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INNOVATIVE DEVELOPMENT OF NUCLEAR DESALINATION TECHNOLOGIES AND COST IMPROVEMENT APPROACHES

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Abstract: It is estimated that about 20-25% of the world's population are suffering from adequate and safe water supply. This proportion will increase due to population growth relative to water resources. During past decades, more interests are paid to the desalination of sea and brackish water resources. Desalination technologies have been now well established, and the total world capacity in mid-012 was 80 million m^3/day of potable water, in some 15,000 plants, majority of these are in the arid and semiarid regions of Middle East and North Africa. Nowadays using nuclear energy for fresh water production from seawater (nuclear desalination) has been drawing broad interests in many countries. In this context, nuclear desalination now appears to be the only technically feasible, economically viable and sustainable solution to meet the future water demands, requiring large scale seawater desalination. These interests are driven by the expanding global demand for fresh water, by concern about global heating emissions and pollutions from fossil fuels and developments in small and medium sized reactors that might be more suitable than large power reactors. Several international organizations, like the IAEA, adopted cooperative active programs for supporting the activities on demonstration of nuclear seawater desalination worldwide. These include optimization of the coupling of nuclear reactors with desalination systems, economic research and assessment of nuclear desalination projects, development of software and training for the economic evaluation of nuclear desalination as well as fossil fuel based plants. In this paper, recent technical and economic developments in nuclear desalination and its future prospects have been reviewed and evaluated.
Keywords: Nuclear desalination; Potable water needs; Water resources scarce areas

1. INTRODUCTION

General

Nuclear power is a proven technology, which has provided more than 16% of world electricity supply in over 30 countries. More than ten thousand reactor-years of operating experience have been accumulated over the past 5 decades. In recent years, the option of combining nuclear power with seawater desalination has been explored to tackle water shortage problem. Over 175 reactor-years of operating experience on nuclear desalination have been accumulated worldwide. Several demonstration programs of nuclear desalination are also in progress to confirm its technical and economical viability under country-specific conditions, with technical co-ordination or support of IAEA. Nuclear desalination is defined to be the production of potable water from seawater in a facility in which a nuclear reactor is used as the source of energy for the desalination process. Electrical and/or thermal energy may be used in the desalination process. The facility may be dedicated solely to the production of potable water, or may be used for the generation of electricity and production of potable water, in which case only a portion of the total energy output of the reactor is used for water production. Furthermore, the combustion of fossil fuels would produce large amounts of greenhouse gases and toxic emissions. Basing the estimations to only the Mediterranean region, it can be shown that around 2020, there will be additional need of water production of about 10 million m^3/day.

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The purpose of this paper is to provide an overview of various nuclear desalination plant design concepts, which are being proposed, evaluated, or constructed in countries with the aim of demonstrating the feasibility of using nuclear energy for desalination applications under specific conditions. Recent technical and economic developments in nuclear desalination and its future prospects have been reviewed and evaluated. Future potential applications of a variety of nuclear reactor designs in nuclear desalination are being proposed for examination.

Desalination Processes, an Overview

Seawater desalination is the process to obtain "pure" water through the separation of the seawater feed stream into 1) a product stream that is relatively free of dissolved substances and 2) a concentrate brine discharge stream. Desalination processes can be broadly categorized into two main types: processes using heat and process using electricity. The first types of processes are mainly the distillation processes, multi-stage flash (MSF) or multi effect distillation (MED). Vapour compression (VC) is a distillation process but it uses electricity, just as the membrane based processes like the reverse osmosis (RO) and the electro- dialysis (ED). Of these, the most commonly used processes are MSF, MED and RO. VC is often combined with MED. In distillation processes, (MSF or MED) seawater is heated to evaporate pure vapour that is subsequently condensed. The heat energy required for distillation is usually supplied as low pressure saturated steam, which may be extracted from the exhaust of a back pressure turbine, from a crossover steam duct or from a dedicated, heat only plant. The amount and quality of steam, required to produce the desired amount of pure water, depends on the seawater temperature, the maximum brine temperature and the type, design and performance of the distillation plant. Usually, the efficiency of distillation plant is expressed in kg of pure water produced per kg of steam used in the first effect: this ratio is called the gain output ratio (GOR). Desalination is an energy intensive process. For the MED and MSF plants, the principal energy is in the form of heat but some electrical energy is required for the pumps and auxiliaries. RO uses only electrical energy to create the required pressure. The total energy consumption of these two processes is a function of many variables: heating fluid temperature and flow rate, seawater temperature and salinity, desalination plant capacity etc. Indicative values are given in Table 1.

Table 1. Reactor types and desalination processes

Reactor Type	Location	Desalination process	Status
LMFR	Kazakhstan (Aktau)	MED, MSF	In service till 1999
PWRs	Japan (Ohi, Takahama, Ikata, Genkai)	MED, MSF, RO	In service with operating experience of over 125 reactor-years.
	Rep. of Korea, Argentina, etc.	MED	Under design
	Russian Federation	MED, RO	Under consideration (floating unit)
BWR	Japan (Kashiwazaki-Kariva)	MSF	Never in service following testing in 1980s, due to alternative freshwater sources; dismantled in 1999.
HWR	India (Kalpakkam)	MSF/RO	Under commissioning
	Pakistan (KANUPP)	MED	Under construction
NHR-200	China	MED	Under design
HTRs	France, The Netherlands, South Africa, USA	MED, RO	Under development and design

LMFR: liquid metal fast reactor; PWR: pressurized water reactor; BWR: boiling water reactor; HWR: heavy water reactor, NHR: nuclear heat producing reactor; HTR: high temperature reactor MED: multi-effect distillation; MSF: multi stage flash distillation; RO: reverse osmosis

2. NUCLEAR DESALINATION: Technical and economic feasibility

Past experience as well as current developments and plans for nuclear-powered desalination based on different nuclear reactor types are summarized in Ref. [10]. The following sections provide additional details on the new developments listed in Table 1.

» Argentina has identified a site for its small reactor (CAREM), which could be used for desalination. A related initiative on safety aspects of nuclear desalination addresses practical improvements and implementation and shares advances around the world.
» China is proceeding with several conceptual designs of nuclear desalination using NHR type heating reactor for coastal Chinese cities. A test system is being set up at INET (Institute of Nuclear Energy Technology, Tsinghua University, Beijing) for validating the thermal-hydraulic parameters of a multi-effect distillation process.
» Egypt has completed a feasibility study for a nuclear co-generation plant (electricity and water) at El Dabaa. Construction of a pre-heat RO test facility at El Dabaa is nearing completion. The data generated will be shared with interested Member States.
» France has recently concluded several international collaborations: one with Libya designed to undertake a techno-economic feasibility study for a specific Libyan site and the adaptation of the Libyan experimental reactor at Tajoura into a nuclear desalination demonstration plant using both MED and RO processes in a hybrid combination. The other collaboration is with Morocco (The AMANE project) for a techno-economic feasibility study of Agadir and Laayoun sites. Under a bilateral collaboration signed between India and

France, it has also been agreed that the two partners will collaborate on the development of advanced calculation models, which will then be validated at Indian nuclear installations (the experimental reactor CIRUS and the Kalpakkam plant, with hybrid MSF-RO systems).

- Israel continues to regularly provide technical and economic information on low cost desalination technologies and their application to large-scale desalination plants.
- Japan continues with its operation of nuclear desalination facilities co-located inside many nuclear power plants.
- The Republic of Korea is proceeding with its SMART (System-integrated Modular Advanced Reactor) concept. The project is designed to produce 40 000 m^3/day of potable water.
- Morocco continues the process of establishing an adequate legal and institutional legislative and regulatory nuclear framework while staying abreast of technical developments in general and nuclear desalination.
- Tunisia has completed its techno-economic feasibility study, in collaboration with France, for the la Skhira site in the southeast part of the country. The final report, presented in March 2005 was very favorably received by the Tunisian authorities who have already announced their willingness to go for the nuclear desalination option.
- USA will include in its Generation IV roadmap initiative a detailed discussion of potential nuclear energy products in recognition of the important role that future nuclear energy systems can play in producing fresh water.
- Further R&D activities are also underway in Indonesia and Saudi Arabia. In addition, interest has been expressed by Algeria, Brazil, Islamic Republic of Iran, Iraq, Italy, Jordan, Lebanon, Philippines, Syrian Arab Republic and United Arab Emirates in the potential for nuclear desalination in their countries or regions.
- India is building a demonstration plant at Kalpakkam using a 6300 m^3/day hybrid desalination system (MSF-RO) connected to an existing PHWR. The RO plant, with a production capacity of 1800 m^3 /day, was set up in 2004 and is since operating. The MSF plant (4500 m^3 /day) is to be commissioned in 2006.
- Libyan Arab Jamahiriya is considering, in collaboration with France, to adapt the Tajoura experimental reactor for nuclear desalination demonstration plant with a hybrid MED-RO system. The MED plant, of about 1000 m3/day production capacity, will be manufactured locally.
- Pakistan is constructing a 4800 m^3/day MED thermal desalination plant coupled to a PHWR at Karachi. It is expected to be commissioned towards the end of 2006.
- The Republic of Korea is exploring a possibility of using a co-generating integral type reactor SMART combined with a multi-effect distillation (MED) plant producing 40 000 m^3/day of fresh water. The basic design of 330 MW (th) SMART is completed. In parallel with out-pile tests, a one-fifth scale pilot plant SMART-P is being planned to construct along with a MED unit by 2008.
- The Russian Federation continues its R&D activities in the use of small reactors for nuclear desalination and has invited partners to participate in an international nuclear desalination project based on a nuclear floating power unit (FPU) equipped with two KLT-40s reactors. The co-generation plant, foreseen for construction in 2006, will be sited at the shipyard in Severodvinsk, Arkhangelsk region in the western North Sea area where the FPU is being manufactured.

3. ADVANCES IN REACTOR DESIGN AND COUPLING SCHEMES

Advanced Nuclear Reactors

There are no specific nuclear reactors for desalination. Any reactors, capable of providing electrical and/or thermal energy can be coupled to an appropriate desalination process. These reactors can operate as dedicated systems (producing only the desalted water) or as co-generation systems producing both water and electricity.

Dedicated nuclear systems are considered more suitable for remote, isolated regions.

Many developing countries may face both power and water shortages. In this case, IAEA studies have shown that the small and medium sized reactors (SMRs), operating in the cogeneration mode, could be the most appropriate nuclear desalination systems for several reasons:

- SMRs have lower investment costs.
- Almost all SMR concepts appear to show increased availability (≥ 90%).
- Because of inherent safety features, most SMRS have a larger potential for being located near population centers, hence lowering the water transport costs.

This section is thus mainly devoted to a very brief description of SMRS, which have been used in the regional case studies (Section 4). These reactors have been discussed in detail in [3]. For the purposes of updating the information, two innovative, generation-4 SMRs (IRIS and ANTARES) are also described. CAREM-D, The NHR-

200 and The AP-600 are the most important advanced reactor systems used for modern nuclear desalination plants, as described in Table 2.

Table 2. Some technical characteristics of advanced nuclear reactors

	CAREM	NHR-200	AP-600	GT-MHR*	PBMR*
Net thermal/electrical power (MW(th)/MW(e))	100/27	200/NA	610/1932	600/286	266/115
Fuel	Enriched UO2	Enriched UO2	Enriched UO2	Enriched UO2 particles	Enriched UO2 particles
Coolant/. Moderator	Water	Water	Water	He /Graphite	He /Graphite
Pressure vessel Height (m) Diameter (m) Material	11 3.2 SA508, grade 3	13.62 5	11.3 4. SS	Reactor Vessel 31.1 8.6	
Coolant circuit pressure (MPa)	12.25	2.5	15.5	71.5	69.6
Coolant circuit in/out temperature (°C)	284/386	153/210	288/322	493.2/854.6	525/892
Plant life time (years)		40	40	60	60
	PHWR	SMART	KL40C	IRIS	ANTARES
Net thermal/electrical power (MW(th)/MW(e))	743/240	330/90	2 X 150/35	335/1002	600/280
Fuel	Nt. UO_2	Enriched UO2	Enriched UO2	Enriched UO2	Enriched UO2 particles
Coolant	D_2O	Water	Water		He
Moderator	D_2O	Water	Water		Graphite
Pressure vessel Height (m) Diameter (m) Material	7.77 i.d of calandria 4.51 304 L SS	10.6 4.6 SA508, CL3		21.3 6.2 SS	9Cr-1Mo or SA508
Coolant circuit pressure (MPa)	10.3	15	12.7	15.5	5.5

Reactor and desalination system coupling optimization

In nuclear desalination systems, two considerations are paramount when coupling the reactor to the desalination process:

- » Ensure that the coupling adequately takes into account the particular conditions of the site and that it is based on the specific optimal solution for these conditions.
- » Verify that that such a coupling does not impact the safety of the reactor in any normal, transient or accidental conditions.

When the reactor is coupled to RO plants at the same site, the coupling is very weak and the only safety verification required is to show that the loss of RO unit, resulting in the loss of load, does not impact the reactor turbine.

In the case of MED (or MSF), the coupling is essentially thermal and it is very strong. Any transients on the reactor side or on the process side can have significant impact on the operation of both. In this case, the task of safety verification is to show that through appropriate design and mitigation measures, this would not happen.

EURODESAL [6] was among the first international projects to report detailed investigations of the possible impact of the coupling of a desalination process on the safety of the nuclear reactor.

The EURODESAL safety study was based on the probabilistic assessment of the frequency of occurrence of certain key transients such as: the loss of heat sink (e.g. loss of the MED plant), the loss of electrical load in the RO plant and the rupture of the tube transporting extracted vapour to the flash tank in the intermediate circuit of the MED based system.

The results and analysis of some safety studies this analysis led to the following conclusions:

- » The coupling of desalination plants to the nuclear reactor does not alter the number of static radioactivity confinement barriers.
- » However, the coupling must provide for an intermediate circuit. This circuit, comprising a heat exchanger and a flash tank to evaporate hot water, should maintain a dynamic pressure barrier (pressure reversal principle i.e. pressure on the process side higher than on the reactor side) and allow the instant isolation of the desalination circuit through the action of a fast acting valve.

- The desalted water must be controlled and continuously monitored in order to avoid any hypothetical contamination.
- The integrated nuclear desalination plant should be modular, with each module having its own intermediate circuit. The flash tanks of these modules must be located on the side of the desalination plant.
- The loss of electrical load, due to the shutdown of several RO (or MED) modules, is negligible, compared to the loss of load transients already studied in the context of reactor safety.
- Similarly, it can be shown that the rupture of the tube feeding steam to the flash tank can be approximated to a small leakage in the secondary circuit. This is largely covered by transient studies of more important leakages in other parts of the secondary circuit, made in the context of the reactor safety.

Thermal couplings to nuclear reactors

In the light of the above considerations, in the so called "conventional coupling scheme", (shown in Figure 1 for a PWR + MED system) the vapour extracted from one (or more) turbine stage(s) is fed to a heat exchanger (which may be similar to the condenser) where the incoming water temperature is raised to an appropriate level (70 to 90°C). The hot water then passes through a flash tank where it is partially evaporated. This vapour then serves as the heating fluid in the first effect of the MED plant.

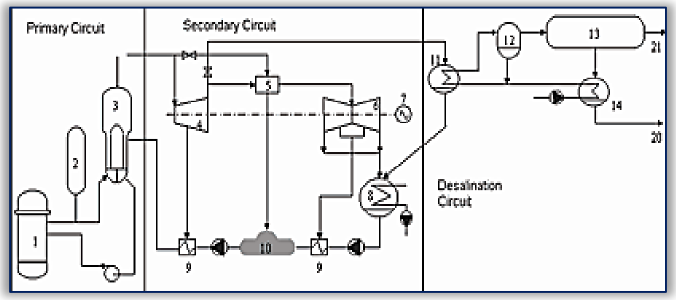

Figure 1. Conventional coupling of a nuclear reactor to a MED plant. 1: Reactor core, 2: Pressurizer; 3: Steam generator; 4: High pressure turbine; 5: Intermediate steam heater; 6: Low-pressure turbine, 7: Generator, 8: Main condenser, 9: Pre-heaters, 10: De-aerator; 11: Seawater heater;12: Flash tank, 13: MED plant, 14: MED output condenser, 20: Fresh water out, 21: Brine out-fall

Results of thermodynamic calculations for PWR-900 are given in Table 3. In all calculations, an initial extracted vapour temperature of 90°C was assumed. The temperature at the inlet of the MED plant would then be about 70°C. Table 4 also includes the electric power lost (the Lost Shaft Power) because of the vapour bleeding for the MED plant. MED plant is assumed to be modular with a unit size of 24 000 m^3/day.

Table 3. Water production in the conventional MED coupling to a PWR

Production Capacity (m^3/day)	Thermal Power Used (MW(th))	Initial Vapour Flow Rate (kg/s)	Lost Shaft Power (MW(e))
216 000	402	190	51
264 000	484	229	61
312 000	581	275	73
336 000	628	297	79
504 000	940	445	119

Thermal coupling scheme optimization

The IAEA has recently published IAEA-TECDOC-1444 on the optimization of the coupling of nuclear reactors (most of which are described above) and desalination systems. As regards PWRs, an effort was also made in the context of the French-Tunisian collaborative project (under IAEA/TC program INT/4/134), known as TUNDESAL [7]. However, this study is illustrative of the search for coupling scheme optimization for any reactor and thermal process coupling.

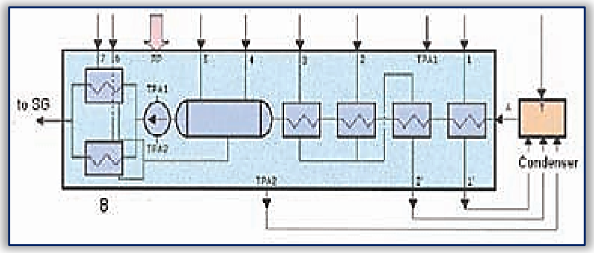

Figure 2. Internal vapour derivations in a typical PWR. 1, 2, 3- LP turbine outputs; 4- Dryer; 5, 6- HP turbine outputs; 7- Super-heater; RP- Condensate return from the desalination plant; 8-Reheater; TPA1-Input to turbine driven feed water pump; TPA2- Output from turbine- driven feed water pump; 1'- Reheater output R1; 2'- Reheater RP output; SG- Input to steam generator.

Initially, the most promising solution seemed to be the coupling of the PWR via the condenser, whereby nearly two-thirds of the PWR thermal power is evacuated to the heat sink (sea or river). However, the temperature of the water coming out from the PWR condenser does not exceed 30–32°C. This is too low for a meaningful distillation even with a low temperature MED plant.

It appeared thus necessary to increase the saturation pressure in the condenser from the usual 0.073 bar to 0.4

bar in order to have reasonably higher water temperature for the distillation plant. This inevitably required the condenser line to be connected to a higher point in the turbine system.

Detailed thermodynamic calculations then showed that such a solution considerably reduced the overall turbine efficiency. The coupling via the condenser was thus abandoned.

The second approach was to investigate the modifications in the PWR secondary circuit internal steam bleed-offs, designed to reheat the fluid re-entering the steam generator (Figure 2). The thermodynamic parameters at some of these points are given in Table 4.

Table 4: Characteristics of the steam bleed-off points in a typical PWR

Steam bleed-off	From	Temperature °C	Pressure bar	Enthalpy kJ/kg	Flow rate kg/s
1	LP Turbine	63.58	0.235	2369.2	41.39
2	LP Turbine	95.45	0.860	2524.4	56.98
3	LP Turbine	137.5	3.373	2722.8	80.29
4	Dryer	186.7	11.68	793.16	118.3
5	HP Turbine	187.7	11.92	2562.3	127.8
6	HP Turbine	225.0	25.53	2675.8	102.9
7	Super heater	265.1	50.98	1160.6	118.7

The first idea was to use part of the vapour bleeding flow rate at point 2 (at about 95.5°C and 0.86 bar), from the low pressure turbine, to feed the MED plant as shown in Figure 3.

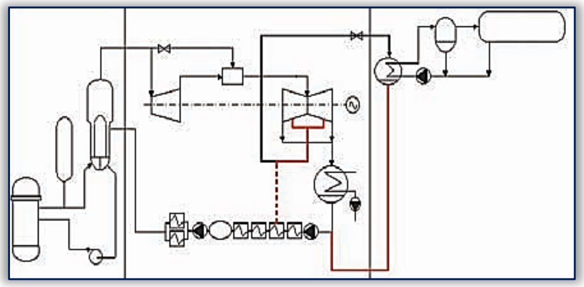

Figure 3. Coupling through the bleed-off point 2

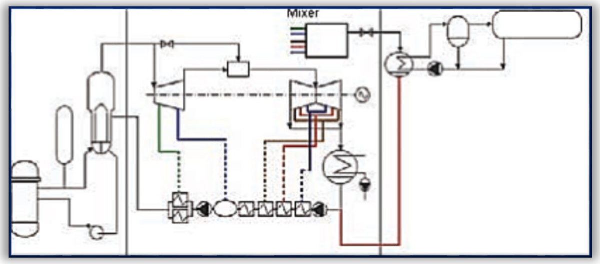

Figure 4. Coupling scheme with mixing the flow rates from the various internal bleed-off points

However, results of calculations were quite disappointing. For a production objective of 216 000 m^3/day, nearly 3% were lost on the turbine efficiency, mainly because the temperature of the fluid re-entering the steam generator was not high enough due to a loss of 121 MW(th) in the required re-heater thermal power.

To compensate this loss, a second idea was tried in which an optimum flow rate and temperature to the MED plant were obtained by mixing a fraction of flow rates from all the bleed-off points, as shown in Figure 4.

Despite numerous efforts to optimize the many possible combinations of vapour bleedings, the results led to the loss of more than 4 points on the overall turbine efficiency. Finally, it was concluded that the least penalizing solution was the extraction of steam from one of the turbine blades, as in the conventional coupling scheme.

4. ADVANCED TRENDS IN DESALINATION TECHNOLOGIES

Desalination technologies have, on the whole, shown continued progress over the past decades. The basic motive behind continued innovation is the reduction of overall process costs.

Thermal processes

Nearly 50% of all world's desalination plants are of the thermal type (MSF or MED). This fraction is about 60% for seawater desalination plants. From a purely thermodynamic point of view, progress in thermal desalination plants has not been considerable. The most notable progress in MED and MSF plants has been the increase in production capacity of the plants as shown in Figure 5. In the particular case of MSF plants, a recent improvement has been the condensate cooling, which leads to a higher heat recovery in the system and consequently the lower vapour consumption of the plants. This improvement also leads to the reduction of fouling in the upper, high

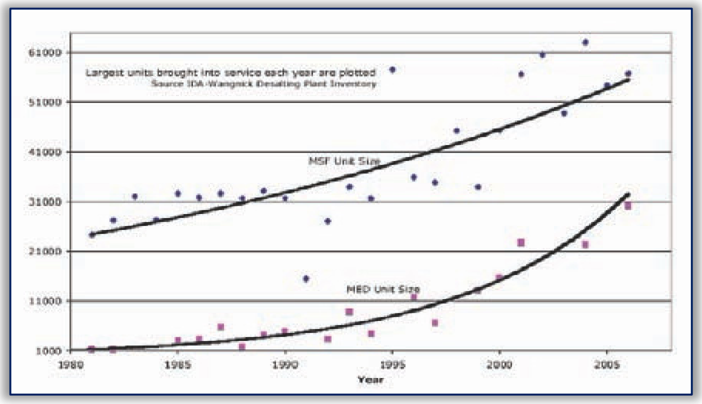

Figure 5. Unit size growth of MSF and MED plants over the years. [8]

temperature stages compared to "normal" operation. MSF, however, is now a saturated technology and, apart from some minor modifications, one does not expect significant new developments.

MED has, on the contrary, known considerable innovations over the last 25 years in particular in the development of tube technology, evaporators with increasing higher and higher efficiencies and a better understanding of the "tube wetness" phenomena. MED, especially when it is combined with a vapour compression system (VC) has some inherent advantages over the MSF process, as shown in Table 5, where comparative data is given for a large sized, projected (340 650 m^3/day) plant in one of the Gulf states.

Table 6. Comparison of MSF and MED parameters

Item	MSF	MED
Number of modules	5	12
Capacity/module (m^3/day)	68 130	28 930
Vapour flow rate (t/h)	1860	1860
Vapour pressure (bar)	1.5	5
Thermal power consumption (MW(th))	42	17
Land surface area (m^2)	127 × 385	110 × 250
Turnkey cost (M$)	375	265

Other new developments in the thermal processes (mainly MED) can be summarized as follows, [8]:

- Choice of high performance materials, (e.g. carbon-steel in place of simple, painted steel), development of high heat transfer alloys for the tubes, increasing use of non-metallic evaporator materials.
- Improvement in corrosion resistance (e.g. utilization of anti-scaling organic products in place of conventional acid treatment).
- Improvements in availability and thermodynamic efficiencies, due to the incorporation of on- line cleaning procedures.
- Modular construction, with improvements in fabrication procedures, reducing construction lead times.
- Development of efficient and more precise process control systems and procedures.

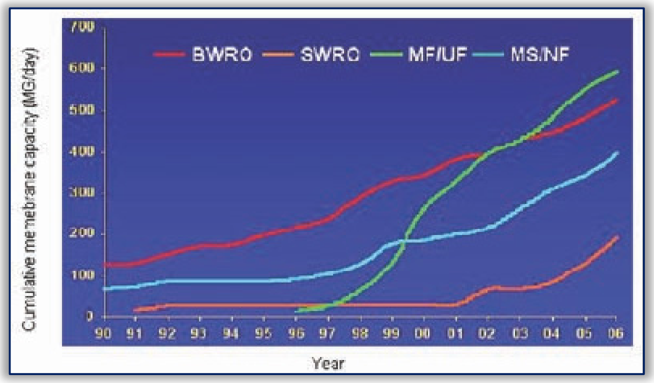

Figure 6. Increase in membrane-based capacity (millions of US gallons) from 1990 to 2006 [8]. BWRO: brackish water RO; SWRO: sea water RO; MF/UF: micro-ultra-filtration; MF/NF: micro- nano-filtration

Membrane based technologies

The advances in membrane based technologies, in particular RO, have led to a dramatic reduction of desalination costs. Not surprisingly, RO systems are the most rapidly expanding ones in today's desalination markets (Figure 6). Membrane based systems have become the corner stone of the strategies for water recycling and recuperation.

Among the notable advances, one may cite:

- Increase of salt rejection efficiency (from 98 to 99.8%).
- Increase in permeate flux (86%).
- Enhanced chlorine tolerance.
- Reduction of the costs of cleaning and pre-treatment thanks to ever increasing resistance against fouling.
- Development of longer life membranes.

Membrane-based pre-treatment

The investment and O&M costs represent more than 50% of a given desalination system.

Ro membranes are in general very sensitive to fouling by organic molecules and by solid particles in suspension. It is of crucial importance to eliminate these molecules before feeding the RO system in order to maintain the desired performances and to avoid irreversible damages to the RO membranes. In fact, the determining factor for the success of a RO system is the efficiency of its pre-treatment.

An important recent innovation in RO pre-treatment is the increasing use of specific membranes in place of conventional chemical pre-treatment, which is relatively more costly:

- use of MF membranes, which eliminate particles and other organic matter in suspension.
- use of UF membranes, which takeout odour, colour, volatile organic matter and other particles in suspension, not eliminated by MF.
- use of NF membranes, which principally eliminate troublesome sulphate-ions in seawater and thus allow raising the top brine temperature. MF/UF systems are so efficient in removing the particles in suspension

that they are now an integral part of all water recycling installations.

Such a Work Exchanger has already been installed on the Ashkelon Plant (Israel), producing 32 510 m^3/day, with a permeate TDS of 300 mg/l (compared to the TDS of 40 700 mg/l for the seawater feed). Thanks to such a system, the specific consumption of the plant is only 3.9 kWh/m^3.

5. COST IMPROVEMENT APPROACHES

Energy cost represents a substantial fraction of the total desalination costs. Although desalination processes have been, and continue to be, considerably improved, there is a strong incentive to further reduce desalination costs. Several approaches are currently under investigation.

Utilization of waste heat of PWRs and CANDUs (the ROph process)

The net electrical efficiencies of the power conversion systems in most PWRs and CANDUs are of the order of 30 to 33%. This means that nearly two thirds of the net thermal power produced in the reactors, is evacuated to the heat sink via the condensers. The temperature of the water from the condensers is too low (30 to 32°C) for a meaningful desalination with distillation processes. However, this relatively hot water can be fed to an innovative variant of the RO process, with preheating now known as the ROph process. In hybrid systems, it is also possible to use the cooling seawater return stream from the thermal desalination component as feed to the RO component. It is known that the viscosity of the feed water is inversely proportional to its temperature. Thus, as temperature increases, water viscosity decreases and RO membrane becomes more permeable, with a consequent increase in production, (Figure 7). CANDESAL first developed an advanced reverse osmosis (RO) desalination system that emphasizes a non-traditional approach to system design and operation [14]. Key features of this advanced approach to RO system design and operation are the use of "preheated" feed water, operation at high pressures, advanced feed water pre-treatment, advanced energy recovery systems, site-specific optimization and automatic real-time plant management systems.

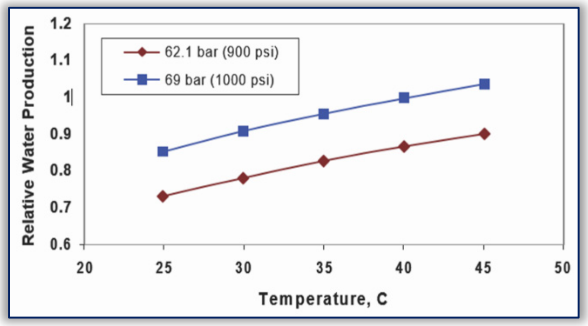

Figure 7. Normalized water production as a function of RO feed water temperature and pressure

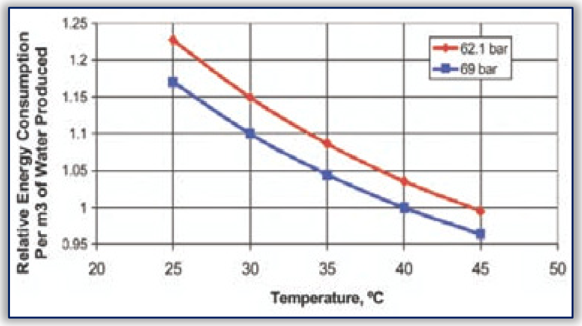

Figure 8. Specific consumption as function of feed temperature and pressure

From the basic RO system equations, we know that, for a given membrane, the rate of water flow is proportional to net driving pressure differential across the membrane. From a theoretical stand point, as temperature increases, osmotic pressure differential across the membrane, $\Delta\pi$ increases If the hydraulic pressure differential, ΔP, is maintained at a constant value the membrane's net driving force, NDP (= $\Delta P - \Delta\pi$) decreases. As a result, the specific power consumption of the RO system decreases with temperature, (Figure 8). The net result of these two effects may then lead to some reduction in the water production cost with the ROph system. This reduction is site dependent and is a complex function of several parameters including feed TDS. According to theoretical calculations for each value of feed TDS, the maximum of recovery ratio is obtained at a specific temperature.

CANDESAL first developed an advanced reverse osmosis (RO) desalination system that emphasizes a non-traditional approach to system design and operation [14]. Key features of this advanced approach to RO system design and operation are the use of "preheated" feed water, operation at high pressures, advanced feed water pre-treatment, advanced energy recovery systems, site-specific optimization and automatic real-time plant management systems.

The amount of feed water preheating depends both on the ambient seawater temperature and the specifics of the nuclear reactor design. The only limitation is that the maximum temperature allowed by the RO membrane design limits must not be exceeded. Currently available RO membranes typically have a limit of about 45°C, although this is expected to increase as membrane performances continue to be improved by the manufacturers. Cost savings are possible at all temperatures where waste heat can be used to preheat the feed water but overall savings depend on a number of factors that are site specific: the salinity of the feed water, the size of the plant, the amount of preheat available, etc. An important consideration in ROph is that it can easily use the hot water from the main condensers of the PWR type of plants. The ROph process was first applied to the economic assessment of nuclear desalination systems in the EURODESAL project [6]. However, at that time, the method used was based on specific empirical formulae and could only be applied to nuclear power plants such as the CANDU and PWR, and for only one value of the seawater salinity (TDS). CEA thus investigated a new method for the mathematical treatment of the process, extending its application to all power producing plants and permitting the understanding of the key performance parameters (e.g. the recovery ratio, the total production, the product salinity, etc.) of the system as functions of operating variables such as the temperature (x), feed salinity (e) and the feed flow (m), [10]. The method was then applied to the specific site study for la Skhira, Tunisia. These correlations have not yet been integrated into the DEEP-3 software but as an illustration of ROph cost reduction, indicative figures, obtained with DEEP-2 and CEA correlations, are shown in Table 7 for 8% discount rate and two plants: the 600 MW (e) gas turbine, combined cycle plant (CC- 600) with a low gas price of 20.62 $/bbl and the PWR-900.

Table 7. DEEP-2 results comparing the water costs ($/m^3) of RO ROPH systems

	CC-600 (20.62 $/bbl)	PWR-900
RO	0.7503	0.6990
ROph	0.6474	0.6032
Δ(%)=(ROph-RO)/RO	-13.7	-13.7

It can be observed that ROph can lead to a desalination cost reduction of about 14% as compared to the desalination cost of a conventional RO system. This reduction is independent of the power source.

6. SUMMARY AND DISCUSSION

Considerable advances have been recently made in several countries on the development of improved or innovative nuclear reactors. These include: Advanced PWRs such as CAREM (integral PWR, Argentina), SMART (integral PWR, Republic of Korea), NHR-200 (dedicated heat only reactor, being developed by INET, China), AP-600 (Westinghouse, USA and ANSALDO, Italy) and the barge-mounted KLT-40 class of reactors, derived from Russian Ice-breakers. HWRs, being modified for nuclear desalination in India and Pakistan.

HTRs such as the GT-MHR (developed by an international consortium, led by General Atomics) and the PBMR (planned to be constructed soon in South Africa by the PBMR company). Other advanced reactors such as the integral PWR, IRIS (being developed by an international consortium, led by Westinghouse) and the innovative HTR, ANTARES (under development by FRAMATOME, ANP, France).

Desalination technologies have, in parallel, also known considerable technological innovations:

» an almost exponential increase in production capacity of the plants: thus, for example, between the years 1980 and 2005, multi-effect distillation (MED) unit plant capacities have increased from 1 000 to 31 000 m^3/day and multi-stage flash (MSF) unit sizes have increased from 31 000 to 80 000 m^3/day.
» choice of high performance materials, (e.g. carbon-steel in place of simple, painted steel), development of high heat transfer alloys for the tubes, increasing use of non-metallic evaporator materials.
» improvement in corrosion resistance (e.g. utilization of anti-scaling organic products in place of conventional acid treatment).
» improvements in availability and thermodynamic efficiencies, due to the incorporation of on-line cleaning procedures.
» modular construction, with improvements in fabrication procedures, reducing construction lead times.
» development of efficient and more precise process control systems and procedures.

The most rapid and significant advances have been reported in membrane based processes, in particular reverse osmosis (RO):

» increase of salt rejection efficiency (from 98 to 99.8 %).
» increase in permeate flux (86 %).
» enhanced chlorine tolerance.
» reduction of the costs of cleaning and pre-treatment due to ever increasing resistance against fouling.
» development of longer life membranes.

Many Member States have undertaken nuclear desalination studies in their specific conditions. Analysis of the results leads to the following conclusions:

» Whatever the nuclear reactor, the desalting capacity and the site-specific conditions, nuclear desalination is by far economically the most interesting option as compared to the gas turbine, combined cycle plant as long as gas prices remain higher than about 21 $/bbl, if nuclear can achieve capital costs at or below the 1500 $/kWth range. In the context of its second CRP on economics, the IAEA has received 8 reports summarizing site- studies from Argentina (CAREM + RO), China (NHR-200 + MED), Egypt (PWR-1000 + RO, PWR-1000 + MED), France (PWR-900 and AP-600, coupled to RO and MED, GT-MHR and

PBMR, coupled to MED, with waste heat utilization), India (PHWR + MED, PHWR + RO and PHWR + hybrid MSF-RO), Republic of Korea (SMART + MED), Pakistan (CANDU + MED) and Syrian Arab Republic (PBMR coupled to MED, MED/VC and RO). Because of very diverse site conditions, production capacities, economic hypotheses, variety of nuclear reactors and even calculation methods, it is very difficult to arrive at specific conclusions regarding different nuclear desalination systems. One may however, obtain a range of values for different combinations:

- For the RO based systems, desalination costs vary from 0.6 to 0.94 \$/m^3.
- In all cases where the nuclear desalination costs are compared with those from the combined cycle plant, it is observed that the nuclear desalination costs are much lower.
- For the MED based systems, the nuclear desalination costs vary from 0.7 to 0.96 \$/m^3.
- In one study, the MED /VC, coupled to a PWR leads to a cost of 0.5 \$/m^3.
- As for RO, wherever comparisons have been made, the desalination cost of nuclear reactors coupled to MED are systematically more than 20% lower than the corresponding cost by the combined cycle + MED systems.
- In a hybrid MSF-RO system, the desalination cost of MSF, coupled to a PHWR is 1.18 \$/m^3, compared to 0.95 \$/m^3 for RO but that of the hybrid MSF-RO system is 1.1 \$/m^3. This cost is likely to be further reduced as hybrid system capacity is increased.

With identical economic hypotheses, used for three cases, DEEP-3 results show that nuclear reactors, coupled to RO would lead to a desalination cost of 0.6 to 0.74 \$/m^3. Corresponding cost for MED would be about 0.89 \$/m^3. Nuclear desalination costs can still be further reduced by adopting certain cost reduction strategies involving the use of waste heat from nuclear reactors and normally evacuated to the sea or river, the launching of optimized hybrid systems and the extraction of strategic and costly minerals from the brine rejected by desalination plants, accompanied by zero brine discharge to the sea. The most crucial problem for the launching of full-fledged nuclear desalination systems remains the financing of projects. However, studies have shown that the project financing method (in which instead of financing the local utility, an independent structure for project financing is created and which seeks to reduce the risks through multiple government and/or international credits) coupled to the leasing (instead of buying all the project equipment, a part is leased) would be a very suitable approach for most developing countries.

7. CONCLUSIONS

Nuclear power is a proven technology, which has provided more than 16% of world electricity supply in over 30 countries. More than ten thousand reactor-years of operating experience have been accumulated over the past 5 decades. In recent years, the option of combining nuclear power with seawater desalination has been explored to tackle water shortage problem. Over 175 reactor-years of operating experience on nuclear desalination have been accumulated worldwide. Several demonstration programs of nuclear desalination are also in progress to confirm its technical and economical viability under country-specific conditions, with technical co-ordination or support of IAEA. In this context, nuclear desalination now appears to be the only technically feasible, economically viable and sustainable solution to meet the future water demands, requiring large scale seawater desalination:

- nuclear desalination is economically competitive, as compared to desalination by the fossil energy sources (Section 4),
- nuclear reactors provide heat in a large range of temperatures, which allows easy adaptation for any desalination process.
- some nuclear reactors furnish waste heat (normally evacuated to the heat sink) at ideal temperatures for desalination.
- desalination is an energy intensive process. Over the long term, desalination with fossil energy sources would not be compatible with sustainable development: fossil fuels reserves are finite and must be conserved for other essential uses whereas demands for desalted water would continue to increase.

Furthermore, the combustion of fossil fuels would produce large amounts of greenhouse gases and toxic emissions. Basing the estimations to only the Mediterranean region, it can be shown that around 2020, there will be additional need of water production of about 10 million m^3/day. If nuclear instead of fossil fueled option is chosen, then one could avoid about: There are no specific nuclear reactors for desalination. Any reactors capable of providing electrical and/or thermal energy can be coupled to an appropriate desalination process. These reactors can operate as dedicated systems (producing only the desalted water) or as co-generation systems producing both water and electricity. Dedicated nuclear systems are considered more suitable for remote, isolated regions.

Many developing countries may face both power and water shortages. In this case, many studies have shown that the small and medium sized reactors (SMRs), operating in the cogeneration mode, could be the most appropriate nuclear desalination systems.

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