awerbuch (8, 25-27) and SWCC published extensively the results on tests of NF at the Research Desalination Center at Jubail and the plant at Umm Lujj, Hassan, Sofi et.al. (28-30). The latest status of both NF Technologies are described in the proceedings of IDA World Conference in Singapore 2005 Awerbuch (31) and Hamad et al. (32). The LET and SWCC have two different solutions but both are based on effective use of Nanofiltration softening membranes to increase efficiency of desalination process.

In case of LET the basic claim is that:

1. An improved desalination process to produce potable water which comprises:

(a) passing a first stream of water containing a high concentration of hardness ions through an ion selective membrane to form a softened water having a reduced content of hardness ions;
(b) blending the softened water with a second stream of water containing a higher concentration of hardness ions than the softened water to form a feed to a desalination system;
(c) introducing the feed to the desalination system to form a water product of potable quality, wherein the improvement comprises the introduction of a feed of variable proportions of the softened and second stream of water to the desalination system to increase the top operating temperature of the system and increase recovery of potable water.

The LET invention of partial softening of the stream feeding desalination processes sufficient to achieve reduction in scaling potential can be directed to both to thermal processes like MSF, MED and VC and membrane processes like RO and as well as is an improvement on hybrid system. The inventions comprises the operation of ion selective membrane at variable pressure as a function of the cost of electricity, use of waste or reject heat to improve fluxes and soften only variable portion of the stream to be able to increase the operating temperature and recovery.

The scaling of seawater concentrate or recycle brine occurs due to inverse solubility of calcium sulphate at higher temperatures. At higher operating temperatures and high recovery or concentration factor the stable crystal form is Anhydrite and Hemihydrate. In order to take advantage of higher productivity of distillation plants, through operation at higher temperature, we need to reduce calcium hardness and/or sulfate ions concentration in the feed water.

**Design Experience with Nanofiltration Hybrid for MSF.**

The great potential of nanofiltration membrane softening technology was brought to focus by recent award by Sharjah Electricity and Water Authority (SEWA) to Besix Leading Edge Water Technologies for the first commercial LET Nanofiltration System to increase capacity of existing MSF plant from nominal 22,7000 m3/d to 32,800 m3/d (5 MIGD to 7.2 MIGD) see Fig 19. This over 40% increase in capacity of MSF unit was a result of a two year demonstration and simulation program developed jointly with SEWA.

The data analysis and modeling of the Test Data provided extremely valuable information allowing improvements in operations as well the development of an integrated program for the optimization of the power-desalination plant. The results demonstrated that the output of the existing plant described by Sommariva et.al. (33) was increased from the designed capacity of 1,010.5 t/h at 105°C (221°F), or the designed capacity of 1,044.4 t/h at 110°C (230°F) to an output of 1253 t/h.
This is equivalent of raising output from 5.33 MIGD to 6.61 MIGD, a 24% increase in plant output without any major modifications having been made to the plant. The maximum production of 1,260 t/h, equal to 6.65 MIGD, was achieved when the TBT was increased to 117°C (242.6°F) with conductivity of product at 454 S/cm² (Fig. 20).

This was the first time anywhere that a commercial MSF plant using chemical additives was operated at these TBT temperatures. At these elevated temperatures the major concern is scale formation of calcium sulfate. Due to the simulated conditions of the LET NF System, no fouling of hard scale or soft scale was encountered at these elevated temperatures, and the plant operated in a reliable fashion throughout the test period. In fact the subsequent analysis of the critical.

Fouling Factor (FF) in the brine heater indicated a decline. This reduction in the FF was possible due to an increased dosing of chemical anti-scalant and was stabilized applying a Tapproge procedure (on-line continuous mechanical cleaning system utilizing specially engineered sponge rubber balls which are cycled with seawater through the condenser tubes.

These very good FF results were achieved not withstanding the fact that during the runs the recycle brine concentration was higher then specified by LET. The on-line acid cleaning which removed soft carbonate scale and brought the MSF to higher production than before the
test demonstrated that there was no build up of hard scale and the lower FF implied that also there was no build-up of soft scale during high temperature runs. Notwithstanding these good FF results the team developed additional means to protect the MSF plants from scale.

Any MSF plant will produce more output with an increased flashing range (defined as TBT minus blowdown temperature), or with an increased recycle flow or both Fig 21. The analysis clearly demonstrated that with achievable increased flashing range and brine recycle flow (normalized) it is possible to produce 1,309 t/h of distillate at 118°C (244°F). One of the main constraints was the increased conductivity in the last stage during the periods of highest temperatures, which forced a reduction in the flashing range, and therefore, reduced the maximum output. The data analysis identified many reasons why the last stage vapor velocity exceeded significantly the normal design. The data analysis identified excessive flashing of the makeup in the deareator, stripping steam flow from stage 13, and heat transfer from upper, high temperature, stages to the last stage, due to the “double-deck” construction of the plant.

![Fig. 21 Distillate production as a function of flash range at the Sharjah plant.](image1.png)

While certain features of the plant need to be adjusted to further increase and maximize the plant output, in response to higher operating temperatures and increased product volumes, no major technical issues were encountered that could prevent the application of the LET technology. Once the plant has been suitably modified and upgraded in accordance with mutually agreed recommendations the MSF plant will operate reliably at maximum output (34).

![Fig 22 Layyah Integrated Upgrading the NF System](image2.png)
The additional capacity (Fig. 22) is achieved without building new intake structure or new power plant in a very limited space which would not allow construction of new desalination plant. The system involves construction of NF plant to provide partial membrane softening of feed to MSF as well as modifications to existing MSF plant to be capable to achieve the increased capacity.

The concentration of sulfate and calcium ions determines in the distillation process the top temperature and concentration factor. Even partial elimination of calcium and sulfate from the feed will dramatically improve the performance of distillation plants. By increasing top temperature from current 95–110°C to 120–125°C would increase water production from existing MSF plants by 25% to 45%. The partial removal of sulfate and calcium ions from the feed has a multiplying positive effect on reduction of scale potential. With the current high quality materials of construction the negative corrosion effects of higher temperature would be minimal. The NF system will substantially increase water production from MSF plants.

![Fig. 23 MSF capacity increase vs. TBT.](image)

**Design and construction of the commercial let NF plant.**

The construction of first commercial nanofiltration Hybrid plant with existing MSF awarded to Besix Leading Edge Water Technologies JV is now completed and the final performance testing boosted the output of the MSF unit to over 7.5 MIGD of desalinated water in the Sharjah Emirate (35).

- Projected benefits of NF—MSF plant at Sharjah:
  - Increase the capacity of the existing MSF plant by 44%, from 22,700 m³/d to 32,800 m³/d (5 MIGD to 7.2 MIGD)
  - Minimum footprint (site has no room new additional plants)
  - Reduction of operating cost
  - No change to existing intake structure
  - No increase of power facilities
  - Reduction of capital cost for additional capacity by 40%

The additional capacity is achieved without building new intake structure or new power plant in a very limited space which would not allow construction of new desalination plant Fig. 23.

**The main features.** The softening process is based on nanofiltration technology, apart from an optimized hydraulic operation; the implementation of the technology allows the thermal units to be safely operated at an increased Top Brine Temperature (TBT) thus allowing to substantially increasing the potable water production.
The plant incorporates the following features:

1. A blending system for hot and cold seawater to keep the feed water temperature in the right range. The blending facilities are located at MSF plant. After blending, the water is pumped to the nanofiltration plant Fig.24.

2. The raw seawater needs to be pre-treated to avoid fouling and clogging of spiral wound NF membrane elements. Therefore, the water is first pre-treated by means of sand filtration.

![Fig. 24 Integrated Upgrading Temperature Blending System at Layyah](image)

In order to enhance the efficiency of this pre-treatment, before it enters the sand-filters, the water is pre-treated by means of pH control and coagulation/flocculation.

3. After sand filtration, the water passes a cartridge filter system which acts as a final barrier to retain water contaminants. This filter system is to be considered as a guard cartridge filter system which “boosts” the feed water quality after the sand filters and which protects the membranes in case the efficiency of the sand-filtration units is reduced.

4. Prior to the injection of the pre-treated seawater in the membrane, the water is conditioned in order to maximize membrane life time and in order to reduce the risk of bio fouling and scaling. The treatment incorporates the injection of SBS to remove free-chlorine, the shock dosing of biocide to control bacteriological growth and the continuous, on-line dosing of anti-scalant.

5. Water then passes a two stage nanofiltration membrane system. In order to pass the water through the membranes, medium pressure pumps are used. After the membranes, seawater is partially discharged as permeate—which is the softened water—and as concentrate—this is rejected and pumped back to the sea.

6. Each membrane system is subject to clogging. This clogging can be caused by biological fouling as well as through scaling phenomena. When this “clogging” reaches a certain level, the system pressures will reach their maximum operational values. Membranes need than to be cleaned by means of different chemicals. This is executed “in situ” (after which the system can be taken back into service.)
7. Due to the specific site conditions at the power plant, the gravity discharge of the rejected concentrate and drains is not possible. Therefore, all waters are collected in a pump-pit below grade level after which the water is pumped to the existing outfall culvert.

8. After leaving the membranes, the softened water is discharged to an intermediate storage tank. From this tank, the water is pumped at a controlled flow to MSF where it is injected in the deaerator and/or in the hot-well. The storage tank offers a spare capacity of approx. 1–1/2 hour which allows TBT of MSF to be reduced when softened water feed is interrupted due to failure of the nanofiltration plant. The feed water source for the NF system is tied in to the seawater piping of the existing MSF unit from where it is pumped to the location of the NF facilities.

In order to obtain the most optimum feed water temperature for the NF membranes, “cold”—and “hot” seawater can be “mixed” before the NF supply pump to achieve constant temperature to NF around the year. Maximum temperature of the water actually entering the membrane should be in range and not exceed 38–40°C with today available membranes.

In order to optimize the performance of the pre-treatment and the NF-membranes, the feed water flow is pre-conditioned by chemicals. This main purpose is to obtain better SDI values after the pre-treatment and to control the pH range of the feed water to optimize the water chemistry with respect to membrane scaling and softened water production. The pH control is obtained through the in-line addition of HCl. Better SDI values are obtained by enhancing the filterability of the feed water flow through the addition of chemicals which favor flocculation. All chemicals are dosed in line and mixed with the feed water by an in-line static mixer prior to the sand filters. There are 8 sand filters which can be operated as a single stage unit or as a dual stage unit Fig 25. The sand filters are pressurized and are of the dual media type which means that two filter media are used (filtration sand 0.45 mm and hydroanthracite) in the same vessel. The cartridge filter serves as safety filter prior to the main booster pump and the membrane system. The system incorporates 12 separate pressure vessels which contain each a cartridge filter with high filtration efficiency. Water can only be directed to this cartridge filter if the sand filtration units work properly and the water after the sand filters meets the quality requirements (SDI <4).

NF-membrane system. The system is of the two stage design and incorporates the following features using Dow Filmtec Nanofiltration XUS229323 elements:

1. **One main-booster pumps** to pressurize the feed water prior to injection in the membrane system. System pressure: 12.5 to 17.5 bar (181–254 psi).

2. **First stage NF membrane treatment**—80 pressure vessels with 480 membranes. The first stage is split-up in two identical skids (arrays), which 40 pressure vessels each and 240 membranes each. During the membrane filtration process, the feed water is split-up into two flows: the permeate (the softened water) which passes the membrane and the concentrate which did not pass the membrane and is “rejected.” The permeate from the first stage is collected and flows to the product water tank, the concentrate serves as feed water for the second stage.

3. **One intermediate booster pump** which re-pressurizes the concentrate of the first stage (= feed water the second stage) prior to injection in the second stage. System pressure: 15–20 bar (218–290 psi).

4. **Second stage NF membrane treatment**—40 pressure vessels with 240 membranes. The second stage incorporates one skid. During the membrane filtration process, the feed water (which is actually the concentrate of the first stage) is split-up into two flows: the permeate (the softened water) which passes the membrane and the concentrate which did not pass the
membrane and is “rejected.” The permeate from the second stage is collected and collected in a product water tank; the concentrate is discharged to the outfall pit from where it is returned to the sea.

The two stage design allows to obtain a high recovery rate (recovery = ratio between useful softened water output and total feed water flow to the membrane system). The recovery rate of this system is approx. 70%. When the NF plant is into operation, the softened water storage tank is full and no alarms from the NF plant are communicated back to the MSF automation system, the output of MSF 9 can be gradually increased until an output a potable water of 7.2 MIGD is reached. Throughout this process, plant data should be monitored (including the plant fouling factor). At first, total NF permeate flow (softened water) is be directed to MSF 9. The water will be injected by preference prior to the de-aerator. However, flooding of the de-aerator should be avoided. Flow can be directed to the de-aerator up to the point of flooding; the remaining softened water flow to be directed to the hot well. This will be tested prior to increasing the TBT. The TBT shall not be increased by more than 2°C (3.6°F) at a time and should never exceed 121°C (250°F). When a capacity of 32,800 m3/d (7.2 MIGD) is reached, TBT should not be further increased, even if TBT at that moment is lower than 121°C. The Control system is arrange in such a way that MSF plant can return safely to lower temperature of operation below 110°C (230°F).

**Fig 24** Configuration of LET NF system for Upgrading MSF capacity
There are many potential variants for NF hybridization with NF-MSF-RO as well as NF-MED-RO. Below are a few examples developed by Bechtel-LET and proposed for large scale implementation.

The case above (Fig. 26) is the basic case of NF system similar to previously described as a SEWA project. The following schematics (Fig. 27) shows a combination of preheated feed being softened and fed to MSF and RO based on optimum split between to desalination processes to achieve the lowest product cost.

In the final scheme (Fig. 28) the seawater is preheated in MSF reject section, and then is softened by nanofiltration membrane, follow by SWRO. The reject brine of SWRO has significantly reduced level of scaling ions sulfate, calcium and magnesium and therefore the reject brine can be the feed for distillation plant.

NF membrane softening technology could significantly improve operation and reduce the cost of the MED process, specifically when applied to MED processes using advanced heat transfer surfaces like double fluted tubes, by eliminating the risk of scaling and fouling. NF
technology will permit increase in the top temperature resulting in significant increase in output and performance ratio.

**Fig. 28** The hybrid with NF and RO reject feeding MSF.

**Hybrid systems using vapor compression distillation**

The Vapor Compression distillation (VC) technology offers unique potential. Today power/MSF/MED/RO plants can be hybridized with VC to take advantage of increase distillation output, using electrically driven technology. Currently the largest scale unit of VC is 3000 m³/d capacity or 0.8 mgd in a single unit, which consists of three evaporator-condenser effects couple to a single high volumetric compressor. This large scale VC guarantee unit specific electricity consumption of 7.5–8.5 kWh/m³ (28.4–32.2 kWh/kgal) of product (excluding sea water supply). They produce high purity 10–20 ppm distillate at high plant availability of 94–96%. In future vapor compression distillation units, will grow in capacity and number of effects. Design of VC over four and more effects, staging compressor in series or parallel will allow effective hybridization of power with MED, MSF and RO. This particularly will be important in cases where power to water ratio has to be minimized in favor of water production.

**Hybrid systems using MSF-MED**

In distillation processes there is no interaction between MSF and MED energy process streams. Substantial efficiency improvements could be obtained if process streams between MSF and MED are exchanged in order to take advantage of the different operating temperature conditions of each plant. In particular due to the low MED operating temperature (61–67°C, 142–153°F) this process could be thermally driven by process streams properly sourced by an adjacent MSF plant. A number of novel technology options for distillate hybridization (LET–Mott McDonald patent pending Fig.29) and feed and heat MSF-MED process coupling (LET patent pending Fig.30) that have been studied and their possible implementation in a real scale plant should be available soon.

The objective of the MSF-MED hybrid is to increase energy efficiency, distillate production and minimize operational costs. Results of such hybridization combined also with RO and NF is well described Sommariva et al. (36).
Hybrid systems and Desalination Aquifer Storage Recovery (DASR)

Cost-effective integration of three proven technologies, desalination, power and aquifer storage recovery (ASR) can secure a reliable, sustainable and high quality fresh water supply for the Gulf States. LET pioneered in the Middle East the concept of strategic and economic storage and recovery of desalinated water (DASR) and waste water (WASR) to the security of its communities. The idea is covered in many papers (37-40).

The seasonal surplus of unused idle power could be used by electrically driven desalination technologies RO and Hybrid Systems including NF/RO/ MSF process in combination with ASR creating a system of Desalination/ Aquifer Storage and Recovery (DASR). The ability to store and recover large volumes of water can contribute to the average downsizing of power
and water facilities with substantial operational cost savings. DASR provides strategic reserves of potable water, to prevent damage or depletion to existing oasis or aquifers, for controlling salt-water intrusion, or improvement in water quality.

DASR is of strategic importance to the Middle East Principle of DASR technology

• Electricity demand drops 30–40% of peak demand during the winter months
• During that period over 50% of power generation plants are idle
• The idle power can be utilized to produce low cost water using hybrid technologies
• Produced water is stored in underground aquifer for summer use

A desalination plant will operate continuously with modulating its output depending on power demand. Typical water storage volumes for desalinated water are limited to providing less than one day of water supply, a highly vulnerable situation.

Hybridization conclusions

Combining thermal and membrane desalination processes and technologies within a single plant or in hybrid plant schemes can reduce desalinated water costs, and, as part of dual-purpose stations; add flexibility to the combined water and power production and reduce any existing water and power demand mismatch problems

It can be seen that applying hybrid solutions will reduce desalinated water costs, compared with non-hybrid schemes, from as little as 2–3% to as much 15%. In large desalination plants, there should also be little loss of economies of scale due to the use of two or more different processes, in two or more smaller units, in lieu of one large, single-technology plant. Many such plants, at the same site, are based on the same process (MSF), but utilize different designs and have different performance figures. All the solutions whether stand-alone high-GOR plants (LT-MED/TVC, HT-MED) or hybrid schemes (MSF/SWRO, MVC/MED, MVC/TVC, etc.) requires use of the largest size plants available. The hybrid of power-desalination systems, from its early concept of power– MSF–RO to blend the products and minimize power generation, leads to many new ideas.

• Hybrid of MED-RO has many of the same advantages than the MSF-RO, but has the ability to cut significantly power water (PWR) ratio
• Hybrid of MSF–MED with VC has the potential of boosting water output through simple or full integration and at the same time reduces power to water (PWR) ratio.
• Hybrid with Nanofiltration–Softening Membrane will provide the ability to increase desalination output of distillation plants MSF and MED, by reducing scaling potential of the feed, increase the top brine temperature and provide significant better concentration factors and recovery for all distillation processes.
• Hybrid with electrically driven desalination technologies RO and VC would allow use off peak power for water production, and minimize power capacity by shutting down RO or VC daily during the peak.

• The seasonal surplus of unused idle power could be used by electrically driven desalination technologies RO and VCR in combination with aquifer storage and recovery to create effective DASR solutions. All of the above ideas have a goal to maximize and optimize benefits of power and water generation in order to provide lower cost water the “Essence of Life.”

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