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Status of Nuclear Desalination in IAEA Member States

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FOREWORD

Some of the IAEA Member States have active nuclear desalination programmes and, during the last few years, substantial overall progress has been made in this field.

As part of the ongoing activities within the IAEA's nuclear power programme, it was thus decided to prepare a status report, which would briefly describe the recent nuclear seawater desalination related developments and relevant IAEA activities.

This status report briefly covers salient aspects of the new generation reactors and a few innovative reactors being considered for desalination and other non-electrical applications, the recent advances in the commonly employed desalination processes and their coupling to nuclear reactors. A summary of techno-economic feasibility studies carried out in interested Member States has been presented and the potable water cost reduction strategies from nuclear desalination plants have been discussed. The socio-economic and environmental benefits of nuclear power driven desalination plants have been elaborated.

It is expected that the concise information provided in this report would be useful to the decision makers in the Member States and would incite them to consider or to accelerate the deployment of nuclear desalination projects in their respective countries.

The report was prepared by S. Nisan (France). The IAEA officer responsible for this publication was B.M. Misra of the Division of Nuclear Power.

EDITORIAL NOTE

CONTENTS

SUMMARY

This status report updates the information and recalls some of the advances made both in the nuclear reactor and desalination technologies. It is expected that the information contained in this report would be of use to decision makers in the Member States considering nuclear desalination options.

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.

Considerable advances have been recently made in several Member States 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).

Industrial desalination technologies are mainly of two types: 1)- thermal processes, based on the utilisation of heat energy for distillation (also requiring some electrical energy for the pumps and other auxiliary systems) and 2)- membrane based processes using only electrical (or mechanical) energy.

Among the thermal processes, the most commonly used are MSF (Multistage Flash) and MED (Multi Effect Distillation). Vapour compression (VC) is a distillation process which uses electrical energy. Reverse Osmosis (RO) and Electro-dialysis (ED) are membrane based processes.

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. utilisation 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 summarising 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 utilisation), 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 optimised 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.

1. INTRODUCTION AND BACKGROUND

1.1. MOTIVATION

1.1.1. The water problem

Water is indispensable for the very existence of mankind and for human development. Water is not only a natural resource, it is a component of prosperity: water being the most important consumption article in the world, its worldwide availability should be guaranteed to all.

The total quantity of water available on earth is about 1000 million km^3 and covers nearly 70% of the globe, whereas the total world water consumption does not exceed 2100 km^3/year. At first sight this would seem rather reassuring.

However, 97.5% of the available water is highly saline or brackish. Of the remaining 2.5%, nearly 70% is in the form of ice (Antarctica, Greenland, etc.). Yet another large fraction is locked in the soil humidity and deep underground aquifers. Consequently the effective amount of water, directly accessible to human beings is only 0.007% (or, about 70 000 km^3).

Even this fraction is very unevenly distributed over the planet. Moreover, rapidly increasing populations, rising standards of living, continued development of tourism, progressive industrialization and expansion of irrigation agriculture have already led to acute water shortages and stresses in many regions of the world as shown in red in Figure 1.

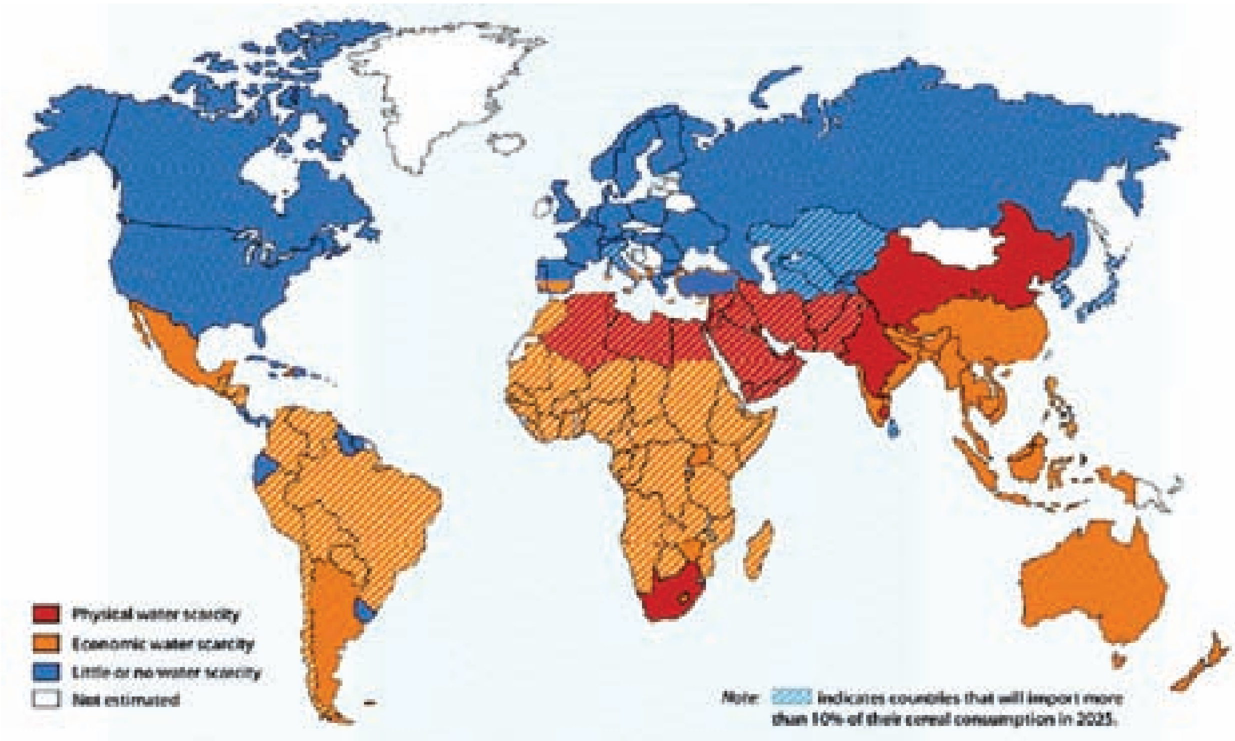


Figure 1. Regions of the world facing water shortages.

In Figure 1 countries which will face "economic water shortages" (i.e. inadequacy of supply and demand) are shown and regions with diagonal lines are the ones which will import more than 10% of their cereal consumption in 2025. It should be recalled that to produce 1 ton of cereals one requires 1000 m^3 of water [1]. The import of cereals is thus indirectly the import of water.

Water resources are not only rare but they are extremely fragile. Because of unprecedented human activities, in addition to reasons given above, they are now rapidly dwindling. Thus, for example, in 1960 the available water resources in Africa were about 15 000 m^3/capita/year. In 2025, they would be only 2000 m^3/capita/year (Figure 2).

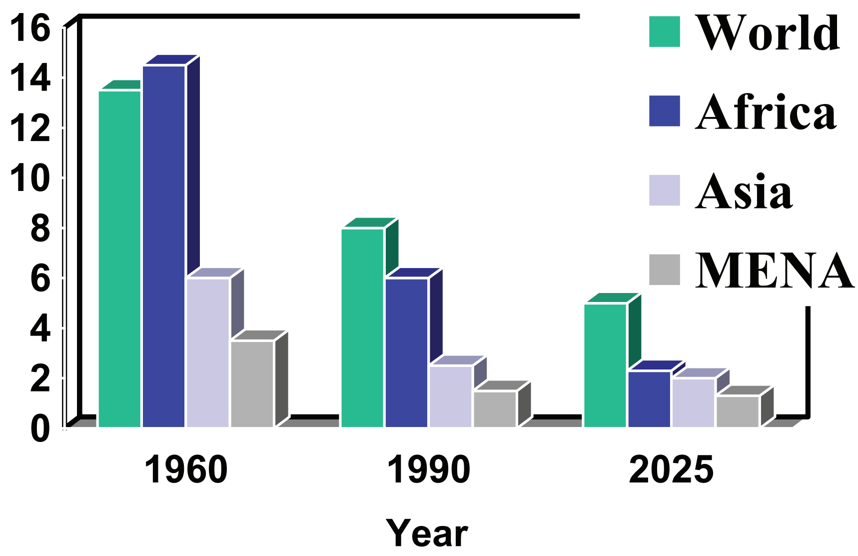


Figure 2. Renewable world water resources (in 1000 X m^3/capita/year) from 1960 to 2025. (MENA: Middle East and North Africa).

If nothing is done and business as usual continues, according to GEO-2000, an assessment by UN's Environmental Program, nearly two thirds of the world population would be without adequate water supplies by 2025. Already several countries in Southern Europe, Middle East, North Africa, South Asia and South America are facing severe water shortages.

As a result "today 1.1 billion persons do not have access to drinking water; 2.5 billion persons live in unsatisfactory hygienic conditions; five million persons (a majority of which are children) die each year of diseases (mostly preventable) related to water related shortage and hygiene"[1]. This is equivalent to a large Airbus, full of children, crashing every hour.

Water related problems are numerous. They are so diversified that there is no single solution to meet the water demands in a given country. All alternate solutions of water supply, notably water recycling, more efficient use of water, modernisation of water distribution networks to avoid leakages and the desalination of brackish or seawater, are thus required to meet the ever increasing water demands.

It has been generally recognised in most international circles, dealing with water related problems, that seawater desalination could be an attractive, non-conventional water resource to meet the rising water demands.

This is because:

- It so happens that a large fraction of the populations of water stressed countries resides near the sea coasts.
- Seawater reserves are practically unlimited.
- Desalination, which was once a technology for the rich, is gradually becoming an affordable process for all. Desalination costs are still high but there is a very high potential in some desalination processes for further research and innovation, leading to considerable cost reductions.

It is for this reason that several IAEA Member States have undertaken R&D in desalination technologies with the aim of producing large amounts of desalted water at the lowest possible cost.

[1] The EU water initiative.

1.1.2. Why nuclear desalination?

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

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 fuelled option is chosen, then one could avoid about:

- 200 000 000 t/year of CO_2,
- 200 000 t/year of SO_2,
- 60 000 t/year of NO_x, and
- 16 000 t/year of other hydrocarbons.

The figures extrapolated to the world desalination capacities would lead to more than double the amounts given above [2].

1.2. PAST EXPERIENCE AND CURRENT DEVELOPMENTS IN NUCLEAR DESALINATION

Table 1 summarizes past experience as well as current developments and plans for nuclear-powered desalination based on different nuclear reactor types.

Japan now has over 150 reactor-years of nuclear powered desalination experience. Kazakhstan had accumulated 26 reactor-years before shutting down the Aktau fast reactor at the end of its lifetime in

1999.The experience gained with the Aktau reactor is unique as its desalination capacity was orders of magnitude higher than other facilities.

Most of the technologies in Table 1 are land-based, but the Table also includes a Russian initiative for barge-mounted floating desalination plants. Floating desalination plants could be especially attractive for responding to temporary demands for potable water.

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

1.3. POTENTIAL OF NUCLEAR DESALINATION IN MEMBER STATES

The following sections provide additional detail on the new developments listed in Table 1 and some others.

1.3.1. Techno-economic feasibility studies

- **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 favourably 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.

1.3.2. Nuclear desalination demonstration projects

- **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 m^3/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.

1.4. HOW IAEA ACTIVITIES PROMOTE SYNERGY BETWEEN MEMBER STATES

The IAEA has been providing its Member States with guidebooks, technical documents, and computer programs on nuclear desalination as well as technical assistance through the framework of technical co-operation programs.

A number of technical cooperation projects have assessed the feasibility of particular nuclear desalination projects. Under the IAEA regional technical cooperation (TC) framework, several international collaboration activities were completed; for example, between the Republic of Korea and Indonesia; France and Tunisia and in Pakistan. TC national projects for UAE, Algeria and Jordon, for their pre-feasibility studies of nuclear desalination plants, are underway.

The Coordinated Research Project (CRP) on Optimization of the Coupling of Nuclear Reactors and Desalination Systems, was completed in 2003 with the participation of 11 Member States. The CRP has produced optimum coupling configurations of nuclear and desalination systems, evaluated the performance and identified technical features, which may require further assessments for the detailed specifications of large scale nuclear desalination plants. The results of the CRP are published as IAEA-TECEDOC-1444 (2005).

The CRP on Economic Research on, and Assessment of, Selected Nuclear Desalination Projects and Case Studies, with the participation of 10 Member States, is progressing well. This CRP is to contribute to the IAEA's efforts to enhance prospects of demonstration and eventually for the successful implementation of nuclear desalination in Member States. The results of this CRP are planned for a TECDOC in 2007 but some of the results have been discussed in this report (Section 4).

The updated version of the IAEA's Desalination Economic Evaluation Program (DEEP), DEEP-3.0 was released in September 2005. It is freely available for down load under a license agreement. A number of scientists/engineers and researchers from Member States have used it for their economic evaluation of fossil/ nuclear desalination projects and case studies.

The IAEA also arranges biennial workshop/training courses on Desalination System Modelling, Technology & Economics, current trends in desalination and on the utilisation of DEEP software at the International Centre for Theoretical Physics (ICTP), Trieste (Italy) for the benefit of young scientists and engineers from the Member States interested in relevant research in nuclear desalination. The lectures are delivered by leading experts in the field.

The IAEA's web-page: www.iaea.org/nucleardesalination provides latest information on the activities in nuclear desalination in the IAEA and in Member States. The website has also links to major organizations involved in desalination science and technology.

2. ADVANCES IN DESIGN AND COUPLING SCHEMES

2.1. 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 centres, 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.

2.1.1. CAREM-D

CAREM-D is a small sized integral PWR providing 100 MW(th) (27 MW(e) jointly developed by CNEA (National Atomic Energy Commission) and INVAP, SE. Both are from Argentina.

The reactor core is cooled by naturally circulating water, which also acts as the moderator. Self pressurisation of the primary system in the steam dome is thus the result of the liquid-vapour equilibrium so that the core outlet bulk temperature corresponds to saturation at primary pressure. This eliminates the heaters and sprinklers of the existing large PWR designs. The natural circulation also produces a self correcting response to flow rate changes under different transients.

The reactor core has 61 fuel assemblies of hexagonal cross section. The core is characterised by strongly negative fuel and moderator temperature coefficients. Initial fuel enrichment is 3.4% leading to a cycle length of 390 equivalent full power days.

The steam generators are of once-through, mini helical, vertical design. The counter current flow leads to secondary coolant flowing upwards inside the tubes which then exits the tubes with ample superheating.

The plant has the standard steam cycle. The steam generators are drum-less “once through boilers” without accumulators. Steam is thus superheated in all plant conditions and the absence of blow-downs reduces waste heat generation.

Twelve such steam generators are connected alternately in two groups to annular collectors.

For the cogeneration of about 18 MW(e) and 10 000 m^3/day of desalted water, the balance of plant of CAREM-D was slightly changed. The principal change is in the design of the main condenser, which provides water at 44°C for the ROph process (Section 3.1.2). Besides, cogeneration has required additional piping for the seawater cooling flow by-passing the condenser.

The plant is equipped with simple, reliable and some passive safety systems. Thus for example the second shutdown system comprises of a gravity driven borated water system.

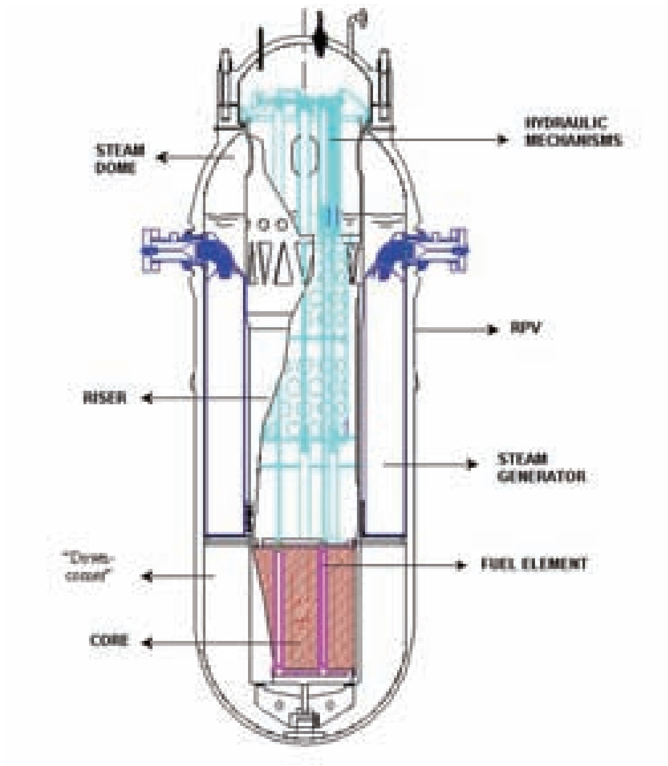


Figure 3. General view of CAREM reactor assembly.

2.1.2. The NHR-200

The NHR-200 is a dedicated nuclear reactor, capable of producing heat (200 MW(th)) for industrial applications, such as desalination, district heating etc. It is being developed by the INET, China.

The NHR-200 is designed as an integral PWR type of reactor in which the core is situated towards the lower side of the pressure vessel, thus allowing a large coolant inventory.

The reactor core comprises of 120 fuel assemblies and 32 control rods. These control rods are driven by an innovative hydraulic mechanism, using the coolant water. The water is pumped into the step-cylinders of which the movable parts contain the neutron absorber.

A pulsed flow is generated by the controlling magnetic valve in the control unit. This flow then gradually moves the movable part of the step cylinder. The mechanism is considered “fail safe” as all the rods can drop into the core by gravitation in case of loss of electric power, depressurisation or any other postulated breaks in piping systems and pump shut down events.

Six sets of modular primary heat exchangers are located on the upper periphery of the pressure vessel. The coolant enters the upper plenum of the exchangers, and then divides into two streams to flow downwards into the U-shaped heat-exchanger tubes. Flow distribution vessels are provided to optimise the heat transfer efficiency.

The pressure vessel is steel lined to minimise coolant leakage.

An intermediate circuit between the reactor and the desalination plant, with pressure reversal principal, is also installed.

The primary coolant absorbs the heat from the reactor, then flows through the primary heat exchangers, where the heat is transferred to the intermediate circuit. The heat is then transferred to the steam supply system through the steam generators. Steam generators then act as the tertiary circuit.

In addition to designed safety systems, the NHR-200 equally disposes of the passive residual heat removal system, with two independent trains.

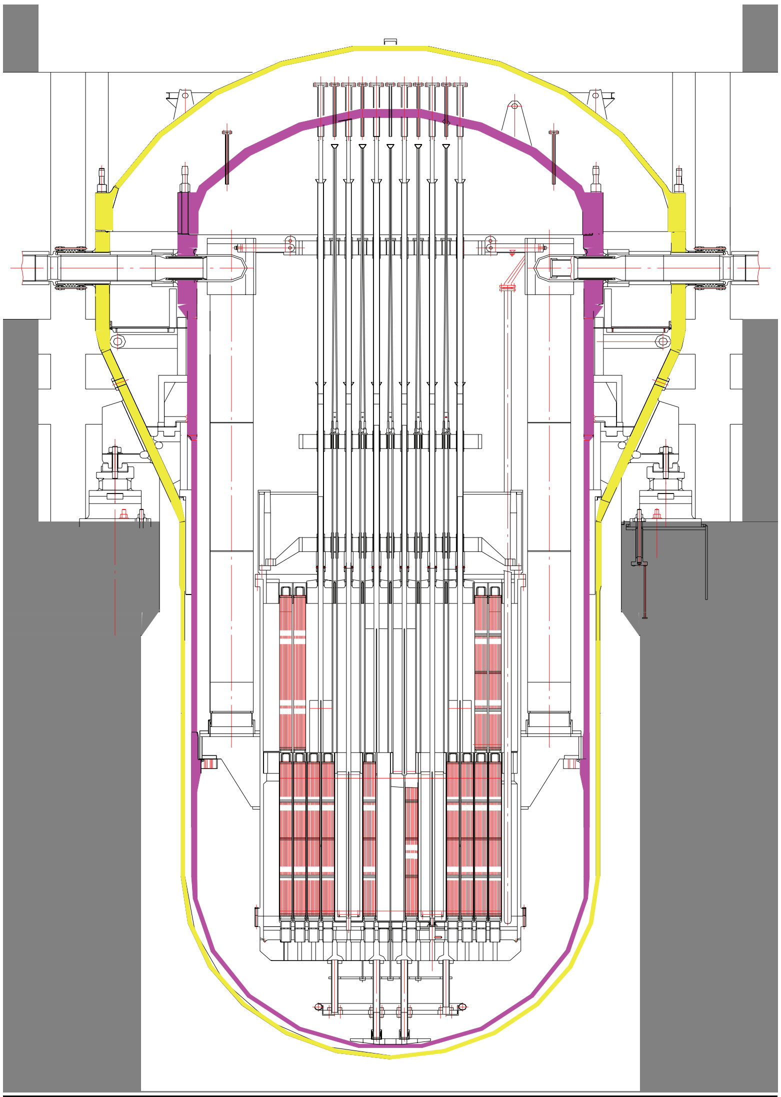


Figure 4. NHR-200 reactor.

2.1.3. The AP-600

The Westinghouse AP-600 is an advanced 600 MW(e) pressurised light water reactor, with two reactor coolant loops. Each loop consists of a steam generator, two canned pumps, a single hot leg and two cold legs for circulating reactor coolant between the reactor and the steam generator. The system includes a pressurizer.

The major innovative features are:

- Low power density reactor design.
- Simplified primary loop configuration employing canned motor pumps mounted on the steam generator lower head.
- Simple, passive safety systems which, once actuated, depend only on natural forces such as gravity and natural circulation.

These passive safety systems result in increased plant safety and can also significantly simplify plant systems, equipment and operational procedure.

According to its designers, the AP-600 requires 50% fewer valves, 80% less safety grade piping, 70% less control cable, 35% fewer pumps (no safety grade pumps) and 45% less seismic building volume than other conventional reactors

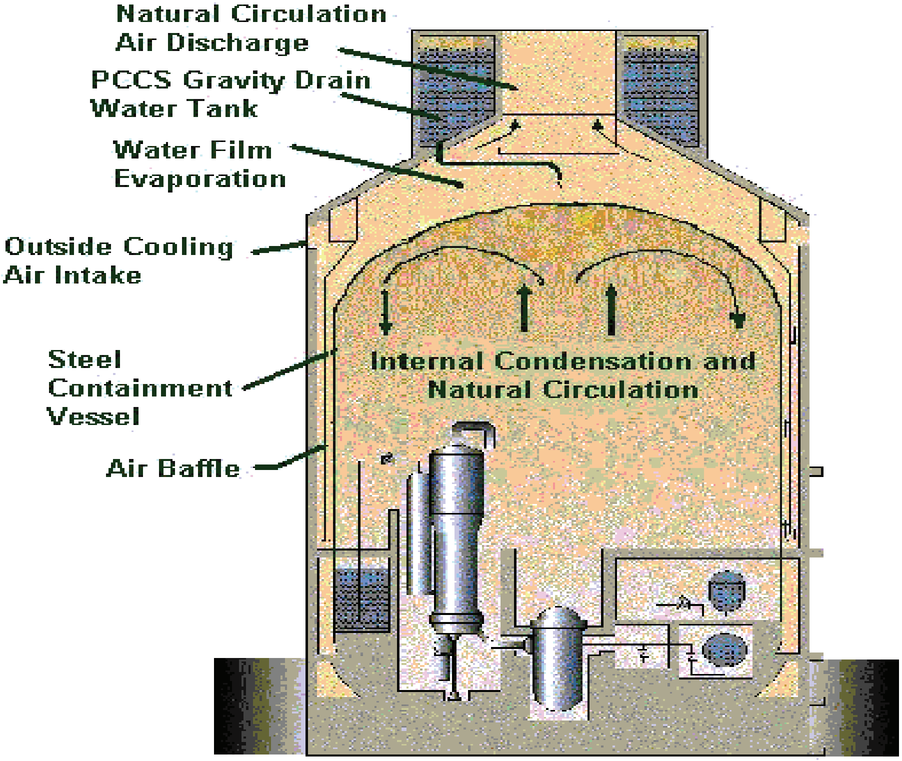


Figure 5. Schematic layout of the AP-600 nuclear island.

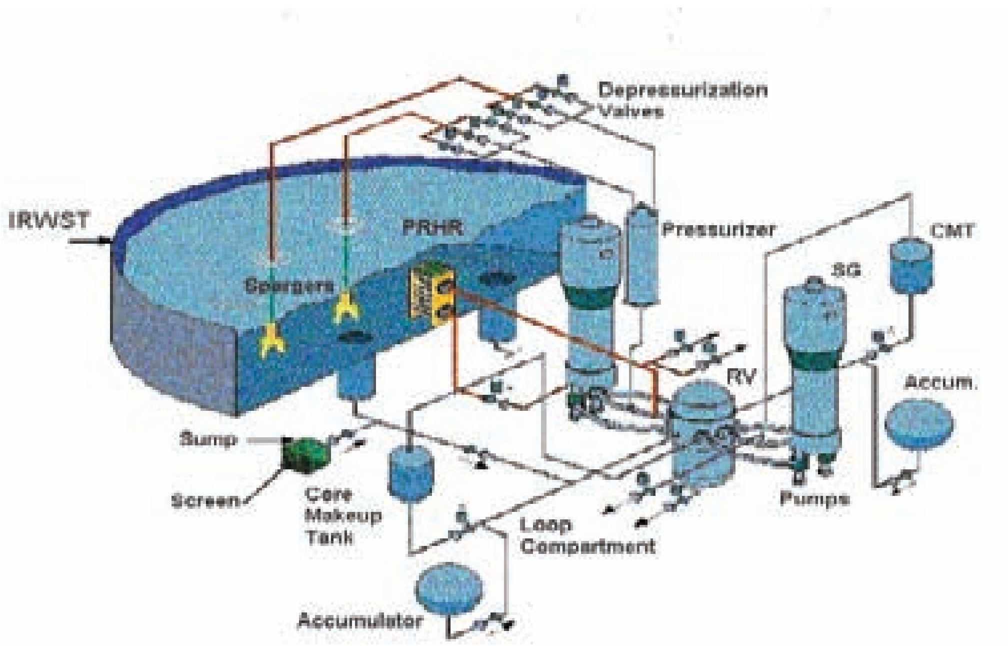


Figure 6. AP-600 Passive Containment Cooling System (PCCS).

This simplification helps to reduce capital cost and provides a hedge against regulatory driven operating and maintenance costs by eliminating equipments which are subject to regulation.

AP-600, certified in 1999, can be considered as an evolutionary design, but it already includes many safety features of innovative reactor systems, under design at present.

These include passive safety injection (CMT and IRWST), passive residual heat removal (PRHR), automatic depressurisation system (ADS) and passive containment cooling system (PCCS).

2.1.4. The GT-MHR

The gas turbine-modular helium reactor (GT-MHR) is a helium cooled, direct-cycle nuclear power plant which the designers claim to have a relatively high electricity production efficiency (~50%) and enhanced safety, economic, non-proliferation and environmental characteristics. The GT-MHR is an advanced reactor design, which integrates demonstrated high temperature gas cooled reactor (HTGR) and industrial gas-turbine technologies, to meet all Generation IV goals with significant margins.

The GT-MHR is at present under development by an international consortium, comprising: General Atomics (USA), FUJI Electric (Japan), MINATOM (RF) and several Russian Institutes, namely: OKBM, Kurchatov Institute, VNIINM, Lutch and Seversk Combinate.

The GT-MHR includes the nuclear heat source (i.e. the reactor system) and power conversion system consisting of equipment needed for electric power generation (turbo-compressor, recuperator, generator, pre-cooler, inter-cooler and connecting pipelines). Components of the reactor and Power Conversion System are located in separate vertical steel vessels interconnected by the horizontal cross vessel, as shown in Figure 7.

The bottom part of the reactor system vessel also houses the shutdown cooling system's "helium-water" heat exchanger and gas blower.

The entire reactor assembly can be sited in an underground concrete silo, which serves as an independent, vented low pressure containment structure.

A simplified cycle flow diagram of the reactor module is given in Figure 8. Helium is used as a coolant in the primary circuit and its circulation is described below.

The high-pressure helium from the reactor upper collector plenum enters the reactor and is heated up as it passes through the core. The hot helium accumulates in the core lower collector plenum and flows through the inner concentric hot duct in the cross vessel to supply the PCS turbine. Helium enters the turbine at 850°C and 7.1 MPa. After expansion in the turbine, the helium at 508°C and 2.63 MPa is directed to the recuperator, where it flows through the hot side of the parallel heat exchange in the recuperator to the temperature of 125°C and then enters the pre-cooler where it is cooled to 26°C.

Down stream of the pre-cooler, the cold helium is compressed from 2.58 MPa to 7.25 MPa in two successive stages (low and high pressure compressors). An intercooler between the compressors cools the helium to 26°C prior to entering the high-pressure unit. Downstream of the high-pressure compressor the helium goes through the recuperator (along its cold side), where it is heated to 488°C and then collects in the Power Conversion System annular outlet chamber. From this chamber, it subsequently flows back to the reactor vessel through the annulus between the cross vessel and hot duct. Within the reactor vessel, the helium moves upwards to the upper collector plenum through flow channels outside the core barrel.

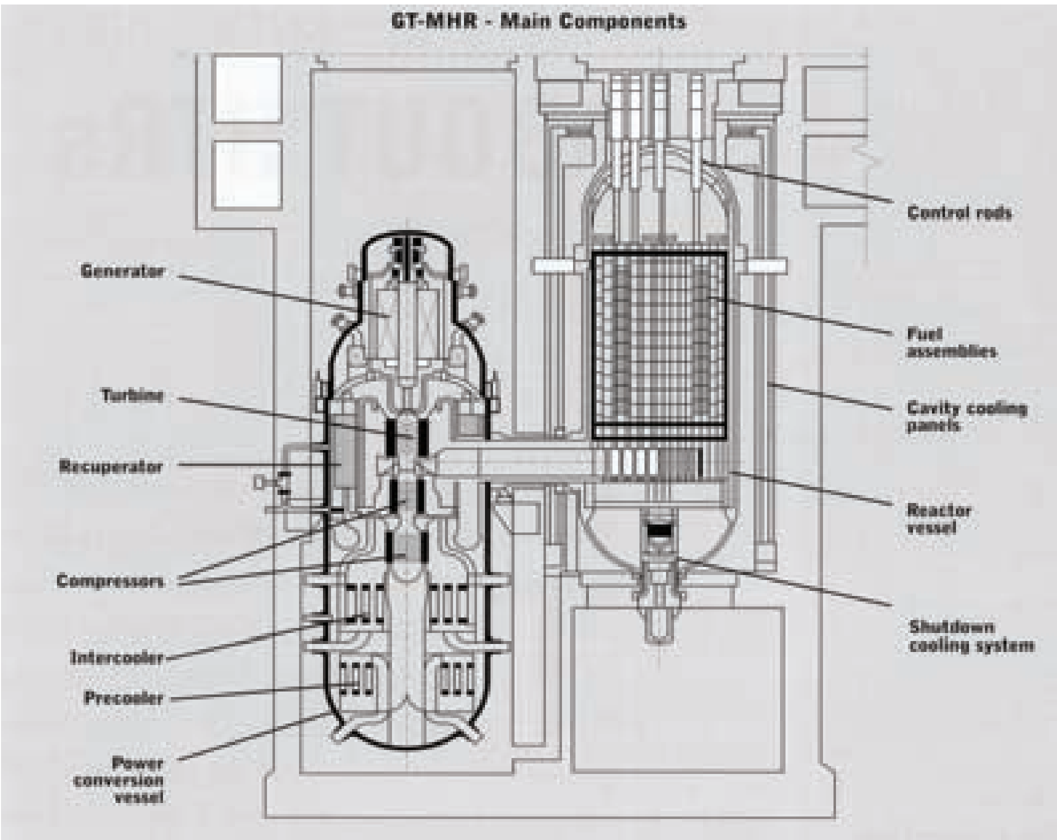


Figure 7. GT-MHR module arrangement.

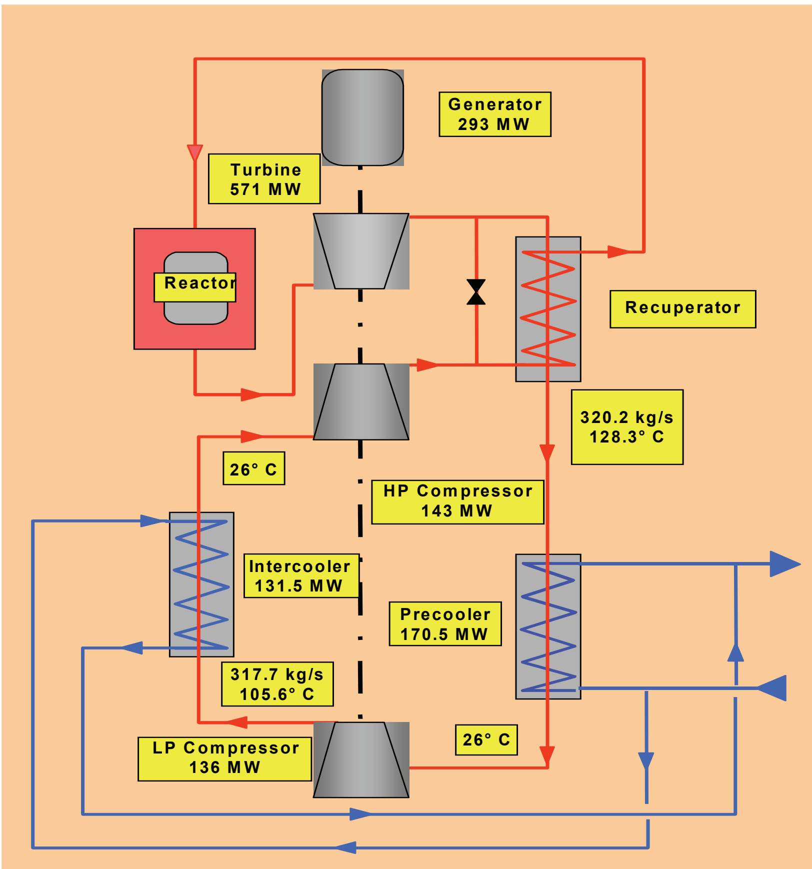
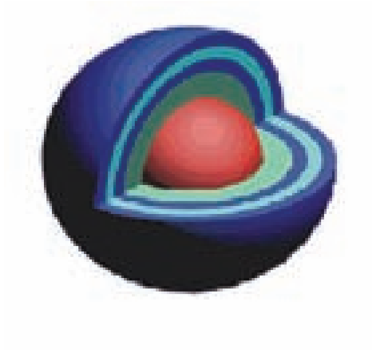
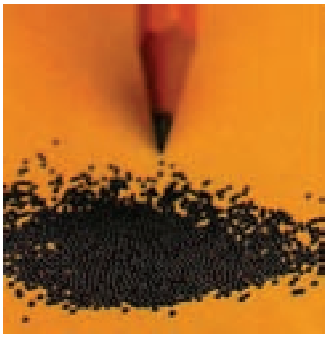
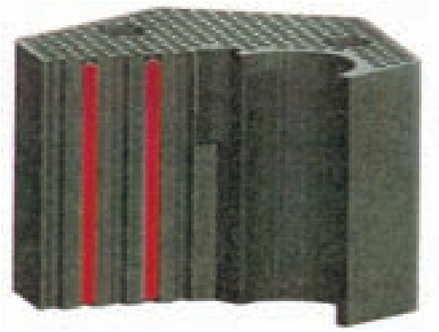


Figure 8. GT-MHR flow diagram.

2.1.5. The PBMR

The pebble-bed modular reactor is expected to be constructed soon by the PBMR (Pty) Ltd Company in South Africa. Commercial PBMRs would be sized to provide 165 MW(e) nominal.

a: TRISO particle (Pebble) b: A bed of pebbles c: A block containing TRISO pebble compacts

Figure 9. Particle, pebble-bed and block used in the PBMR and the GT-MHR.

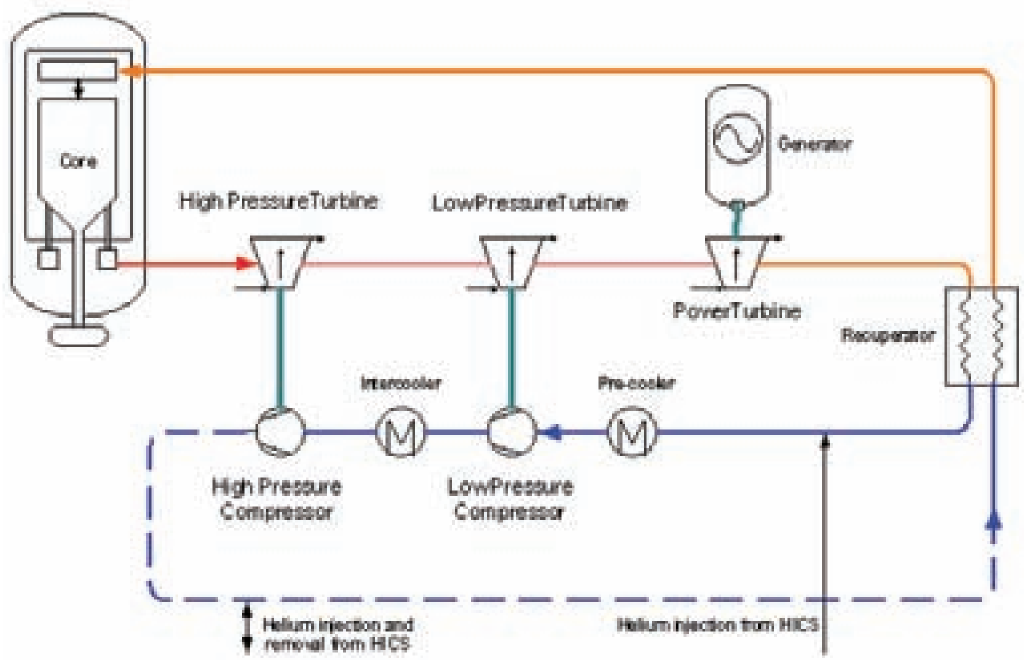


Figure 10. Power conversion system of a PBMR.

Its working principle is the same as the GT-MHR. The main difference is that, as compared to blocs containing compacts of pebbles in the GT-MHR, the PBMR uses a bed of pebbles. The other difference is that the PCS of PBMR uses three shafts (Figure 10) instead of one in the GT-MHR.

The PBMR[2] essentially comprises a steel pressure vessel, lined with graphite, which serves as an outer reflector and a passive heat transfer medium. The graphite brick lining is drilled with vertical holes to house the control elements.

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[2] Information obtained from the PBMR site: https://www.pbmr.com/

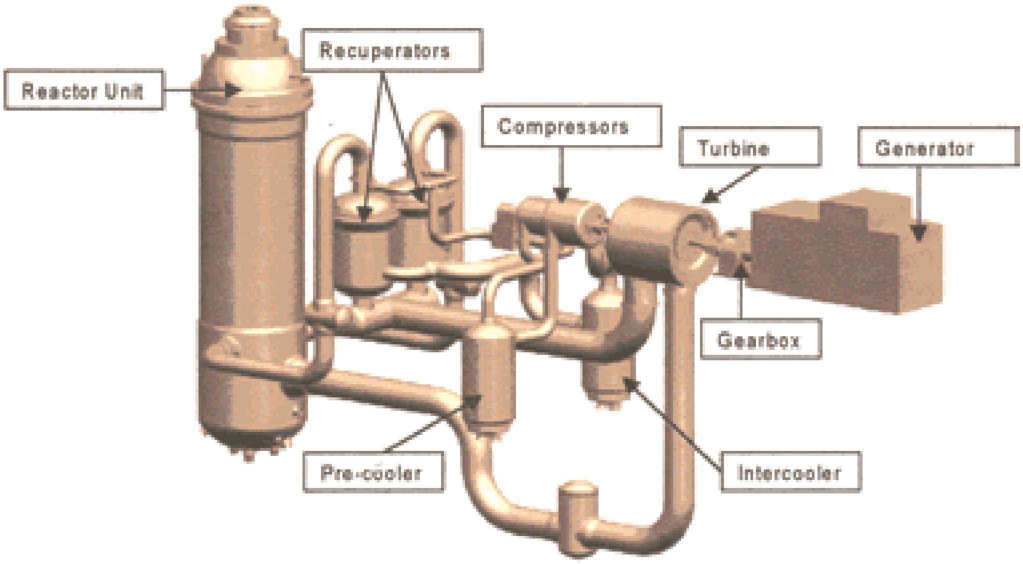


Figure 11. PBMR layout.

The pressure vessel contains a metallic core barrel, which supports the annular core holding about 450 000 low enriched, UO_2 fuelled TRISO particles. Two diverse systems are provided for shutting the reactor down, one being the central rods inserted into the borings in the side reflector and the other being small neutron absorbing spheres which are dropped into the borings in the central reflector.

To remove the heat generated in the core, helium enters the vessel and moves down between the hot spheres, after which it leaves the bottom of the vessel at a temperature of about 900°C. The hot gas then enters the turbine, which is mechanically connected to the generator through a speed reduction gear box on the one side and the gas compressor on the other side. He gas, leaving the turbine at 500°C, is cooled, recompressed, reheated and returned to the vessel.

PBMR is designed to operate 6 years before scheduled maintenance is performed.

The size of the PBMR core ensures a high surface area to volume ratio. This ensures that the heat lost through radiation is greater then the total decay heat generated by the fission products. This inherent safety feature of the PBMR renders obsolete the need for safety backup systems and leads to considerable cost reductions.

2.1.6. The PHWR-220

Pressurized heavy water reactors (PHWR) form the main stay of the Indian nuclear power program. These PHWRs are mainly derived from the CANDU type of reactors, which are also deployed elsewhere (e.g. Pakistan, Romania etc).

The PHWR at Kalpakkam (Figure 12), constituting the nucleus of the Indian Nuclear Desalination Demonstration Plant, generates 170 MW(e).

The PHWRs use double containment principle. The containment structure consists of a cylindrical pres-stressed cement concrete (PCC) primary containment with a PCC dome and a secondary containment of reinforced cement concrete structure, completely surrounding the primary containment.

The PHWRs are horizontal pressure tube type reactors, using heavy water as moderator. Their fuel is in the form of natural uranium oxide.

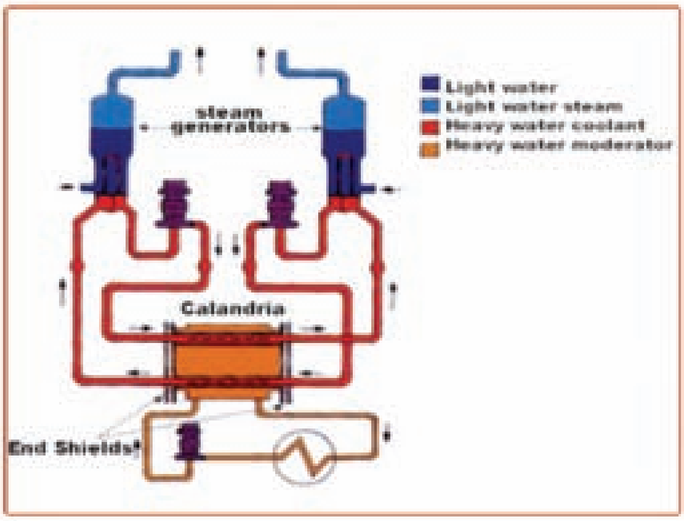


Figure 12. Simplified flow diagram of the MAPS PHWR at Kalpakkam.

The fuel is cooled by a high pressure, high temperature circulating heavy water system, called the primary heat transport system (PHT). The PHT is divided into two independent loops, connected to a common pressurizer.

Although the PHT pumps are provided with flywheels to ensure better flow coast down in case of pump trip, the reactor has an additional system to remove decay heat during cold shut down.

The PHWR concept has several advantages:

- Relatively large neutron generation time (≈0.001 second).
- On-power continuous refuelling, minimising the reactivity reserves.
- Promotion of the thermo-siphon mode of core cooling through specific core and steam generator configuration.
- Availability of a large body of cool heavy water around the pressure tubes in the core.
- Availability of large body of cool light water around the calandria vault.

2.1.7. SMART

SMART (*S*ystem-integrated *M*odular *A*dvanced *R*eac*T*or) is currently being developed by KAERI, Republic of Korea.

SMART is a small sized (330 MW(th)) integral type PWR, containing all major primary components in a single pressurized vessel. The in-vessel self-controlling pressurizer is one of the advanced design features. The system pressure is passively adjusted by partial pressure of steam and nitrogen gas filled in the pressurizer in accordance with variation in pressure and temperature of the primary coolant. CEDM (control element drive mechanism) has a very fine-step manoeuvring capability to compensate the core reactivity change caused by fuel depletion during normal operation of the SMART. The modular type once-through steam generator has an innovative design feature with helically coiled tubes to produce superheated steam at normal operating condition.

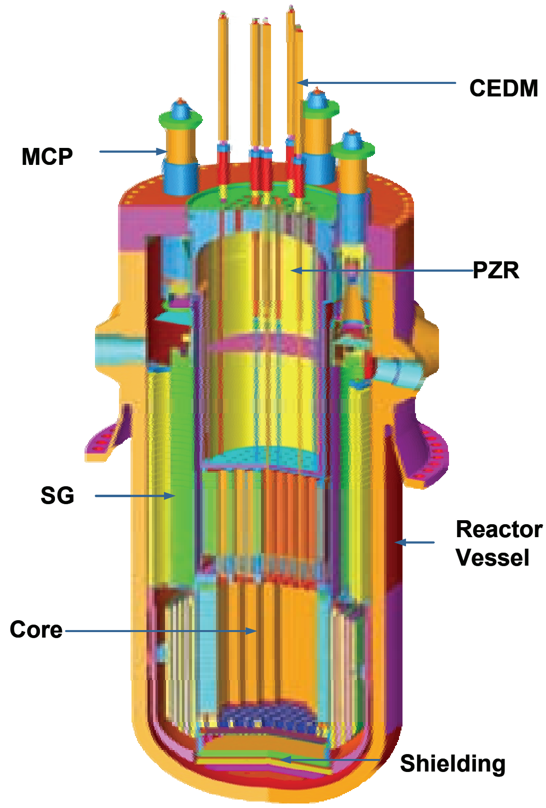


Figure 13. SMART reactor assembly.

SMART core is characterized by a 3 year cycle length with single batch reloading scheme and a large negative moderator temperature coefficient.

Major engineered safety systems function passively on demand. These consist of a reactor shutdown system, residual heat removal system, emergency core cooling system, reactor overpressure protection system, and safeguard vessel. The designer claims that under any condition, the reactor can be shutdown by inserting only control rods. In addition, a boron injection system is installed as an active backup system for the emergency case. Four independent passive residual heat removal systems with 50% capacity each remove core decay heat by natural circulation at any design bases events, and have the capability of keeping the core undamaged for 72 hours without any corrective action by operators. When small break LOCA occurs, core uncovering is prevented by two independent emergency core cooling systems with 100% capacity each which automatically operate by pressure difference. The reactor overpressure at the postulated design basis accidents related with control failure can be reduced through the opening of the PSV (pressurizer safety valve).

A leak-tight, pressure retaining (3 MPa) steel-made safeguard vessel (SV) surrounding the reactor assembly has the function of confining any radioactive products within the vessel at any postulated design bases accidents and thus protecting any primary coolant leakage to the containment. The steam released into the SV at the postulated design basis accidents is sprayed into the external shielding tank by the passive opening of the SV relief valve.

2.1.8. The barge mounted, KLT-40C reactor

KLT-40C is a twin reactor system largely derived from nuclear reactors for the Russian Ice-breakers.

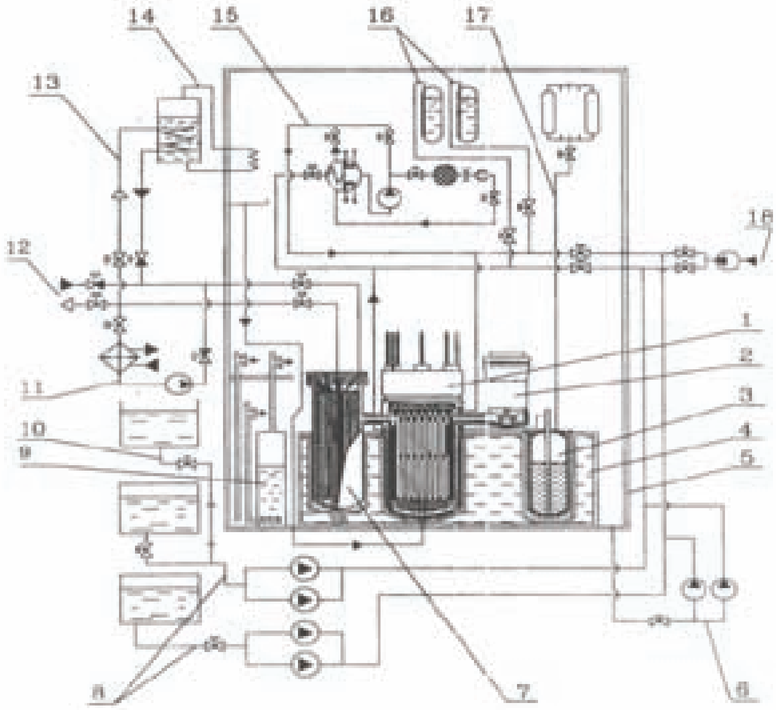


Figure 14. General layout of the KLT-40 reactor.

1- reactor; 2- main primary pump; 3- Pressurizer; 5- containment shell; 7- Steam generator; 8- High pressure ECCS; 11- Active emergency heat removal system; 12- to steam turbine plant; 16- passive ECCS; 18- low pressure ECCS.

Main technical features of the reactor are:

- Modular PWR concept, with all the advantages associated with the integral designs.
- Forced circulation of primary coolant, although natural circulation can be used in the emergency core cooling mode.

The plant comprises the reactor, four steam generators and four primary pumps joined with short loaded bearing nozzles of tube-in-tube type in a compact steam generating unit.

Steam generators are once-through type. They are housed in the pressure vessel. The vessel is made of heat resistant high strength steel with corrosion-resistant brazing.

KLT-40C can provide up to 2 × 35 MW(e) and 2 × 25 Gcal/h of heat.

KLT-40C is associated with a floating power unit (FPU) both acting as small floating nuclear cogeneration plant capable of supplying electricity and/or desalted water (or district heating energy) in remote coastal areas.

A closed intermediate circuit provides the heat for the district heating or desalination systems. Both, steam extracted from the turbine and the live steam extracted directly from the main steam line can be used as heat sources.

2.2. EVOLUTIONARY REACTORS FOR NEAR OR MEDIUM TERM DEPLOYMENT

Two innovative SMRs, currently under development mainly in the USA and in France, merit to be described here: the PWR, IRIS and the HTR, ANTARES.

2.2.1. IRIS

The International Reactor, Innovative and Secure (IRIS) is an integral and modular PWR, generating from 100 to 300 MW(e)/module [4].

It is being developed by a consortium of 13 organisations from six countries, led by Westinghouse, USA.

As in all other integral systems, the IRIS vessel houses all the major components namely the core, the core barrel, the upper internals, control rod drives, steam generators, pressurizer, heaters and primary coolant pumps.

IRIS core is designed with the objective of a longlife core (8 years) with no shuffling or refuelling to satisfy the non-proliferation concerns. With such cycle lengths, the capacity factor is increased and thus leads to positive economic effect.

In longlife cores, the limiting factor is principally the maintenance outages, which determine the capacity factor. IRIS aims to minimise these through on-line diagnostic and maintenance as well as simple, reliable design of components.

Depending upon the nominal power rating of the plant (100 or 300 MW(e)), IRIS pressure vessel has a height of 18–22 m and an outside diameter of 4–6 m. These are well within the present fabrication capabilities.

Hot coolant, rising from the reactor core to the upper part of the vessel is pumped into the steam generator annulus by six reactor coolant pumps. The axial location of the pumps is determined by the trade-off between the deteriorated pump performance at high coolant temperatures and the objective of minimising vessel penetrations near the top of the core.

An important feature of IRIS is the safety by design approach which prevents accidents through designed features as opposed to the common safety approach which focuses on the engineering to minimise the consequence of accidents.

It is for this reason that steam generators are located in a peripheral annular configuration for ease of maintenance and for allowing the core change over without prior removal of steam generators. This allows an open space above the core (≥ 10 m), which could be used to accommodate the control rod drive mechanisms. This automatically negates the reactivity insertion accident as all control systems are inside the vessel and there are no vessel head penetrations.

The most innovative IRIS feature in terms of safety by design is the management of small to medium LOCAs, which are historically the accidents yielding the worst consequences. This is achieved in IRIS by reducing the pressure differential between vessel and containment through 1) adopting a high pressure containment which increases the pressure downstream of the break and 2) - an efficient heat removal system inside the vessel, which reduces the pressure upstream of the break.

In IRIS design, full natural circulation, as in CAREM or NHR-200, is considered unfeasible. However, the advantages of natural circulation are retained through partial circulation aided by low head pumps.

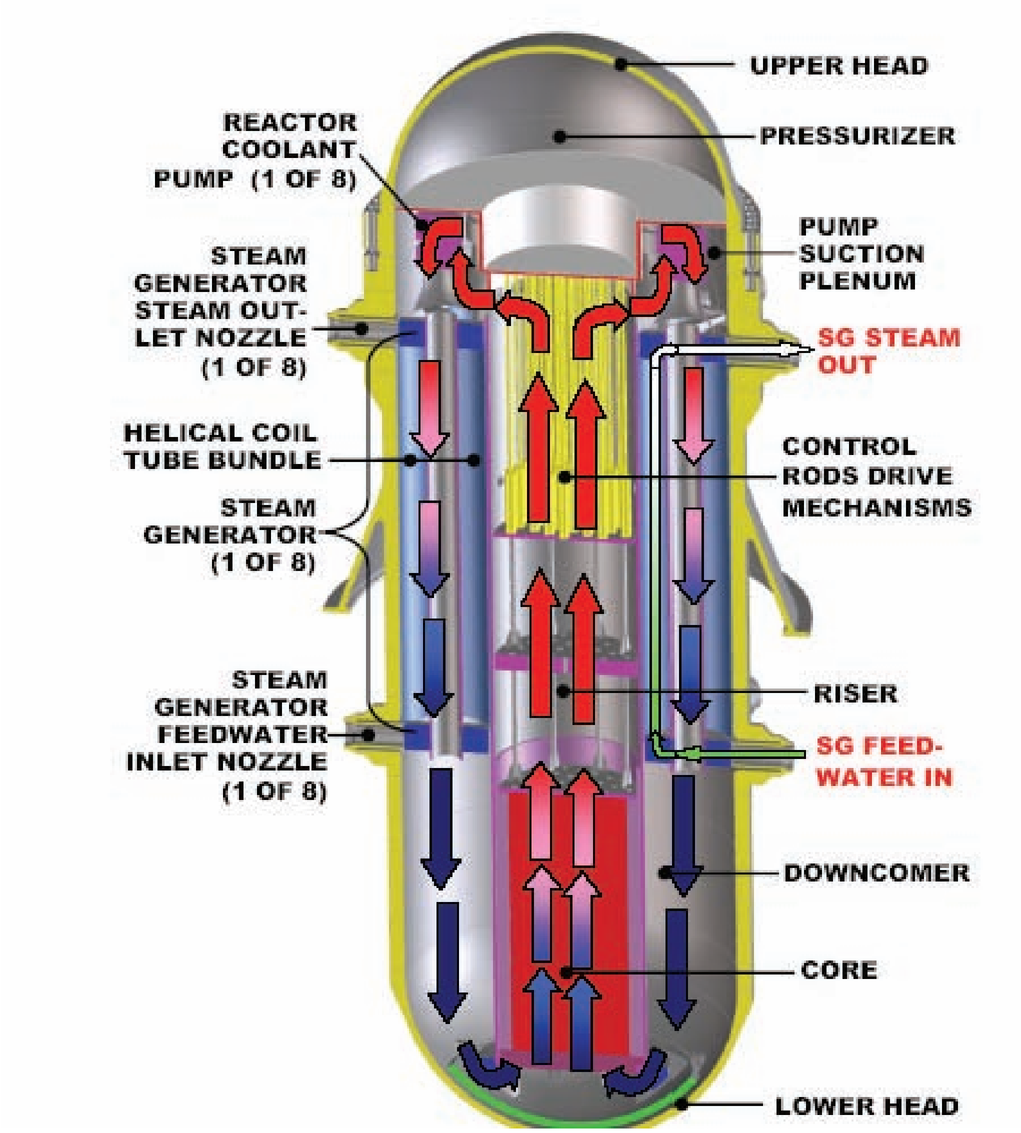


Figure 15. IRIS layout.

2.2.2. ANTARES

Based on its considerable experience in the design of MODUL, and its past participation in the GT-MHR development, AREVA NP (previously known as FRAMATOME, ANP), AREVA[3]'s joint subsidiary with SIEMENS, is developing a new generation HTR, utilising the combined cycle power conversion system [5]. Such a system promises a very high efficiency (≥47%), while avoiding technological risks.

[3] French vendor company, regrouping nuclear reactor construction and all fuel cycle services.

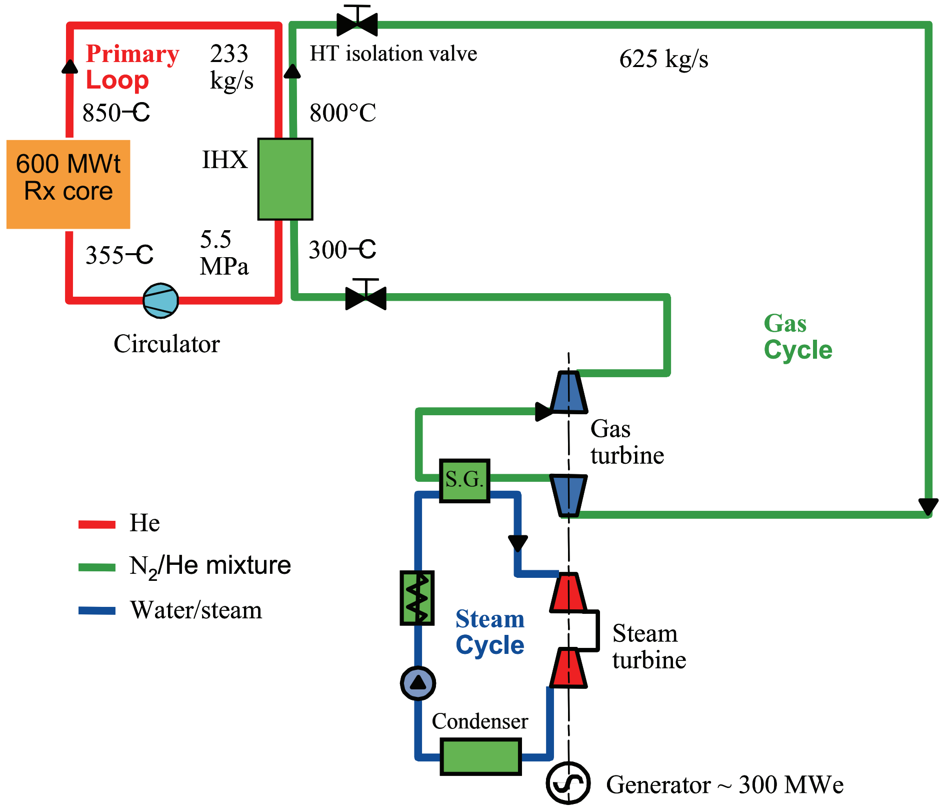


Figure 16. Principle of ANTARES operation with a combined cycle power conversion system.

The plant, known as ANTARES, is a modular design in which the core is contained in a metallic pressure vessel designed to evacuate residual heat, through radiation, in case of a major accident. This passive means is sufficient to limit the fuel kernel temperature below the design limit of 1600°C.

In order to optimise the power level, the core is of annular design. In order to minimise the core pressure drop and to simplify future spent fuel recovery, the fuel TRISO particles are embedded in compacts which in turn are contained in graphite blocks (Figure 9), arranged in a hexagonal geometry.

The primary loop in ANTARES is considerably simplified thus reducing not only component costs but also the maintenance operations in a radiological environment. The primary circuit pressure (5.5 MPa) is considerably lower than the pressure required in direct cycle systems (7 to 9 MPa). This leads to a reduction of pressure vessel wall thickness and relatively thinner welds. The lower pressure is also compatible with present day blower volumetric flow rates.

The blower is a variable rotating speed type whose flow rate can be adapted to the reactor power level. This feature virtually eliminates inventory control, unavoidable in direct cycle reactors.

The combined cycle system in ANTARES uses a gas Brayton cycle (via an intermediate heat exchanger, IHX) to recover core heat (at 800°C) and to convert it into electricity. While the gas Brayton cycle is indeed efficient at high temperatures, it leads to a loss of heat at temperatures between 120 and 26°C via the pre-cooler and intercooler exchangers as in the GT-MHR. In the ANTARES design, all the gas energy is recovered in the steam generator (SG) and passed to the steam cycle for further electricity production.

The gas loop power production is about 83 MW(e) while the steam cycle produces about 210 MW(e). These are gross power values.

The choice of the combined cycle makes ANTARES a multipurpose reactor for hydrogen production at high temperatures, for industrial heat production and for desalination as shown in Figure 17.

ANTARES is at present in the conceptual stage. R&D is in progress to investigate the behaviour of IHX materials and of the fuel particles under very long service period. Mechanical characteristics testing and corrosion behaviour in different environments are also being investigated.

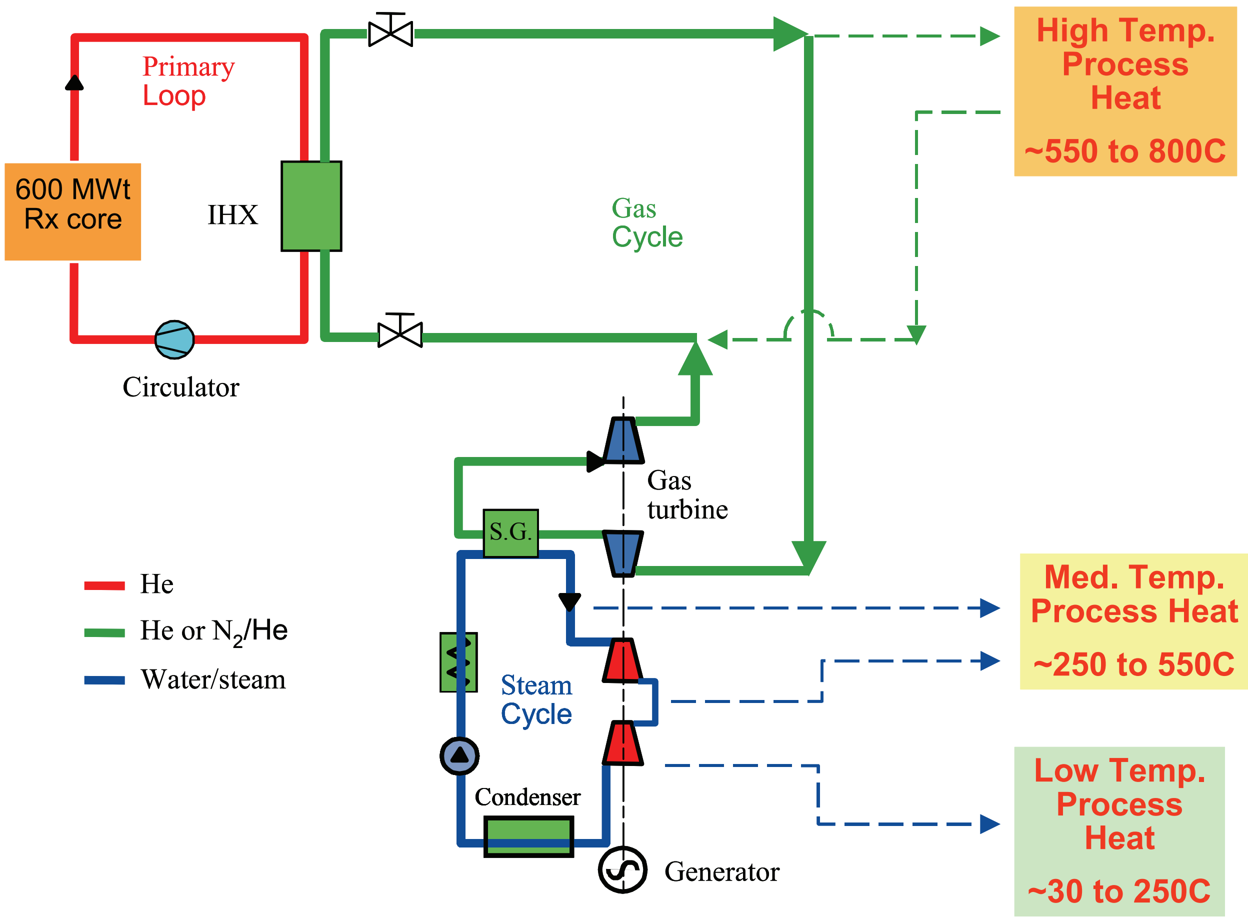


Figure 17. Different uses of ANTARES.

TABLE 2. SOME TECHNICAL CHARACTERISTICS OF DIFFERENT 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	Water	Water	Water	He	He
Moderator	Water	Water	Water	Graphite	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
Secondary circuit feed water pressure (MPa)	4.7		57.5	-	-
Secondary circuit feed water (fluid) temperature (°C)	200			-	-
Intermediate (or tertiary) circuit pressure (MPa)		3.0		7	7
Intermediate (or tertiary) circuit in/out temperature (°C)		135/170		100	100
Plant life time (years)		40	40	60	60
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

TABLE 2 (cont.). SOME TECHNICAL CHARACTERISTICS OF DIFFERENT NUCLEAR REACTORS

	PHWR	SMART	KLT-40C	IRIS	ANTARES
Coolant circuit in/out temperature (°C)	249/293.4	270/310		292/328.4	395/850
Secondary circuit feed water pressure (MPa)	4.2	5.2		6.4	(N2/He) 5.5
Secondary circuit feed water (fluid) temperature (°C)	170	180		224	(350/800)
Intermediate (or tertiary) circuit pressure (MPa)					
Intermediate (or tertiary) circuit in/out temperature (°C)			130		30/550
Plant life time (years)	40	60	40	60	60

** Calculated characteristics for MED couplings based on waste heat utilisation (Section 3.1).*

2.3 DESALINATION PROCESSES

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.

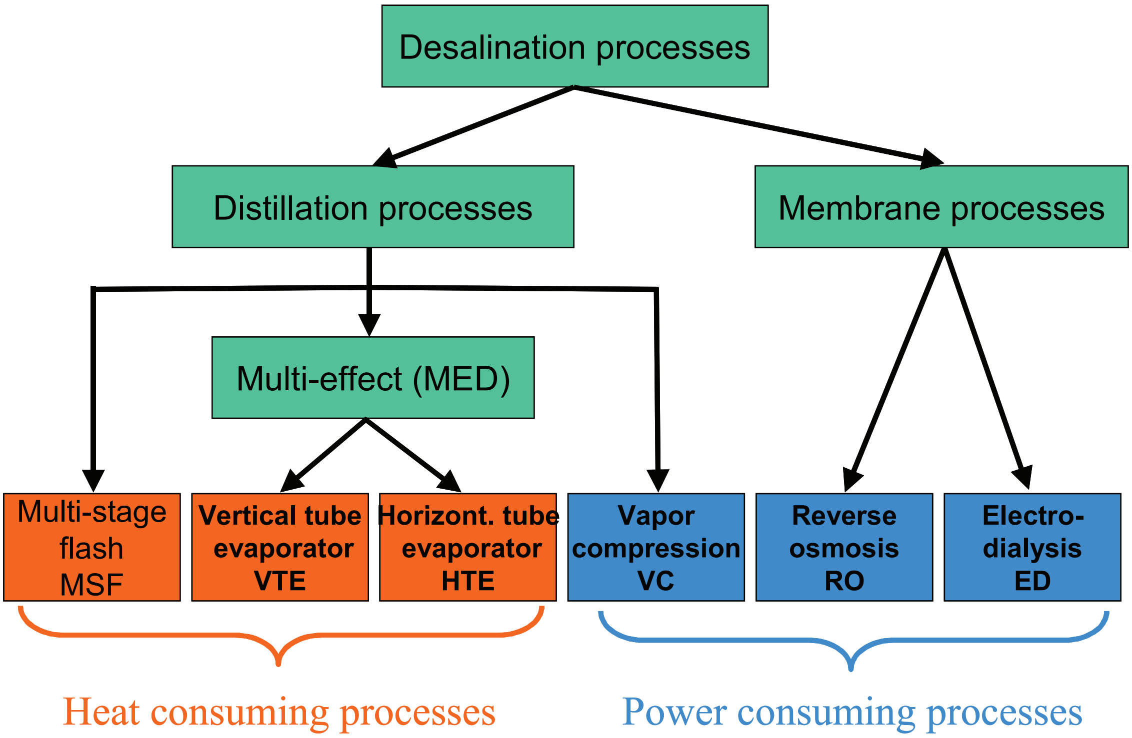


Figure 18. Desalination processes.

Desalination processes can be broadly categorised into two main types: processes using heat and process using electricity. The first type 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).

2.3.1. Multi-stage flash (MSF)

Figure 19 shows the operating principle of the MSF plant.

Consider a vessel under vacuum, isolated from its environment and containing only seawater in equilibrium with its vapour at temperature t and pressure p. When a heating fluid (generally hot water) at a temperature $t+\Delta t$ is introduced in the vessel, and if the pressure p is less than the saturation pressure, an instantaneous vaporisation will be produced by a flash. The latent heat of vapour can then be transferred to cold seawater tubes passing through the vessel and the vapour condensed and recovered in the receptacle.

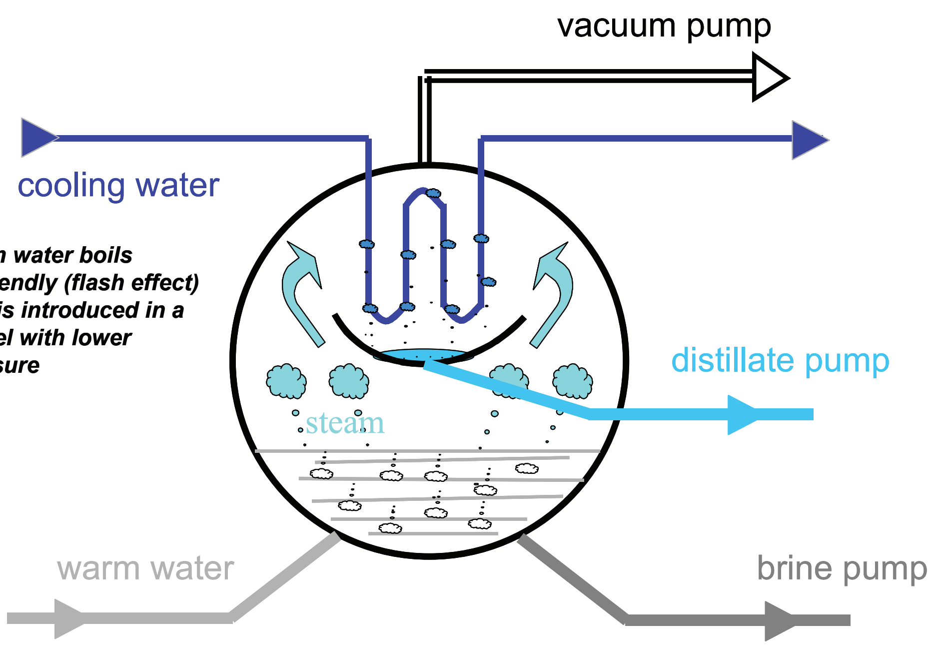


Figure 19. Operating principle of a single stage MSF.

The efficiency of the system can be considerably increased by having several stages in series (about 20 or more) for industrial production, as shown in Figure 20.

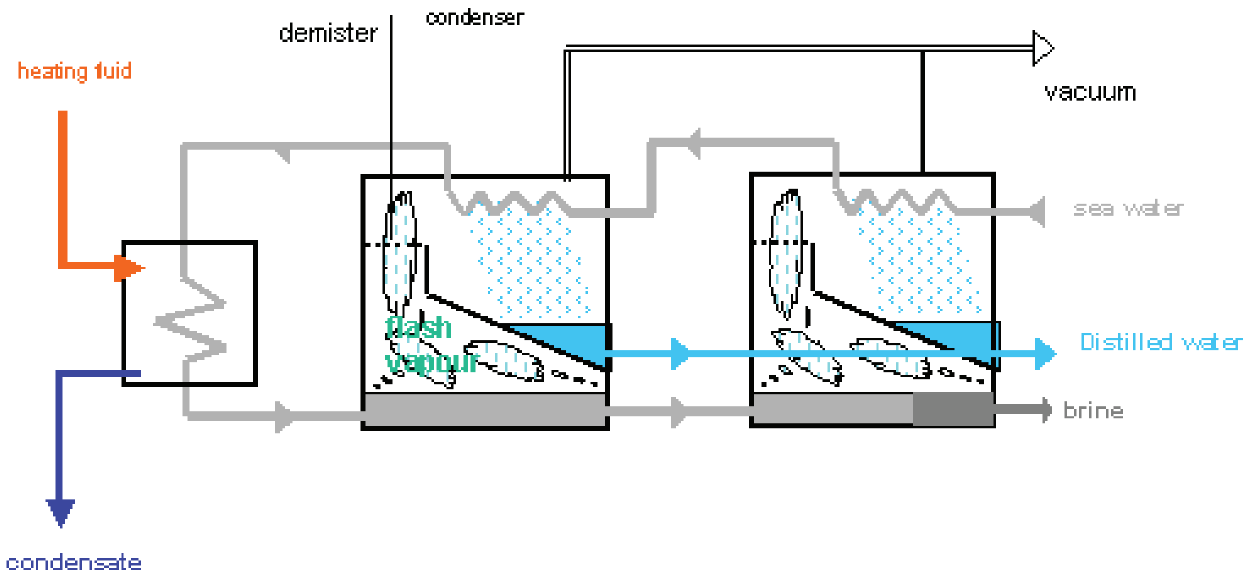


Figure 20. Schematic diagram of an industrial MSF design.

Seawater is first sent to a pre-treatment system where chemical additives or acids are added to avoid the formation of alkaline cruds or deposits on the tube surfaces. The water then passes through a de-aerator to reduce the quantity of oxygen and CO_2 to minimise corrosion risks.

Incoming seawater, passing through successive stages in the opposite direction gets heated and is finally brought to a temperature of about 80 to 120°C in a “brine heater”. It is then fed at the bottom of the first MSF stage where the initial flash takes place. It then passes into the next stages maintained at lower and lower pressures to ensure successive flashes in each stage. The condensate also passes from stage to stage and is collected in the distilled water reservoir.

MSF is particularly interesting where heat is easily available and one requires very large desalting capacity. This for example is the case in Saudi Arabia where about one million m^3/day is produced at Al-Jubail plant.

The heat consumption of the MSF plant depends on the temperature of the heat source and on the GOR of the system but generally varies from 55 to 120 kWth/m^3.

Distilled water from MSF is of very high quality with the residual salinity of about 25 ppm.

Although 60% of the desalination plants in the world are of MSF type, the technology has reached its limits and is gradually being replaced by RO or MED plants which have a much higher potential for further development and which consume less energy.

2.3.2. Multi-effect distillation (MED)

Figure 21 shows the schematic flow diagram of a MED process, using horizontal tube evaporators (HTE). In each effect, heat is transferred from the condensing water vapour on one side of the tube bundles to the evaporating brine on the other side of the tubes.

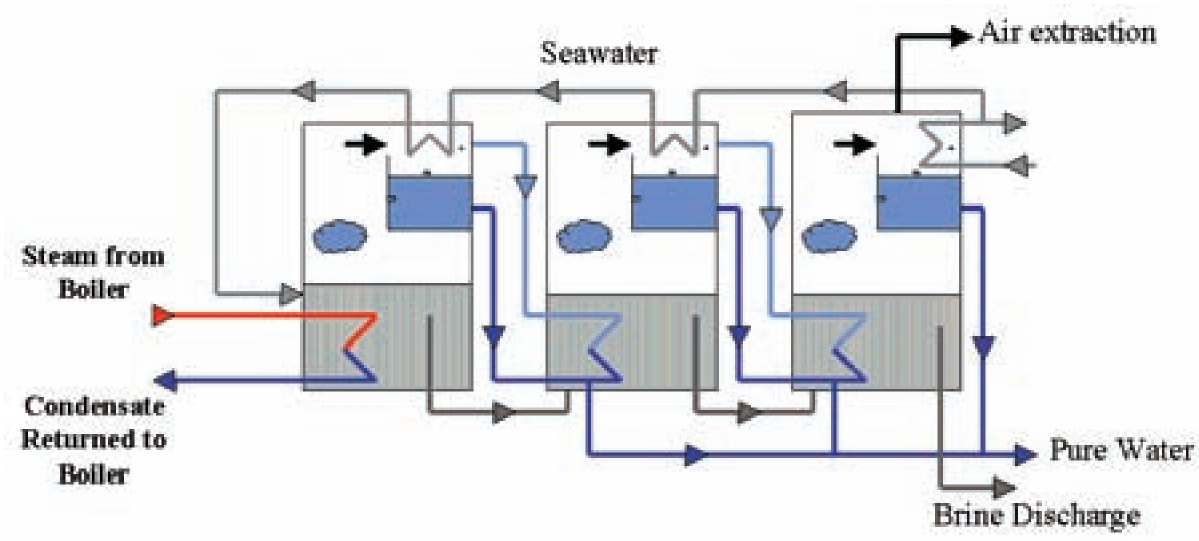


Figure 21. Schematic diagram of an MED system.

This process is repeated successively in each of the effects at progressively lower pressure and temperature, driven by the water vapour from the preceding effect. In the last effect, at the lowest pressure and temperature, the water vapour condenses in the heat reject heat exchanger, which is cooled by incoming seawater. The condensate distillate is collected from each effect.

According to the direction of vapour and brine flow, there are “forward feed” and “backward feed” arrangements. In forward feed MED plants, vapour and brine move through the evaporators as parallel flows from the first high pressure evaporator to the last low pressure one. The pre-heating of feed water occurs in separate heat exchangers. In backward feed MED plants, vapour and brine move through the evaporators in opposite directions, whereby feed water pre-heating is eliminated.

Currently, MED processes with the highest technical and economic potential are the low temperature horizontal tube multi-effect process (LT-HTME) and the high temperature vertical tube evaporation process (HT-VTE).

The main differences between LT-HTME plants and HT-VTE plants are in the arrangement of the evaporation tubes, the side of the tube where the evaporation takes place and the evaporation tube materials used. In LT-HTME plants, evaporating tubes are arranged horizontally and evaporation occurs by spraying the brine over the outside of the horizontal tubes creating a thin film from which steam evaporates. In HT-VTE plants, evaporation takes place inside vertical tubes. Furthermore, in LT-HTME plants, the maximum brine temperature is limited to 70°C, in order to avoid corrosion and scaling problems. Most LT-HTME plants now use low cost materials such as aluminium for heat exchanger and carbon steel as shell material.

2.3.3. Reverse osmosis

Osmosis is a natural process in which water molecules migrate across a semi-permeable membrane from a solution of low concentration (e.g. pure water) into a solution of higher concentration (e.g. seawater). Reverse osmosis (RO) is a separation process in which pure water is “forced” out of a concentrated saline solution by flowing through a membrane at a high static trans-membrane pressure difference (Figure 22). This pressure difference must be higher than the osmotic pressure between the solution and the pure water.

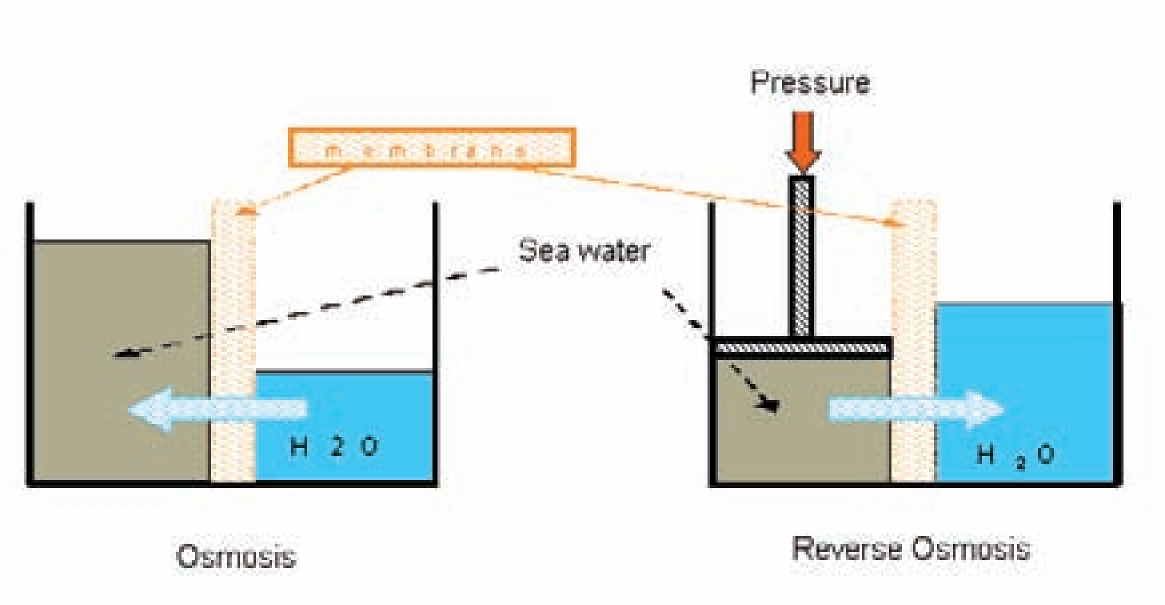


Figure 22. Osmosis and reverse osmosis processes.

The saline feed is pumped into a closed vessel where it is pressurised against the membrane. As a portion of water passes through the membrane, the salt content in the remaining brine increases. At the same time, a portion of this brine is discharged without passing through the membrane.

RO membranes are made in a variety of modular configurations: two of the commercially successful configurations are spiral-wound modules and hollow fibre modules. In both configurations, module elements are serially connected in pressure vessels, up to 7–8 in the case of spiral wound and up to 2–3 in the case of hollow fibre modules.

Figure 23 presents a schematic diagram of an industrial RO process.

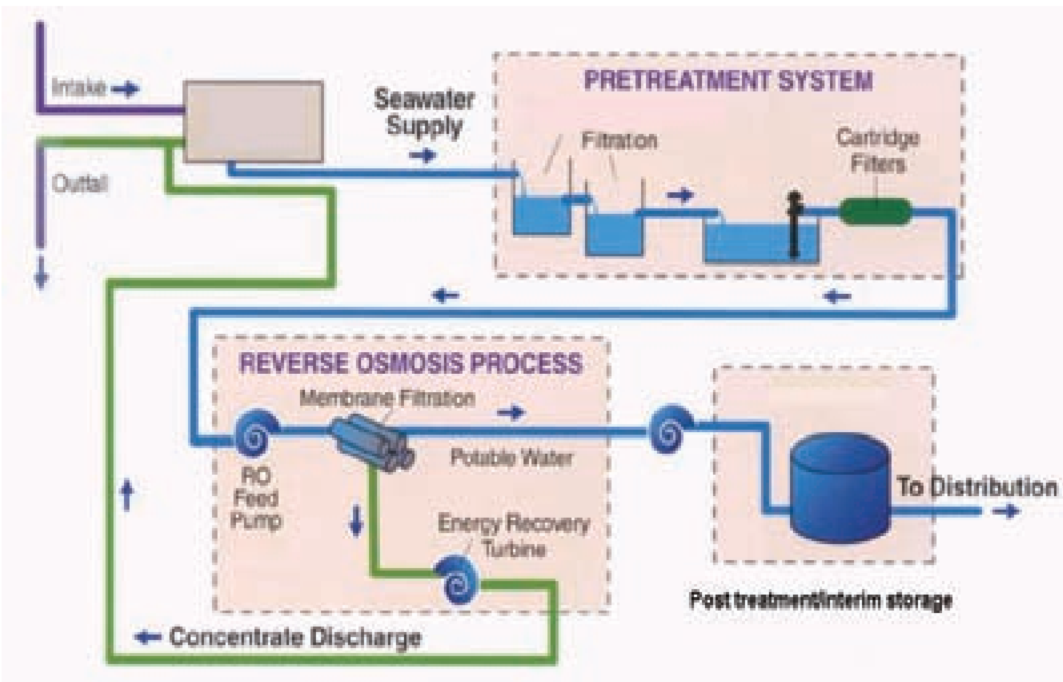


Figure 23. Schematic illustration of an operating RO plant.

2.3.4. Energy consumption in desalination plants

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 3.

TABLE 3. AVERAGE ENERGY CONSUMPTION IN DESALINATION PROCESSES

Process	Specific Heat Consumption $kW_{th}.h/m^3$	Specific Electricity Consumption $kW_e.h/m^3$
MSF	100	3*
MED	50	2*
RO	–	4.5

** Some electricity is required to run the pumps and other auxiliary systems in MSF and MED.*

It can be shown that typically, in order to produce about 290 000 m^3/day, MED process would require about 530 MW(th) and 13 MW(e). To produce the same amount of water, RO would require only about 54 MW(e). The thermal energy requirements for MSF could be twice as much as those for the MED plant

2.4. NUCLEAR REACTOR AND DESALINATION SYSTEM COUPLING AND OPTIMISATION

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.

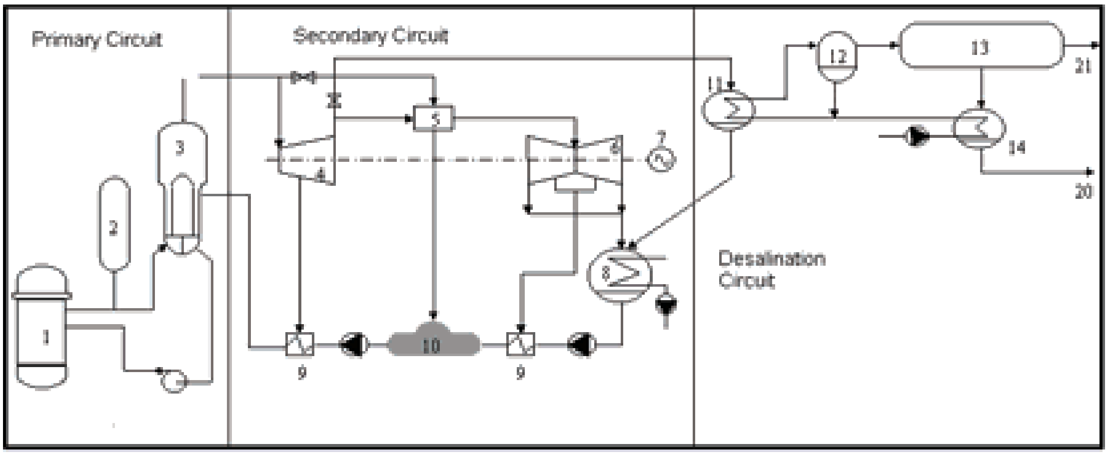
The EURODESAL safety study was based on the probabilistic assessment of the frequency of occurrence of certain key transients such as: the loss of heat sink (e.g. loss of the MED plant), the loss of electrical load in the RO plant and the rupture of the tube transporting extracted vapour to the flash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

The results of 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.

2.4.1. Thermal couplings to nuclear reactors

In the light of the above considerations, in the so called "conventional coupling scheme", (shown in Figure 24 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.



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.

Figure 24. Conventional coupling of a nuclear reactor to a MED plant.

Results of thermodynamic calculations for PWR-900 are given in Table 4. 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 4. 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

2.4.2. Thermal coupling scheme optimisation

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.

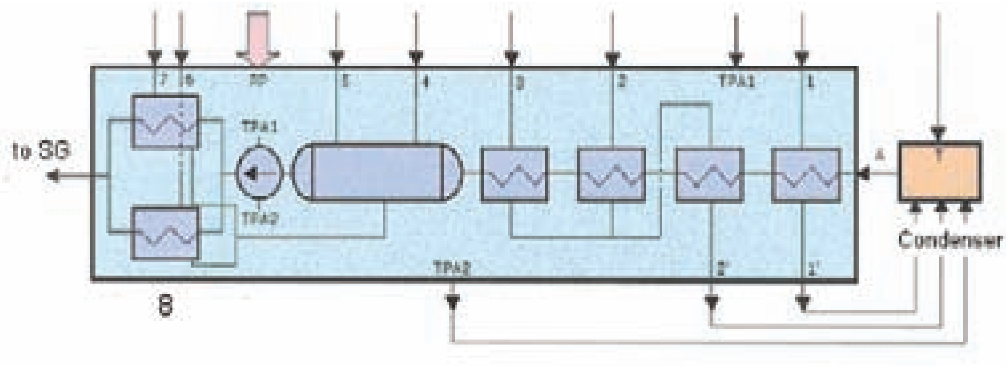
As regards PWRs, an effort was also made in the context of the French-Tunisian collaborative project (under IAEA/TC program INT/4/134), known as TUNDESAL [7].

However, this study is illustrative of the search for coupling scheme optimisation for any reactor and thermal process coupling.

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 over all turbine efficiency. The coupling via the condenser was thus abandoned.



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.

Figure 25. Internal vapour derivations in a typical PWR..

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 25).

The thermodynamic parameters at some of these points are given in Table 5.

TABLE 5: 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 26.

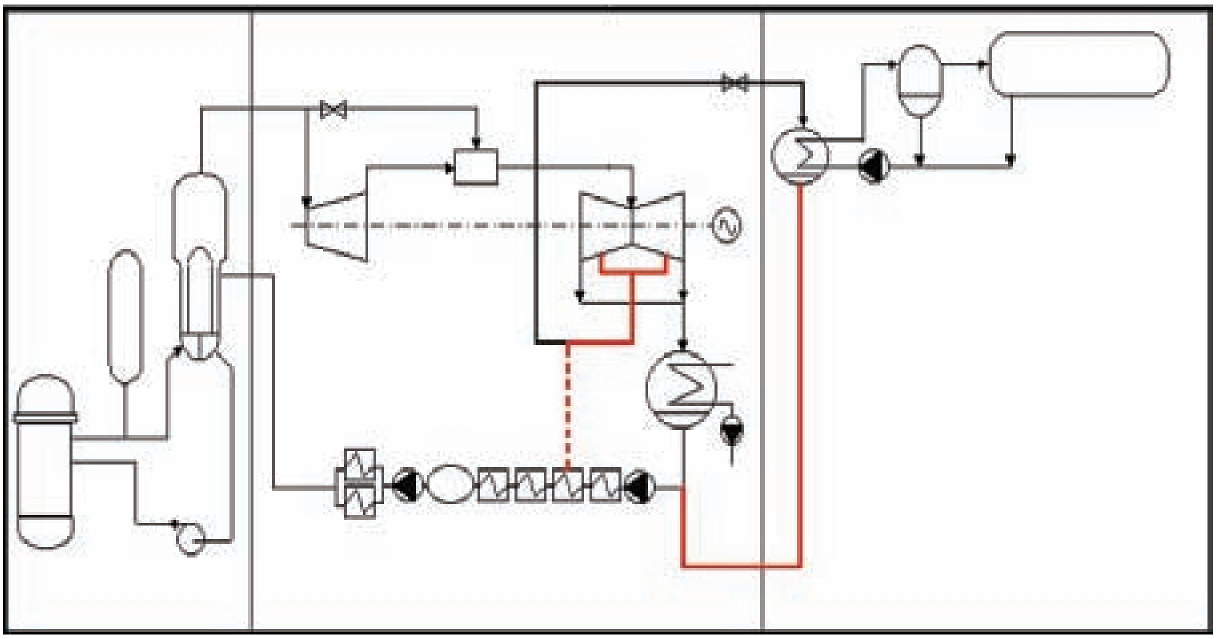


Figure 26. Coupling through the bleed-off point 2.

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 27:

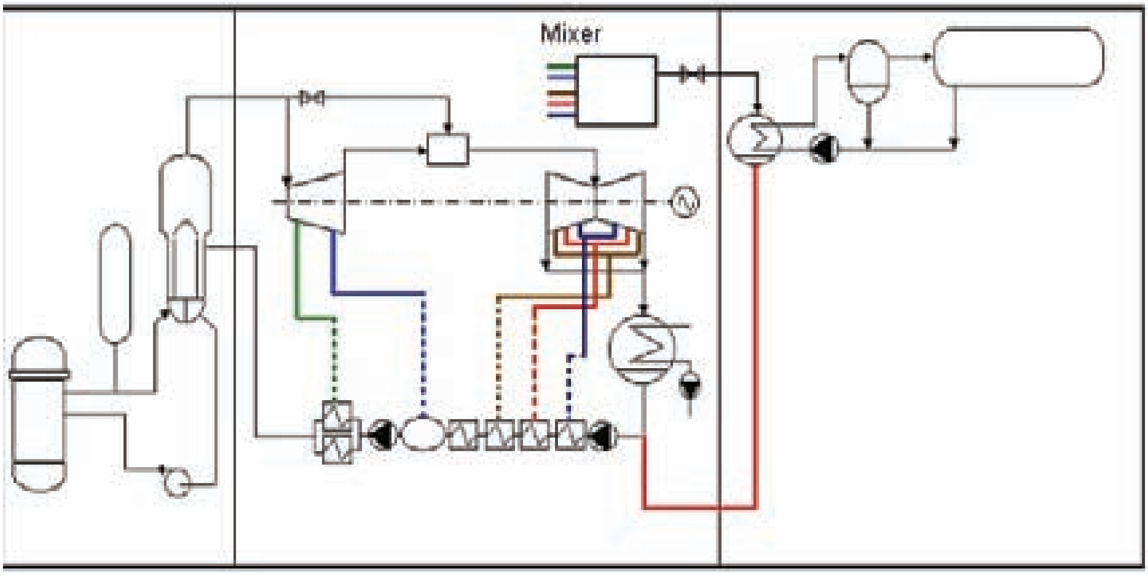


Figure 27. Coupling scheme with mixing the flow rates from the various internal bleed-off points

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 penalising solution was the extraction of steam from one of the turbine blades, as in the conventional coupling scheme.

2.5. ADVANCES AND 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.

2.5.1. 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 28.

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 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.

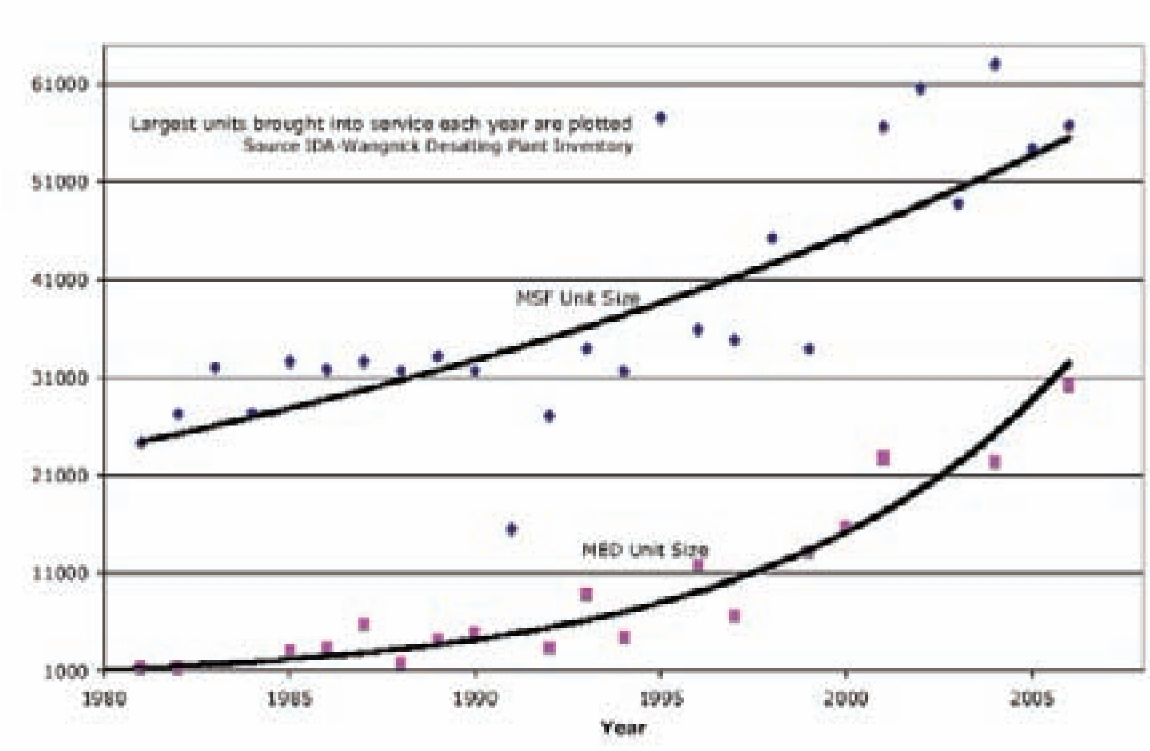


Figure 28. Unit size growth of MSF and MED plants over the years. [8].

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 6, 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
Turn key cost (M$)	375	265

Other new developments in the thermal processes (mainly MED) can be summarised 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. utilisation 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.

2.5.2. 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 29). 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.

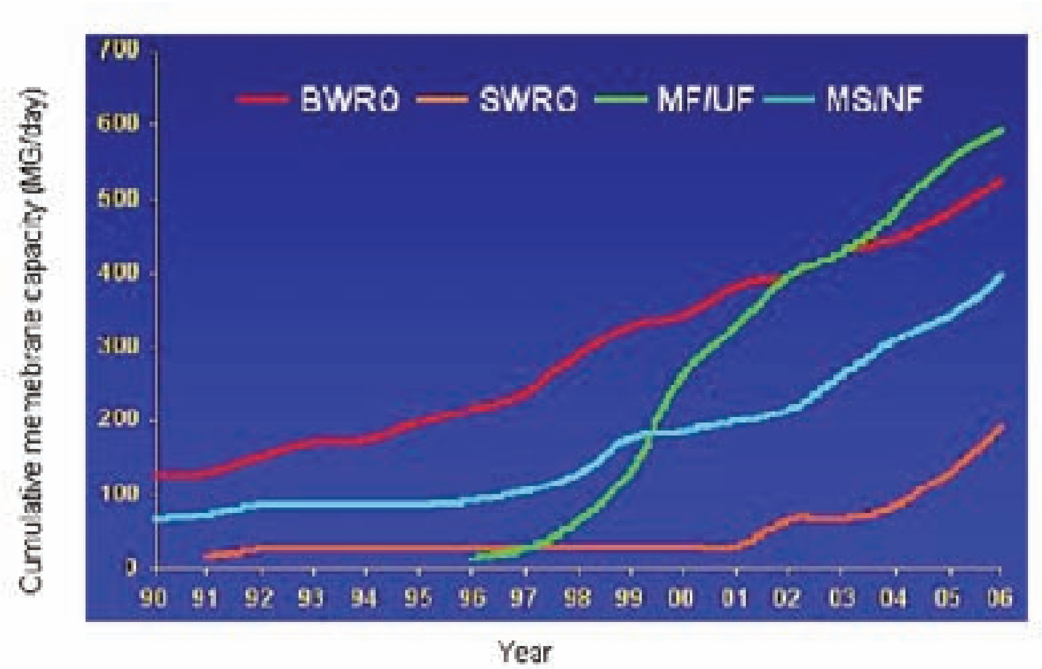


Figure 29. Increase in membrane-based capacity (millions of US gallons) from 1990 to 2006 [8]. BWRO: brackish water RO; SWRO: sea water RO; MF/UF: micro-ultra-filtration; MF/NF: micro-nano-filtration.

2.5.2.1. 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.

2.5.3. Energy recovery devices

The energy cost of a desalination system is a complex function of several parameters, including the choice of the process and the site specific conditions. In general this cost is from 30 to 60% of the total cost. It is for this reason that there is an increasing tendency to recover, at least partially, the energy used to pressurise the RO systems. Such systems can recover from 10 to 50% of the energy needs of a seawater RO system.

An innovative, energy recovery device, known as the "Work Exchanger" is shown in Figure 30.

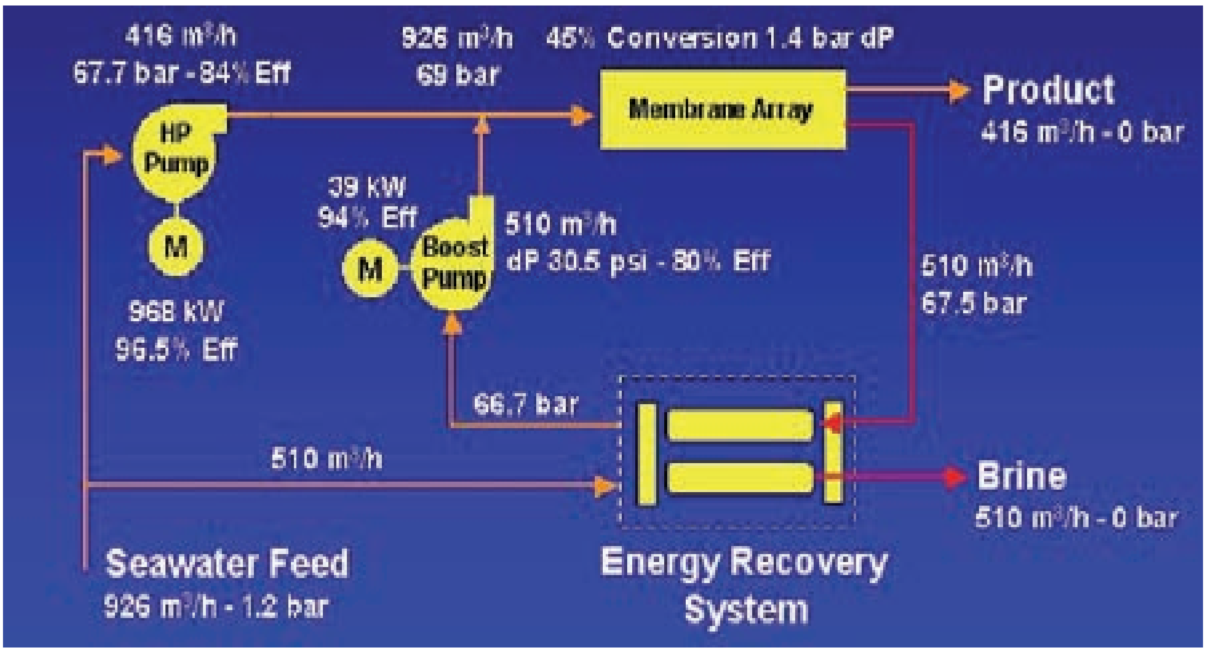


Figure 30. Principle of a RO Work Exchanger [8].

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.

2.6. IMPROVEMENTS IN DESALINATION COST EVALUATION METHODS

In the early nineties, following the first few General Conference resolutions on nuclear desalination, IAEA developed a spreadsheet code for Co-generation and Desalination Economic Evaluation, (CDEE), with the help of General Atomics.

Towards the end of 1998, CDEE evolved into what has since then been known as the Desalination Economic Evaluation Program, (DEEP).

Progressively, DEEP became an internationally used "reference" code for desalination costs. It can thus be safely stated that improvements in desalination costs evaluation methods, notwithstanding local developments in Member States, are equivalent to improvements in successive DEEP versions.

The latest of these versions is DEEP-3 [9] which includes, thanks to extensive discussions under IAEA's on-going CRP on Economic Evaluation, many important improvements in the calculation with thermal and RO systems [10]. Notable among these are:

2.6.1. Thermal systems

A. The GOR model

In DEEP-3, the top brine temperature, T_{tbt}, retained as a design parameter**,** can be input by the user or calculated as follows for a given steam temperature:

$$T_{tbt} = T_{steam} - \Delta T_{aproach} \tag{1}$$

GOR can also be input by the user or calculated in terms of the ratio of the entrained steam vapour to the motive steam flow, R_{tvc}. This is an input parameter:

$$GOR_{tvc} = GOR_{new}(1 + R_{tvc}) \tag{2}$$

Where, GOR_{new} is dependent on T_{tbt}. Equation (2) is a generalised expression, which takes into account the coupling of an MED or MSF plant to a vapour compression stage.
Once ***GOR*** is calculated, the calculation of the steam flow rate is straight forward.

For a given salt concentration factor, ***CF,*** the cooling sweater temperature gain, ΔT_c and the produced distillate flow rate, W_d, the reject brine flow rate, W_b, the make up feed flow rate, W_f and the condenser cooling water flow rate, W_c can be estimated:

$$W_b = W_d / (CF - 1) \tag{3}$$

$$W_f = CF \times W_b \tag{4}$$

$$W_c = Q_c / C_c \Delta T_c \tag{5}$$

Where, Q_c is the final condenser heat load and C_c is the specific heat capacity of cooling water.

B. The lost shaft work model

In previous DEEP versions, the lost shaft work was only calculated for backpressure thermal coupling schemes. DEEP-3 has extended the model to both extraction and backpressure configurations:

2.6.2. RO systems

As for the ***GOR*** in thermal systems, the user can specify the system recovery ratio, ***R***, or have it calculated by DEEP-3:

$$R = 1 - C.S_f \tag{6}$$

Where S_f is the feed salinity (ppm) and C is a parameter defined as:

$$C = 1.15e^{-3} / P_{\max} \tag{7}$$

$P_{\max}$ is the maximum design pressure of the membrane (bars).

For permeate salinity and feed pressure, specific expressions taking into account the feed temperature and salinity corrections are used.

Similarly, for the energy recovery, previous versions of DEEP considered only the Pelton-Wheel. In DEEP-3, the energy recovery fraction is introduced as an input design parameter (which could also be valid for the pressure and work exchangers).

2.6.3. Other developments

In the context of CRP on economic evaluation, various participants have started working on some new developments, which are expected to be available for integration into future DEEP versions:

(1) This is the case for example for CEA, currently in the process of finishing three developments:

- Elaboration of detailed correlations for main RO performance parameters such as the recovery ratio, feed pressure, permeate flux etc as functions of three variables: the feed temperature, the feed flow and the feed salinity [11]. These correlations established initially for Filmtec SW30-HR380 membranes will be generalised to other membranes and seawater compositions under the Indo-French collaboration agreement and experimentally verified on Indian RO installations.
- Development of an MED plant simulator (under a specific IAEA contract), based on the analytical treatment of thermal-hydraulic phenomena, utilising general energy and mass conservation laws. Thermodynamic parameters calculated by the simulator will then be input into DEEP for more precise calculations of desalination costs.

- The actual versions of DEEP use the power credit method to allocate costs to water and electricity plants. CEA is developing a new method, based on the exergy principle, to remove some elements of arbitrary allocations in the power credit method.

(2) Syrian and Egyptian participants in the CRP have developed spread sheet software to estimate the desalted water transport costs, which are up till now not included in evaluations with DEEP.

(3) Yet another participant in the CRP, ANL from USA, has proposed more economics oriented method for desalination cost evaluations.

3. COST REDUCTION 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:

3.1 UTILISATION OF WASTE HEAT FROM NUCLEAR REACTORS

3.1.1. High temperature, gas cooled reactors

Two of the most commonly used desalination processes are the multi-effect distillation (MED) and the reverse osmosis (RO). In both cases, part of the useful energy is diverted to produce the desalted water (see coupling schemes in Section 2). If the desalting capacity is high, this energy loss could be very significant.

An alternative, providing virtually free heat to be used with the MED process, is based on the utilisation of gas cooled, high temperature reactors.

Thus, for example, in the two such reactors currently being developed (the GT-MHR and the PBMR), circulating helium, which has to be compressed in two successive stages, cools the reactor core. For thermodynamic reasons, these compression stages require pre-cooling of the helium to about 26°C through the use of the pre-cooler and intercooler helium-water heat exchangers.

Considerable thermal power (≈300 MW(th)) is thus dissipated in the pre-cooler and the intercooler. This thermal power is then evacuated to the heat sink.

Depending upon the specific designs, the temperature ranges of the water in these exchangers could be between 80 and 130°C. This is an ideal range for desalination with the MED plant, which can be coupled between a mixer (of the flows from the pre-cooler and the intercooler) and the switch- cooling unit, evacuating the heat to the heat sink, (sea or river).

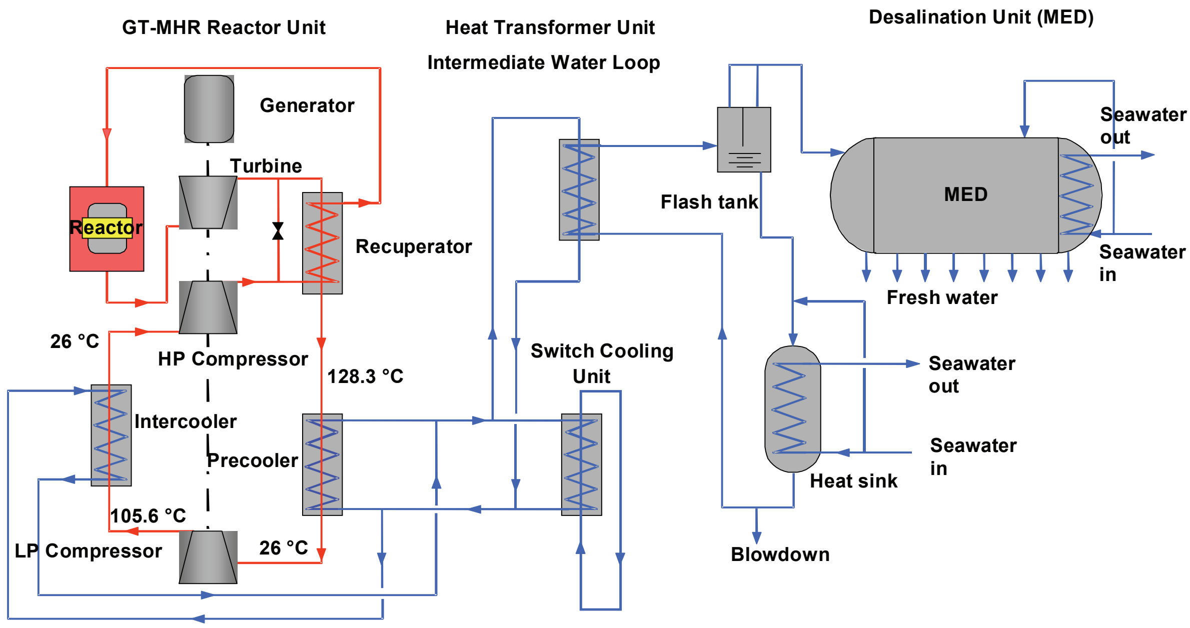


Figure 31. Principle of waste heat utilisation from a GT-MHR (or PBMR).

CEA, France has thus recently developed thermodynamic models [12] to determine the total amount of waste heat from the GT-MHR and the PBMR, which could be input to the MED plant without in anyway degrading the thermodynamic conditions on the reactor side yet at the same time respecting the specific site characteristics.

The thermal powers, produced in the pre-cooler and the intercooler of the GT-MHR, are respectively 171.6 and 134.3 MW(th). If the fluids coming out of these two exchangers are mixed, one would expect a total thermal power of about 305.9 MW(th), which should be theoretically available for desalination with the MED plant.

In practice only a fraction of this power can be used. It was shown in [6] that, for safety reasons, it is essential to maintain a dynamic pressure barrier between the mixer and the MED process. This is achieved by interposing the intermediate circuit, comprising a heat exchanger and a Flash tank.

Results of calculation then show that, in this case, the total thermal power available for desalination is only 69.3 MW(th)/module for the GT-MHR, i.e. about 23% of the theoretical available thermal power.

As shown in [11], two modules of the GT-MHR would thus provide 573 MW(e) and 38 720 m^3/day of desalted water. These are respectively 95% of the required power and 81% of the required desalted water at the la Skhira site in Tunisia.

A similar reasoning can be applied to the PBMR in which case the available heat for desalination would be about 22%.

In this case 3 modules of the PBMR would provide 345 MW(e) and 25 562 m^3/day of desalted water

Certain economic parameters of the two reactors, as announced by their developers [13] and presented in Table 7, were then input into the new DEEP-3 model to evaluate the desalination costs in Tunisian conditions. Similar calculations were performed for the PBMR and the 600 MW(e) gas turbine combined cycle plant, CC-600.

TABLE 7. ECONOMIC PARAMETERS OF THE HTRS AND CC-600 (YEAR OF REFERENCE 2006)

Parameters	Units	GT-MHR*	PBMR*	CC-600**
Net electrical power/module	MW(e)	286.6	114.9	545.2
Net thermal power/module	MW(th)	592.6	265.9	1069
Efficiency	%	48.3	43.2	51
Availability	%	91.2	91.2	90.3
Number of units at site		2	3	1
Construction lead time	yrs	4	2	2
Plant life time	yrs	40	40	25
Specific construction cost claimed by designer	$/kW	**1073**	**1650**	**525**
Specific investment cost at 5% discount rate claimed by designer	$/kW	**1182**	**1733**	**551**
Specific investment cost at 8% discount rate claimed by designer	$/kW	**1251**	**1782**	**567**
Specific investment cost at 10% discount rate	$/kW	**1298**	**1815**	**578**
Fossil fuel price escalation rate	%/year			**2**
kWh cost at 5% discount rate	10^{-3} $/kW.h	**26.0**	**31.3**	**48.8**
kWh cost at 8% discount rate	10^{-3} $/kW.h	**30.5**	**37.5**	**49.64**
kWh cost at 10% discount rate	10^{-3} $/kW.h	**33.8**	**41.7**	**50.25**

* As published or announced by the developers.
** Under Tunisian conditions, with gas price of 150 $/toe (20.62 $/bbl).

The results obtained for desalination costs evaluations are presented in Table 8.

TABLE 8. DESALINATION COSTS, AT 8% DISCOUNT RATE, BY GT-MHR + MED, PBMR + MED SYSTEMS, USING WASTE HEAT AND CC-600 + MED

Parameters	Units	GT-MHR	PBMR	CC-600*
Year of industrial operation	2020			
No. of modules		2	3	1
Net electricity generation	MW(e)	548	345	600
Discount rate	%	8		
Desalted water production	m^3/day	38 143	41 969	39 288
Spec. const. cost of desalination plant	$/($m^3$/day)	1242	1242	1112
Specific investment cost of desalination plant	$/($m^3$/day	1307	1307	1171
Desalted water cost	$/$m^3$	0.6271	0.9241	0.9450

** With gas price of 20.62 $/bbl (150 $/toe) and 2% annual escalation rate.*

Detailed economic evaluations, undertaken in the context of the Tunisian site (see Section 4), show that the above coupling schemes lead to the lowest desalination costs. Thus for example, at 8% discount rate and fossil fuel price of 150 $/toe (20.62 $/bbl), the desalination cost of the GT-MHR + MED system is 34% lower than that by the gas turbine, combined cycle plant + MED. In the same conditions, this cost is 2% lower for the PBMR + MED system.

3.1.2. Utilisation of waste heat from the condensers 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 32).

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, $\Delta \mathbf{P}$, is maintained at a constant value, the membrane's net driving force, **NDP** $(=\Delta \mathbf{P} - \Delta\pi)$ decreases. As a result, the specific power consumption of the RO system decreases with temperature, (Figure 33).

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.

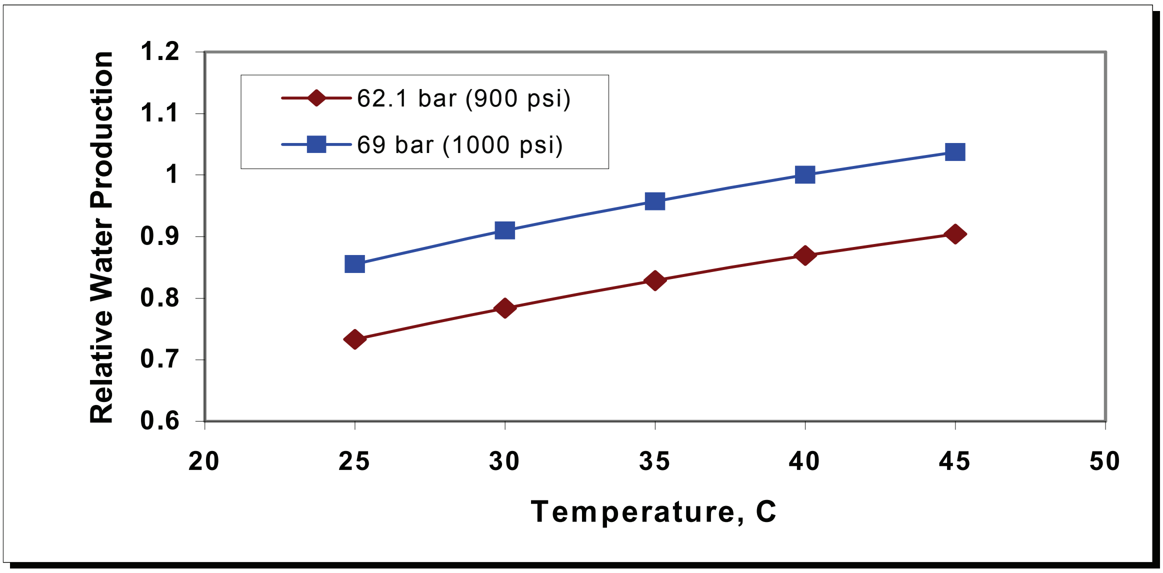


Figure 32. Normalized water production as a function of RO feed water temperature and pressure.

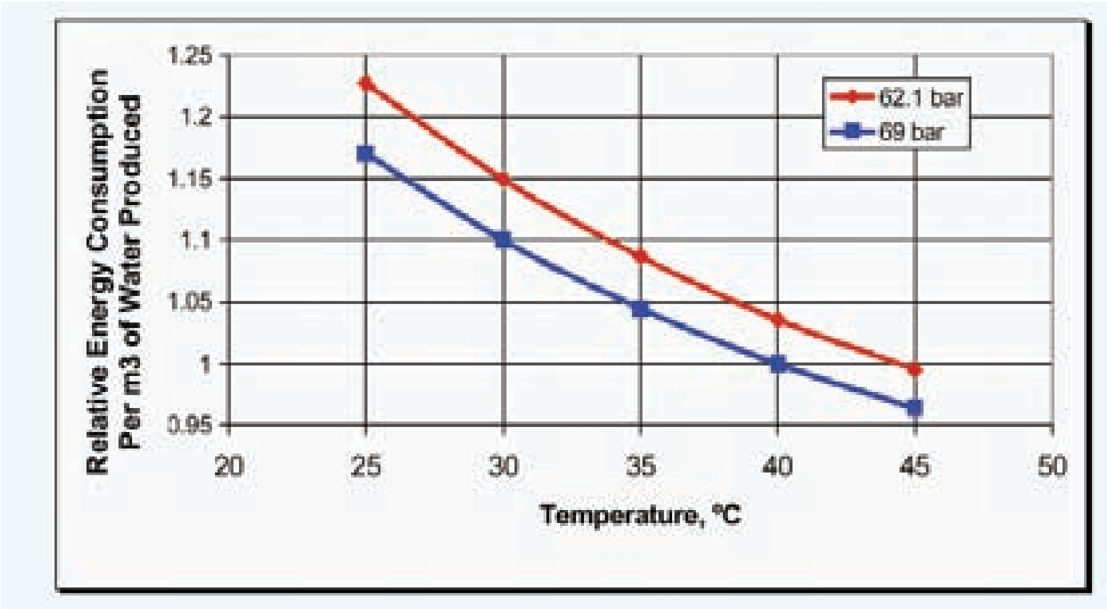


Figure 33. Specific consumption as function of feed temperature and pressure.

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 (Section 4).

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 9 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 9. DEEP-2 RESULTS, COMPARING THE WATER COSTS ($\$/m^3$) OF RO AND 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.

3.1.3. Waste heat utilisation from Indian PHWRs

3.1.3.1. The research reactor CIRUS

For conducting a practical demonstration of waste heat utilisation, BARC (India) designed a low temperature vacuum evaporator (LTE) desalination plant and coupled it to the research reactor CIRUS (Figure 34).

The product water from this plant meets the make up water requirements of the reactor.

The reactor produces 40 MW(th), using metallic fuel, heavy water moderator, demineralised water coolant and seawater as the secondary coolant.

To ensure protection against any radioactive contamination, an intermediate circuit has been incorporated between the reactor and the LTE plant.

Table 10 summarises the operating data of this plant, which could then be used for a larger sized plant utilizing waste heat.

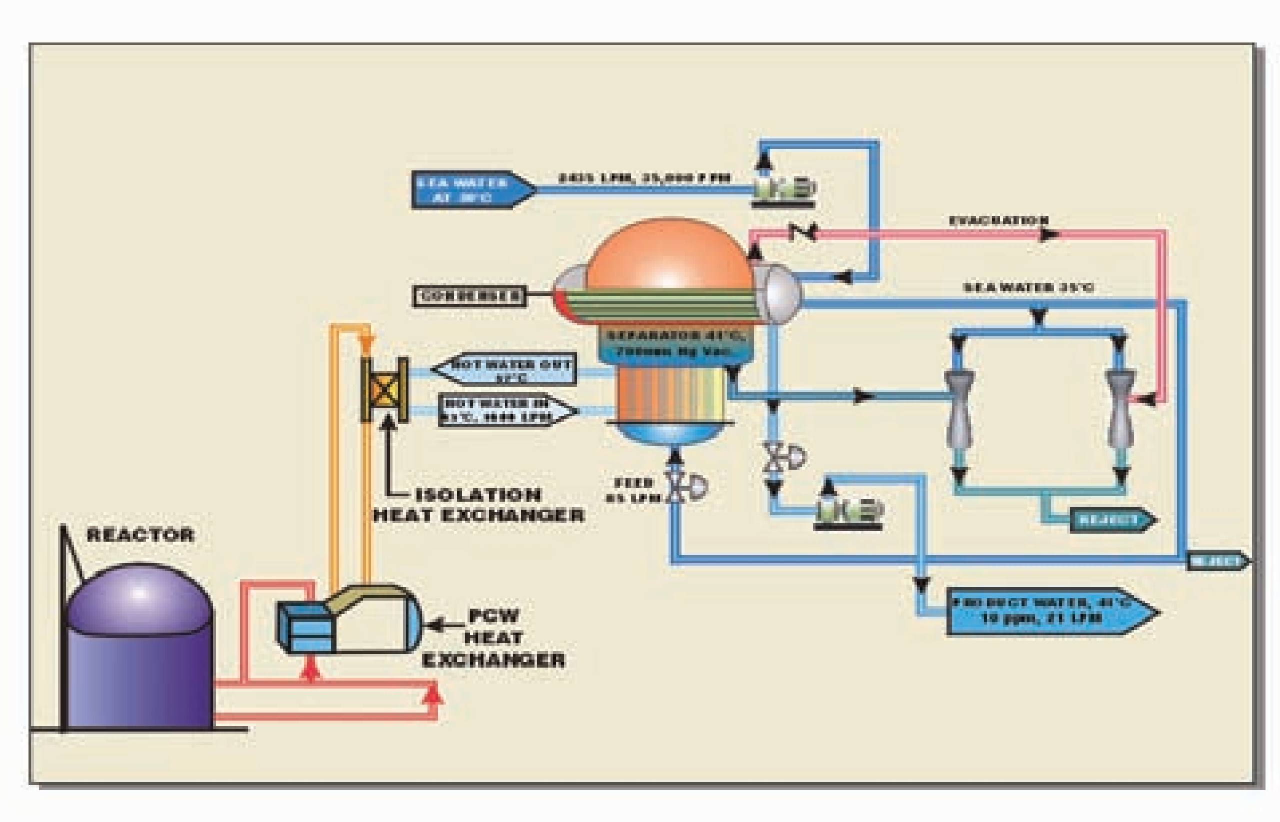


Figure 34. LTE-MED system coupled to CIRUS reactor.

TABLE 10. TYPICAL OPERATING DATA OF THE CIRUS REACTOR PROVIDING WASTE HEAT FOR DESALINATION

Parameter	Unit	Value
Hot water flow rate	l/minute	1500
Hot water inlet temperature	°C	53.6
Hot water outlet temperature	°C	47.5
Seawater flow rate	l/minute	1200
Seawater TDS	ppm	35 000
Seawater inlet temperature	°C	27.6
Seawater outlet temperature	°C	35.5
Vacuum in the evaporator	mm Hg	700
Product water flow rate	l/minute	15.5
Product water conductivity	µS/cm	7

3.1.3.2. Waste heat utilisation from the 500 MW(e) PHWR

In the 500 MW(e) Indian PHWR, the heavy-water moderator is cooled from 80 to 55°C by process water, which in turn is cooled from 55 to 35°C by seawater that enters at 32°C and comes out at 42°C. About 100 MW(th) is thus available as waste heat for seawater desalination.

The details have been worked out using 55°C process water temperature to avoid any changes in the moderator system. The coupling scheme is presented in Figure 35.

The nuclear desalination system produces about 1000 m^3/day of desalted pure water, which is about 25% more than the total makeup demineralized (DM) water requirements of the 500 MW(e) PHWR.

It is considered more economical to use this water as make up DM water because:

- Energy cost for the LT-MED plant is zero, since it only uses waste heat.
- Direct production of distilled water eliminates the need for demineralizers and regeneration chemicals.
- The raw water, otherwise used as feed for the DM plant, can be made available for other purposes e.g. drinking.

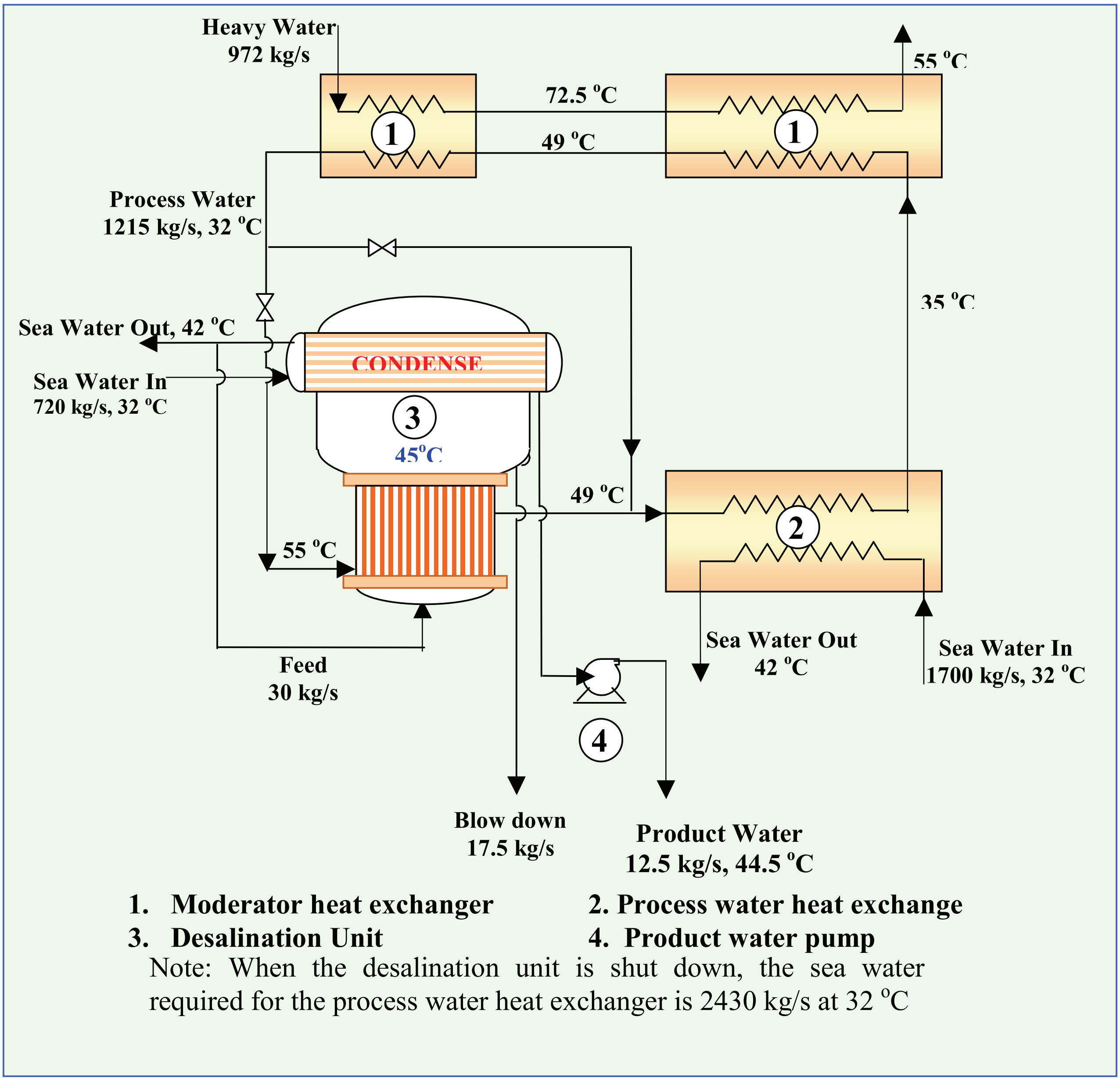


Figure 35. PHWR500 coupling scheme, utilising waste heat.

3.2. UTILISATION OF HYBRID SYSTEMS

The advantages of hybrid desalination systems will be illustrated by a specific example: that of the hybrid MSF-RO system, coupled to the MAPS PHWR at Kalpakkam (India) as shown in Figure 36.

As one of the leading and oldest desalination processes, MSF is preferred due to its operational simplicity and proven performance. MSF is advantageous for large desalting capacities and high purity water, in particular where inexpensive thermal energy is available.

However, its installed cost and specific power consumption remain relatively high. Since the energy cost is high in India, an MSF system, with large GOR leading to lower water production costs, has been chosen.

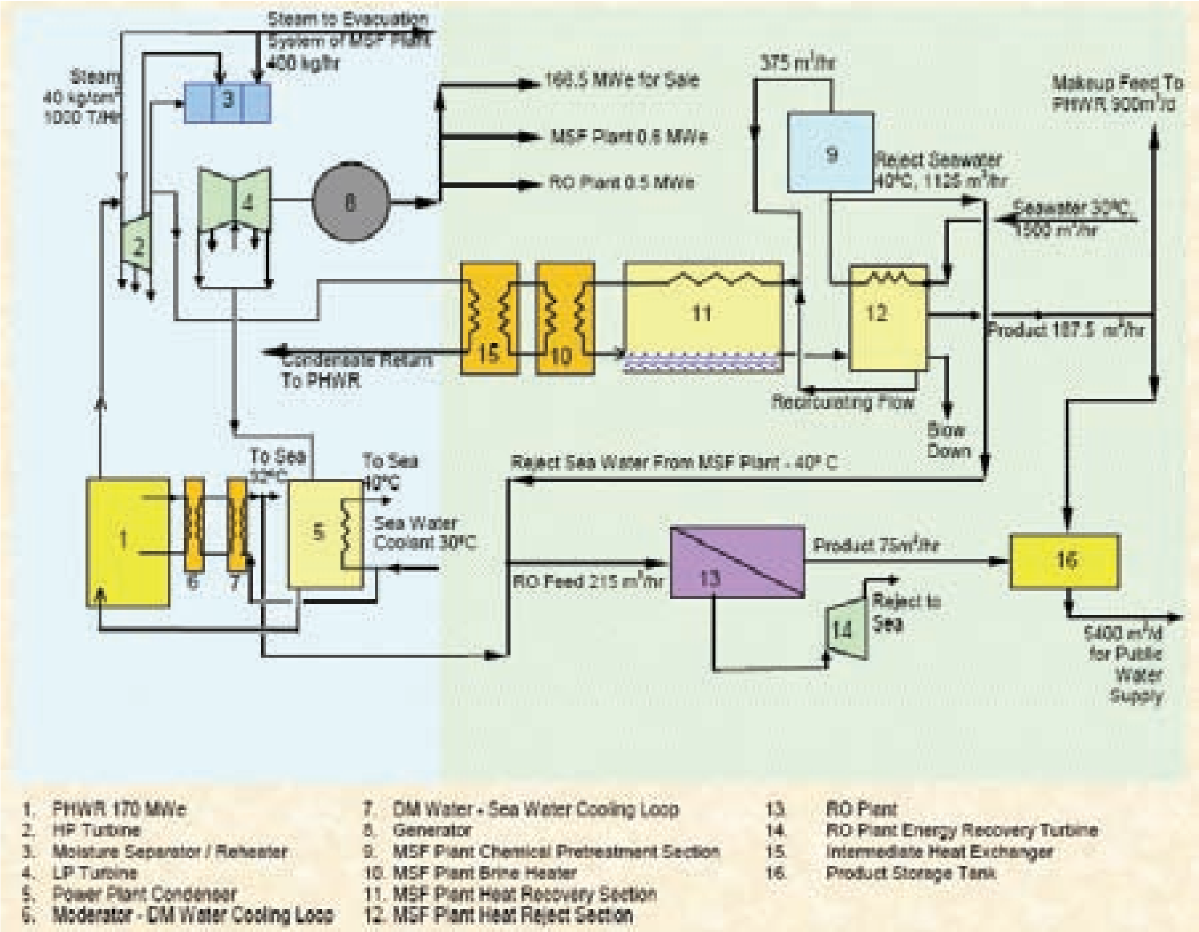


Figure 36. Hybrid MSF-RO coupling to the PHWR at Kalpakkam (India).

Seawater desalination by RO has proved to be most economical as has been shown in the case studies from IAEA member States (Section 4). Apart from its need for an elaborate pre-treatment plant, RO has many advantages:

- Enhanced flexibility due to modular structure.
- Operation at ambient temperature, reducing corrosion risks.
- Possibility of coupling with energy recovery devices, thus further reducing the costs.
- High rate of development and considerable potential for further innovations as compared to the MSF technology, which has almost reached a saturation point in development.

Because of the particular advantages of MSF and RO technologies, it is logical to consider that a hybrid MSF-RO system may lead to greater cost reductions in water costs because:

- Use of common, smaller seawater intake and outfall structures and other facilities.
- Flexible and/or improved water quality by blending distillate from the MSF plant and the permeate from the RO plant.
- Extension of the membrane life-times as a result of blending.
- Enhanced flexibility of operation to meet various power and water ratios in case of a co-generation plant. Thus for example, one can operate the MSF plant during day time, when electricity demands are higher and the RO plant during night when electricity demands are lower and its cost are reduced.
- Possibility of operation of the RO plant in the ROph mode through appropriate use of the MSF reject heat.

The water costs from the Kalpakkam hybrid system are shown in Table 11.

It can be noted that the cost of desalinated water depends on its quality. The product water quality from RO plant is about 350–500 ppm TDS and the water cost is US \$0.95/m^3. The desalinated water from MSF plant is of almost distilled quality (10 ppm TDS) and the water cost is higher (US \$ 1.18/m^3). The water from hybrid system is of 125–175 ppm quality and the water cost (US \$ 1.10/m^3) is in between RO and MSF. Hybrid system provides distilled quality water (10 ppm TDS) for the industries which require high quality, high value desalinated water for their process requirement and better quality water for drinking purpose.

TABLE 11. COSTS OF DIFFERENT QUALITY WATERS IN THE HYBRID SYSTEM

No.	**Type of desalination process**	**Product quality (ppm)**	**Water cost (US \$ /m^3)**
1	RO	350–500	0.95
2	MSF	10	1.18
3	Hybrid (MSF & RO)	125–175	1.10

Figure 37 shows the variation of water costs with the energy costs. It is observed that the water cost from the RO plant is most sensitive to changes in energy costs.

Over a range of 0.3 to 2 for the power cost multiplier, the water cost from the MSF plant is highest, whereas the water cost from the two-stage RO plant is less than the corresponding costs from MSF and hybrid systems.

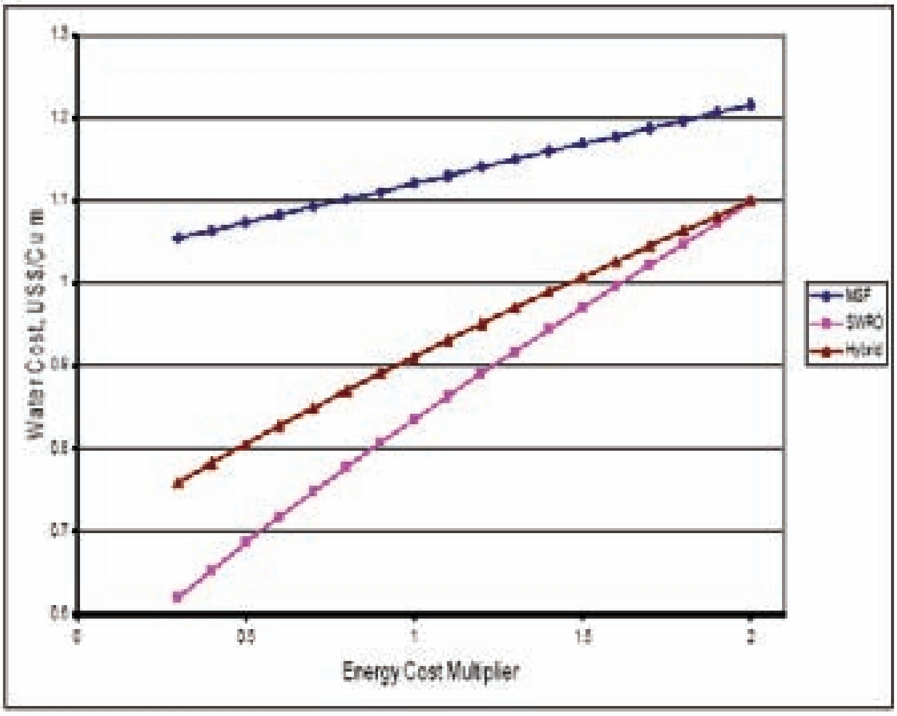


Figure 37. Variation of hybrid, RO and MSF water costs with the power cost.

3.3. EXTRACTION OF VALUABLE MATERIALS AND MINIMIZATION OF BRINE DISCHARGE

Seawater usually contains sixty elements from the Periodic Table. The brine, rejected by a desalination unit, is a concentrate of all compounds contained by seawater. However, some of the elements are very scarce on land and/or are very expensive. There is thus a strong motivation for extracting these materials.

Current practice in countries using large-scale desalination is to reject brine back to the sea. Increasing ecological objections are now being voiced since this rejection may lead to a degradation of local fauna and flora unless the concentrated brine is rejected far from the cost, which would unnecessarily increase overall costs. Extraction of materials and subsequent brine conditioning for surface storage would therefore be also another advantage for these integrated desalination plants, making them more environmentally friendly.

Yet another advantage of this extraction will be the reduction of overall costs of the cogeneration nuclear desalination systems since the benefits of a third product would be added.

The methods of material extraction are still in preliminary stages of development but significant progress has been reported [15].

3.3.1. Selection of materials

Not all the materials contained in seawater are worth extracting unless there are specific motives (e.g. extraction of uranium). As an important first step in [15] a short list of interesting materials was therefore established.

The selection criteria used for this list were:

- Economic criteria: current price, estimated evolution of the market, production cost, occurrence on land.
- Physicochemical criteria: formulation of the element in seawater, concentration, reactivity.
- Technical criteria: considered extracting methods from a complex aqueous system.

The resulting list is constituted by eight different elements (Table 12). The products would either allow large-scale production of useful materials such as fertilizers or the extraction, in lesser amounts, of some rare materials with high added values and often used in high technologies. In Table 12, annual production calculations are based on the hypothesis of a plant equipped with reverse osmosis desalination system for the la Skhira site in Tunisia, producing about 168 000 m^3 per day. The recovery ratio of this process equipment is supposed constant at 40% with an availability factor of 91%. The total seawater consumption of the plant is therefore 420 000 m^3 of seawater per day.

It should be noted that most of the elements in Table 12 (e.g. Na, K, Rb, Cs) are from the same chemical family, the alkali metals. These elements have therefore similar properties. One can thus imagine their separation from the rest of the mixture by a common extraction process. Magnesium can also be assimilated to this family because it's an alkaline-earth with approaching properties.

TABLE 12. LIST OF VALUABLE ELEMENTS, WHICH COULD BE EXTRACTED FROM THE BRINE REJECTED BY A REVERSE OSMOSIS PLANT PRODUCING 168 000 m^3/DAY

Element	Seawater content (**mg/L**)	Available quantity (**t/year**)	Major use	Selling price (**$/kg**)	Value (**M$/year**)
Na	$1.05\ 10^{4}$	$1.5\ 10^{6}$	Fertilizers	0.13	180
Mg	$1.35\ 10^{3}$	$1.9\ 10^{5}$	Alloys	2.8	525
K	$3.8\ 10^{2}$	$5.3\ 10^{4}$	Fertilizers	0.15	8
Rb	$1.2\ 10^{-1}$	17	Laser	79 700	1300
P	$7.0\ 10^{-2}$	10	Fertilizers	0.02	0.0
In	$2.0\ 10^{-2}$	3	Metallic protection	300	0.9
Cs	$5.0\ 10^{-4}$	0.07	Aeronautics	63 000	4
Ge	$7.0\ 10^{-5}$	0.01	Electronics	1700	0.02

3.3.2. Principle of operation of the final method of extraction

After several other attempts, investigating the sequence of extractions, a final global process was established allowing the separation of each element one after another and finishing with sodium chloride. The principle of extraction is shown in Figure 38(a) and (b).

In fact the global extraction protocol comprises two phases:

Phase 1:

- Preliminary evaporation to reduce work volumes
- Addition of Alum to precipitate phosphates
- Addition of HCl to lower pH up to 3
- Extraction of caesium by the calixarenes
- Extraction of indium (mixed with gallium) by a mixture of organic acids

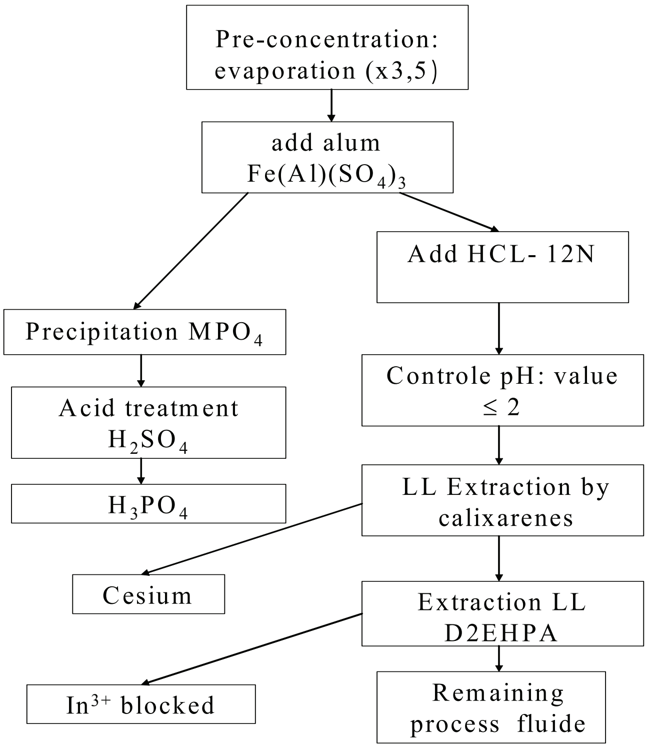


Figure 38(a). Phase 1 of the global extraction protocol.

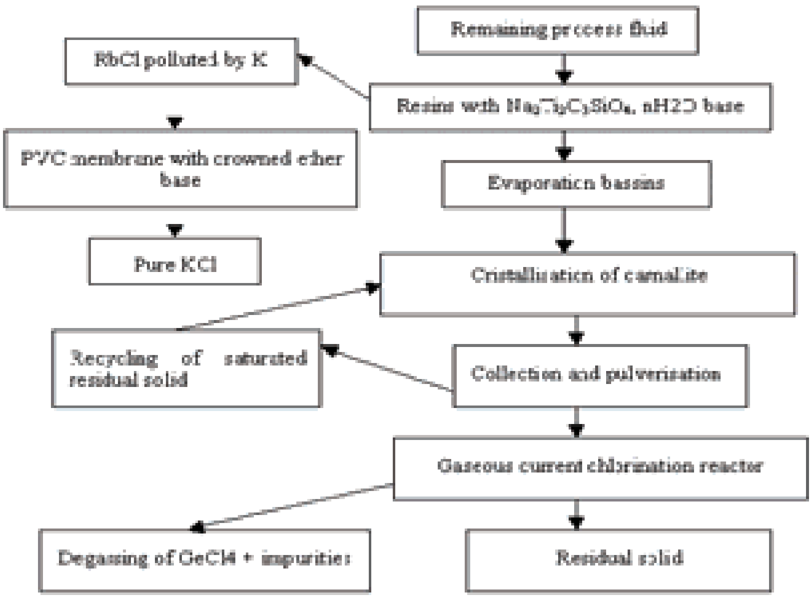


Figure 38(b). Phase 2 of the global extraction protocol.

Phase 2:

- Recovery of Rb on resins
- Complete evaporation (solar still or other)
- Recovery and pulverisation of carnallite crystals + precipitation of impurities
- Eventual Recycling of saturated liquid
- Chloration of the solid: gaseous HCl current, 1 bar, 90°C
- Degassing of $GeCl_4$

These two phases are currently being refined to reduce further the extraction costs. Some of the reactions mentioned require further R&D for the comprehension of phenomena involved. Efforts are being made to concentrate the rejected brine by a combination of RO, Once-through MSF and MED processes.

4. TECHNO-ECONOMIC FEASIBILITY STUDIES IN MEMBER STATES

4.1. BACKGROUND

A significant number of studies on the economic aspects of nuclear desalination systems have been, and still are, carried out in IAEA Member States. It was for this reason that, in its April 2000 meeting, the International Nuclear Desalination Advisory Group (INDAG) recommended that the IAEA launch a coordinated research project (CRP2), in addition to CRP1 on the optimization of the coupling of nuclear reactors and desalination systems.

The justifications for the CRP2 were, therefore, to:

- Provide a framework for various activities-in the field of nuclear desalination- currently planned or conducted in Member States.
- Transfer knowledge, expertise and guidance to and between Member States to efficiently conduct reliable site specific studies on the economics of nuclear desalination.
- Provide the basis for coherent and credible economic data for decision makers.
- Evaluate alternative methods and software for economic studies and thus, through comparison, further validate the results of IAEA software package, DEEP.

The CRP2, entitled Economic Research on, and Assessment of, Selected Nuclear Desalination Projects and Case Studies, was effectively launched by the IAEA in February 2002, with the participation of 11 Member States. The main objectives of this CRP are:

- Evaluation of economic aspects and investigations on the competitiveness of nuclear desalination options under site specific conditions.
- Identification of innovative techniques leading to further cost reductions in nuclear desalination systems (Section 3).
- Further refinement of economic assessment methods and tools.

To date, eight summary reports on various techno-economic studies have been received by the IAEA, as contributions to the CRP2 (Table 13).

4.2. MAIN RESULTS AND ANALYSIS OF THE CASE STUDIES

Table 13 clearly shows that out of the eight reported studies, six are site specific and two are generic but representing potential sites. Similarly, the studies cover a large spectrum of operating or future reactor options, ranging from three PWRs, two HWRs, two PBMRs, one dedicated, heat only reactor and one experimental reactor. These reactors have been coupled either to RO, ROph, MED, MED/VC or hybrid RO-MSF processes. These will be discussed one by one and according the desalination processes used.

4.2.1. Nuclear reactors coupled to the RO process

The studies include:

1. CAREM + RO for the Porto Deseado site in Argentina.

Three different capacities of the RO plant have been considered: 48 000 m^3/day (base case and two other cases, with 12 000 and 24 000 m^3/day for sensitivity study. Power and water cost calculations have been made using the DEEP-3 model and the method used by the local Process Engineering Group for chemical plants evaluations (the IPEE method).

TABLE 13. SUMMARY OF THE TECHNO-ECONOMIC SITE SPECIFIC STUDIES IN SOME MEMBER STATES[3]

CRP2 Participating Country (CSI name)	Organisation	Site	Reactor(s) and/or fossil energy based source	Desalination process(es)
Argentina (S. M. Gomez de Soler)	National Atomic Energy Commission	Several sites in Latin America, in particular Porto Deseado	CAREM; gas turbine, combined cycle (CC)	RO
China (S. Wu)	INET, Tsinghua University	Possibly a small or medium sized town in Shandong province	NHR-200	HT-VTE MED, LT-HTE-MED
Egypt (I. El-Desoky)	Nuclear power plants Authority	Generic feasibility study	1000 MWe PWR	RO
France (S. Nisan)	CEA, Cadarache Atomic Centre	La Skhira[4] (Tunisia)	PWR-900, AP-600, GT-MHR, PBMR; CC-600	MED, RO, ROph
India (P.K. Tewari)	Bhabha Atomic research Centre	Trombay and Kalpakkam	Cirus research reactor at Trombay, MAPS PHWR at Kalpakkam	LT-MED, hybrid MSF-RO
Republic of Korea (S.S. Kim)	Korea Atomic research institute	Generic study for a coastal town	SMART	MED
Pakistan (K. Mahmood)	Pakistan Atomic Energy Commission	Karachi	CANDU reactor at Karachi (KANUPP)	MED
Syrian Arab Republic (S. Suleiman)	Atomic Energy Commission of Syria	Al-Hamidiah	PBMR	MED, MED/VC, RO

[3] The table does not include the US study, which is discussed in detail in the forthcoming IAEA-TECDOC, Economics of Nuclear Desalination-New Developments and Sites Specific Studies.

[4] In the context of Franco-Tunisian study: the TUNDESAL project, carried out jointly with CNSTN, STEG and SONEDE of Tunisia.

In all the compared cases, the results of the two methods are almost identical. Other important parameters of the study are presented in Table 14:

TABLE 14. MAIN ASSUMPTIONS OF THE PORTO DESEADO STUDY (ARGENTINA)

Parameter	Units	RO plant	CAREM	CC
Net electrical power	MW(e)		125	125
Plant efficiency	%		29	54
Water plant nominal capacity	m^3/day			
Water plant specific base cost	\$/m^3/day			
Feed water temperature	°C	15		
Feed water salinity	ppm	34 000		
Plant life time	years	20	40	25
Construction lead time	months	18	60	36
Availability	%	90	90	95
Average management salary	\$/year	66 000		
Average labour salary	\$/year	29 700		
Fossil fuel Prices	\$/bbl			10, 15, 20, 35, 50, 60
Fossil fuel escalation rate	%/year			2
Currency reference year	2005			
Interest/discount rate	6, 8 and 10%			
Levelized energy cost (8%)	\$/kW.h		0.038	0.043 (for 20 \$/bbl)°

In these conditions, the water costs with the CAREM + RO and CC + RO plants are respectively 0.68 and 0.7 \$/m^3. Evidently, as the fossil fuel prices are greater than 20 \$/bbl, the costs with the CAREM option will be lower and lower**.**

2. A 1000 MW(e) PWR + RO for a site in Egypt

The assumptions for DEEP-3 calculations are given in Table 15:

TABLE 15: HYPOTHESES USED FOR THE EGYPTIAN CASE STUDY

Parameter	Units	RO plant	PWR1000
Net electrical power	MW(e)		951
Plant efficiency	%		31
Water plant nominal capacity	m^3/day	140 000	
Water plant specific base cost	\$/m^3/day	800	
Feed water temperature	°C	23	
Feed water salinity	ppm	38 500	
Plant life time	years	30	60
Construction lead time	months	12	60
Availability	%	90	90
Average management salary	\$/year	6000	
Average labour salary	\$/year	2400	
Currency reference year	1998		
Interest/discount rate	8 %		
Levelized energy cost	\$/kWh		0.045

Economic data for the 1000 MW(e) PWR are taken from the MIT report [17]. Using this data in DEEP leads to the power cost of 0.045 \$/kW.h at 8% discount rate. The corresponding desalination cost for a 140 000 m^3/day RO plant, coupled to the PWR, is estimated to be 0.65 \$/m^3.

3. The 900 MW(e) French PWR + RO and the 600 MW(e) Westinghouse PWR, AP-600 + RO for the Skhira site in Tunisia

Initially, the calculations were made with the DEEP-2 version in the context of the TUNDESAL project, completed under IAEA, TC program. The costs have, however, been revised using the DEEP-3 model. [11]. The new results are compared with the corresponding costs of a 600 MW(e) CC plant in Tunisian conditions (CC-600). The nominal RO plant capacity was 48 000 m^3/day. Results for a higher capacity of 150 000 m^3/day, show the same tendencies. The various hypotheses of calculation are presented in Table 16.

TABLE 16. ASSUMED CHARACTERISTICS OF THE FRENCH-TUNISIAN STUDY

Parameter	Units	RO plant	PWR-900	AP-600	CC-600
Net electrical power	MW(e)		951	610	600
Plant efficiency	%		33	33	51
Water plant nominal capacity	m^3/day	48 000			
Water plant specific base cost	\$/m^3/day	900			
Feed water temperature	°C	15			
Feed water salinity	ppm	34 000			
Plant life time	years	25	40	40	25
Construction lead time	months	16	60	48	24
Availability	%	90	90		95
Average management salary (Tunisian conditions)	\$/year	20 000			
Average labour salary (Tunisian conditions)	\$/year	7000			
Fossil fuel Prices	\$/bbl				20.62, 40, 60
Fossil fuel escalation rate	%/year				2
Currency reference year	2006				
Interest/discount rate	5, 8 and 10%				

The energy and water costs, with all these plants are compared in Table 17. The fossil fuel price for the CC-600 plant is 20.62 \$/bbl. The discount rate is 8%.

TABLE 17. COMPARATIVE COST OF NUCLEAR AND FOSSIL FUELLED RO DESALINATION SYSTEMS

	Units	Nuclear desalination systems		
		PWR-900 + RO	AP-600 + RO	CC-600 +RO
Energy cost of the power plant	\$/kWh	0.0377	0.044	0.0496
Water cost	\$/m^3	0.611	0.632	0.885

It can be observed that the desalination costs by the two nuclear options are respectively 31 and 29% lower than the corresponding cost by the CC-600 plant even in most favourable conditions (gas price of 20.62 \$/bbl or 150 \$/toe).

4. PHWR + RO for the Kalpakkam site (India)

The assumptions made for cost calculations with DEEP-3 and with BARC's own method (Figure 39), based on the separate estimation of all relevant expenditures, are presented in Table 18. The fundamental difference between the two methods is the input for plant base cost which is 1177 \$/m^3/day for DEEP-3 and 1100 m^3/day in the BARC method.

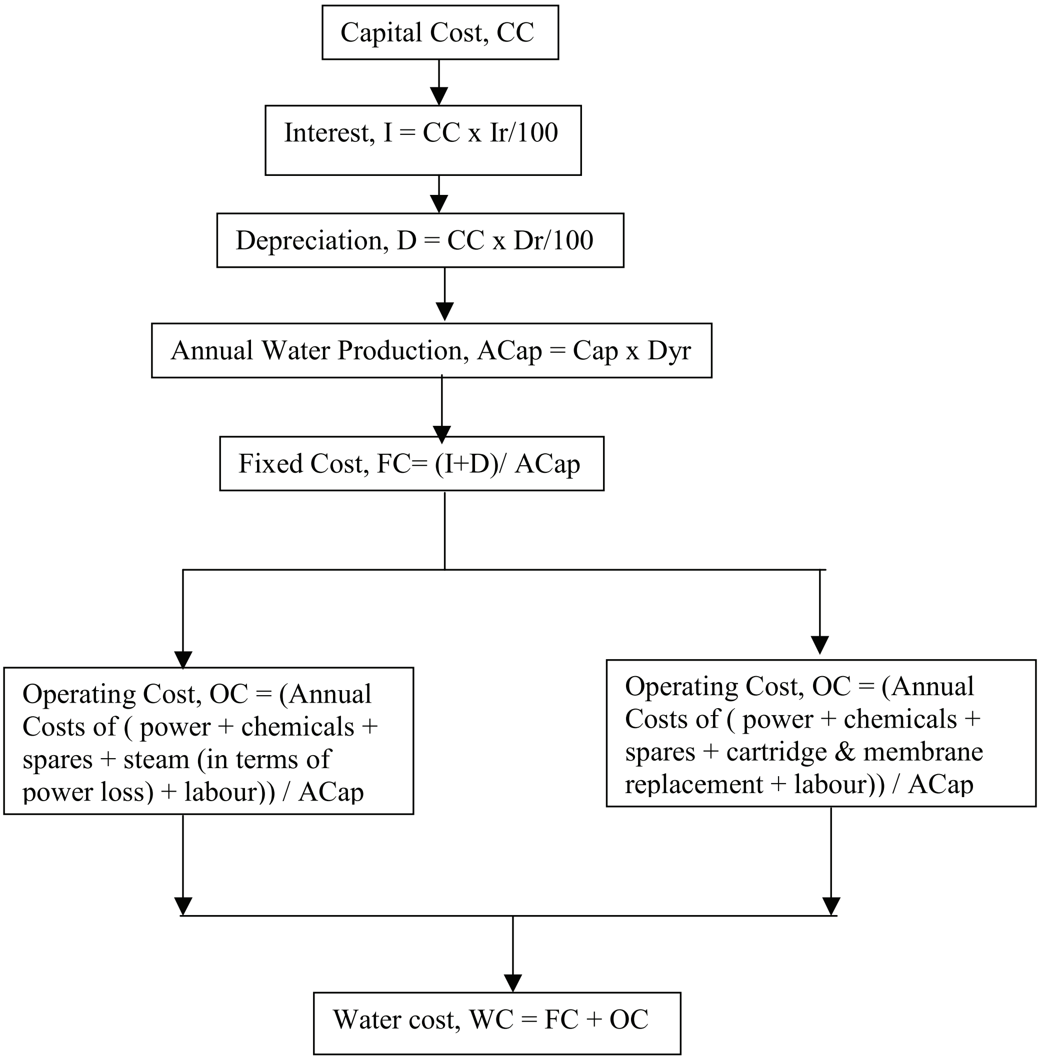


Figure 39. Logical sequence of BARC method.

Ir = Rate of interest; Dr = Rate of depreciation; Cap = Plant capacity, m^3/day; Dyr = No. of days of operation in a year

TABLE 18. HYPOTHESES FOR CALCULATION (INDIAN STUDY)

Parameter	Units	RO plant	PHWR
Net electrical power	MW(e)		170
Plant efficiency	%		32
Water plant nominal capacity	m^3/day		
Water plant specific base cost	\$/m^3/day	1177	
Feed water temperature	°C	30	
Feed water salinity	ppm	35 000	
Plant life time	years	25	40
Construction lead time	months	16	60
Availability	%	90	90
Average management salary	\$/year	9300	
Average labour salary	\$/year	2700	
Levelized power cost	\$/kWh		0.045
Currency reference year	2005		
Interest/discount rate	4, 5, 6, 7 ,8 %		

For 7% interest and discount rates, the desalination cost by DEEP-3 is 0.94 \$/m^3 as compared to 0.95 \$/m^3 obtained from the BARC method. The slight difference is due to the different base costs of the RO plant.

Detailed sensitivity studies have also been performed, which show the variation of desalination costs as functions power costs, interest rate and feed temperature.

5. PBMR + RO (Al-Hamidia site, Syrian Arab Republic)

Al-Hamidia is situated close to the Lebanese border and 19 kilometres from the town of Tartous. Its characteristics and other calculation assumptions are summarized in Table 19.

TABLE 19. INPUT DATA FOR THE SYRIAN STUDY

Parameter	Units	RO plant	PBMR
Net electrical power	MW(e)		115
Plant efficiency	%		46
Water plant nominal capacity	m^3/day	180 000	
Water plant specific base cost	\$/m^3/day	800	
Feed water temperature	°C	20	
Feed water salinity	ppm	40 000	
Plant life time	years	30	40
Construction lead time	months	16	60
Availability	%	80 to 95	95
Currency reference year	2005		
Interest/discount rate	6, 8 and 10%		
Levelized PBMR power cost (at 8% discount rate)	\$/kWh		0.018 (Escom), 0.03 (Exelon), 0.033 (MIT)
Local power cost (at 8% discount rate)	\$/kWh		0.04

In these conditions, and taking the power cost of the PBMR, as estimated by Exelon, the cost of desalination by the RO plant would be of the order of 0.6 \$/m^3 at 8% discount rate. It should be noted that this is about 13% lower than the desalination cost based on the local power cost of 0.04 \$/kW.h.

4.2.2. Nuclear reactors coupled to distillation processes, MED and MSF

With the exception of Argentina, the 7 other case studies have investigated the economics of nuclear desalination systems based on the distillation processes. Out of these 6 have retained MED or MED/VC systems. India has considered an indigenously manufactured MSF plant. Pakistan has also retained the locally constructed MED system.

In what follows, the main assumptions made for the calculations of distillation plants will only be briefly recalled for case studies not mentioned in the context of RO coupled systems, discussed above:

6. The dedicated heat only reactor, NHR-200 + MED (China)

The study is undertaken for some islands and medium sized coastal towns in China. Two types of MED processes have been investigated for comparative analysis: the low temperature, horizontal tube evaporator (LT-HTE-MED) and the high temperature, vertical tube evaporator (HT-VTE-MED).

The design parameters and other calculation hypotheses are presented in Table 20.

The reactor provides saturated steam to the steam generator at about 125°C. This steam is directly injected into the first effect of the HT-VTE-MED system.

The motive steam in the mixing chamber of the ejector is also mixed from a fraction of the steam derived from the intermediate stages of the LT-HTE-MED process and blended with part of the motive steam of the ejector. The mixed steam at a temperature of 73°C is then injected into the first effect of the LT-HTE-MED system.

For these reasons, the GOR of the LT-HTE-MED is relatively lower (15) as compared to that (21.5) for the HT-VTE-MED.

TABLE 20. MAIN ASSUMPTIONS OF THE CHINESE STUDY WITH NHR-200

Parameter	Units	LT-THE-MED	HT-VTE-MED	NNHR-200
Net thermal power	MW(th)			200
Water plant nominal capacity	m^3/day	120 000	170 000	
Water plant specific base cost	\$/m^3/day	787.5	746	
Feed water temperature	°C	20	20	
Feed water salinity	ppm	31 500	31 500	
Plant life time	years	30	30	40
Construction lead time	months	24	24	40
Availability	%	80 to 95	95	93
Average management salary	$/year	10 000		
Average labour salary	$/year	3000		
Levelized energy cost	$/ton of steam			5.44
Currency reference year	2004			
Interest/discount rate	5.85%			

With the above assumptions, the desalted water costs from the two plants, coupled to the NHR-200, are respectively 0.76 \$/m^3 (LT-MED) and 0.72 \$/m^3 (HT-MED).

7. The PWR-1000 + MED system (Egypt)

The principal hypotheses of calculation for these two systems are analogous to those presented in Table 15 above.

Desalination cost at 8% discount rate is 0.89 $\$/m^3$. It is thus about 37% higher than the corresponding cost with the PWR-1000 + RO plant.

8. The 900 MW(e) French PWR + MED and the 600 MW(e) Westinghouse PWR, AP-600 + MED and the CC-600 + MED systems for the Skhira site in Tunisia

The main assumptions for these cases are similar to the ones presented in Table 16.

Desalination costs for these systems, at 8% discount rate, are respectively 0.888 (PWR-900 + MED), 0.951 (AP-600 + MED) and 0.945 $\$/m^3$ (CC-600 + MED; gas price 20.62 $/bbl).

Interestingly enough one observes that the desalination cost by the CC-600 + MED system is about 6.5% higher than the PWR + MED system but about 0.6% lower than the AP-600 system. However, as gas price increases, all nuclear options lead to lower desalination costs. Thus, for example, at a gas price of 60 $/bbl, the desalination cost with the PWR-900 + MED system is 46% lower than that by the CC-600 + MED system. The desalination costs of the AP-600 + MED system then is 42% lower.

9. The GT-MHR + MED and the PBMR + MED systems, utilising waste heat, for the La Skhira site (French-Tunisian study)

As shown in Section 3.1.1, the desalination costs, at 8% discount rate, for these two systems, providing virtually free heat, are respectively 0.627 (GT-MHR + MED) and 0.924 $\$/m^3$ (PBMR + MED). Compared to the CC-600 + MED system, for a fossil fuel price of 20.62 $/bbl, these costs are respectively 62 and 44% lower in Tunisian conditions.

10. The PHWR + MSF for the Kalpakkam site (Indian study)

With most of the basic assumptions as presented in Table 20, the PHWR + MSF system, producing 15 000 m^3/day, and a base cost of 994.3 $\$/m^3$/day, was evaluated separately.

Desalination cost with this system, as calculated by DEEP-3 is then 1.2 $\$/m^3$ for discount rate of 7%.

11. SMART + MED system for a coastal site (Republic of Korea)

The main hypotheses of the study are presented in Table 21.

TABLE 21. INPUT DATA AND HYPOTHESES OF THE KOREAN STUDY (2005 US$)

Parameter	Units	MED plant	SMART
Net electrical power	MW(e)		100
Plant efficiency	%		30.3
Water plant nominal capacity	m^3/day	40 000	
Water plant specific base cost	$\$/m^3$/day	900	
Feed water temperature	°C	21	
Feed water salinity	ppm	38 500	
Plant life time	years	30	40
Construction lead time	months	12	36
Availability	%	85- 95	95
Average management salary	$/year	66 000	
Average labour salary	$/year	29 700	
Interest/discount rate	5, 7, 8, 10%		
Levelized power cost (8% discount rate)	$/kWh	0.033(90% availability)	

In these conditions, at 8% discount rate, the desalination cost of the system is 0.68 $\$/m^3$.

12. The PHWR (CANDU) + MED system at Karachi (Pakistan)

Pakistan is in the process of coupling its 137 MW(e) CANDU reactor with a locally manufactured MED plant.

First cost estimates have been made with DEEP3, using the following input data and hypotheses (Table 22, with base values). Comparison has been made with an oil-fired boiler

TABLE 22. INPUT DATA AND CALCULATION HYPOTHESES OF THE CASE-STUDY FROM PAKISTAN

Parameter	Units	MED plant	CANDU	Oil-fired plant
Net electrical power	MW(e)		137	137
Plant efficiency	%		31.3	DEEP default value
Water plant nominal capacity	m^3/day	10 000		
Water plant specific base cost	$/$m^3$/day	1800		
Feed water temperature	°C	27		
Feed water salinity	ppm	42 000		
Plant life time	years	30	Remaining 10 years*	Remaining 10 years
Construction lead time	months	12	N/A	N/A
Availability	%	97	77	77
Average management salary	$/year	24 000		
Average labour salary	$/year	11 000		
Fossil fuel Prices	$/bbl			65
Fossil fuel escalation rate	%/year			2
Currency reference year	2005			
Interest/discount rate	8%			
Levelized energy cost (8%)	$/kW.h		0.017*	0.116 (for 65 $/bbl)°

** Plant already exists*

Detailed sensitivity studies have been carried out with the variation of most parameters given above.

It has been shown that at 65 $/bbl fossil fuel price, the desalination cost by the nuclear option is 0.99 $/$m^3$ as compared to 1.79 $/$m^3$ by the oil-fired boiler.

13. PBMR + MED, PBMR + MED/VC systems for Al-Hamidia site (Syria)

Thermodynamic characteristics of the MED and MED/VC plants, each producing 60 000 m^3/day, were obtained with the help of a locally developed software. The data was then used to make the desalination cost evaluations for the two plants. These costs are compared in Figure 40 for 8 % discount rate and for three power costs estimations of the PBMR and for a local electrical power cost.

Figure 40 shows that the lowest desalination costs are obtained from the MED/VC system. Thus at the base power cost of 0.033 $/kWh (MIT estimation) and 8% discount rate, the water cost from the PBMR + MED/VC system is 0.5 $/$m^3$ as compared to 0.6 $/$m^3$ for the RO system and 0.7 $/$m^3$ for the MED system.

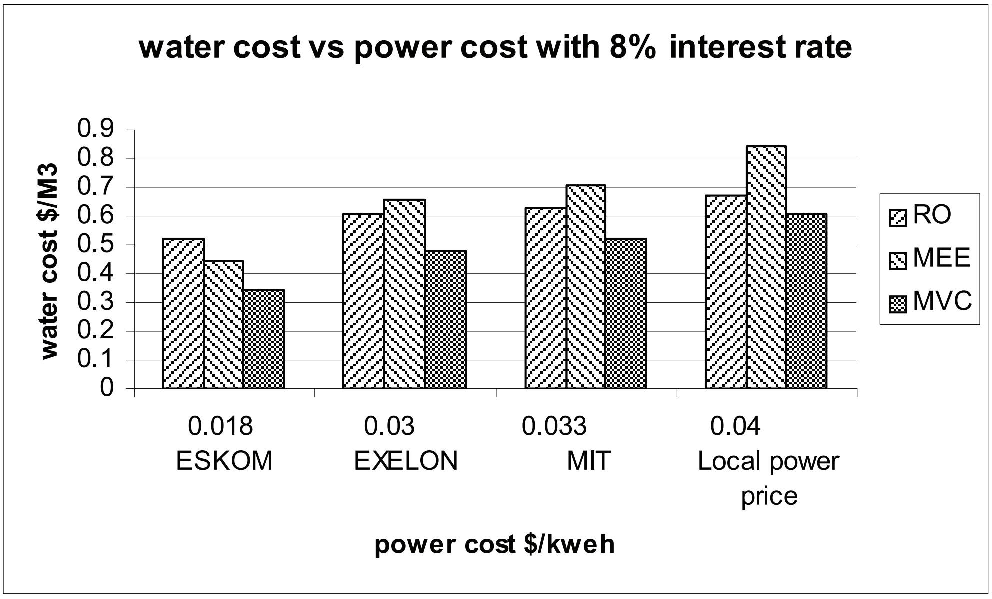


Figure 40. Water cost estimations from the Syrian study.

4.3. SUMMARY OF MEMBER STATES' SITE-SPECIFIC CASE STUDIES

The water production costs from a given nuclear (or fossil fuelled) desalination system are a complex function of several parameters, notably the power cost, the discount and interest rate, the water plant production capacity, the combined power and water plant availability and the water plant specific base cost.

As all these parameters have been specific to each study, it is difficult to arrive at general conclusions regarding a given power plant and desalination technology.

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 + RO, 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 in the case of 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. The cost will be further reduced when 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 0.88 $/m^3.

Furthermore, sensitivity calculations performed in the context of above studies can also lead to certain conclusions.

Thus for example, for an MED plant coupled to a PHWR (Pakistan study), a ± 30% variation in discount rate leads to a variation of about 16% in the water cost.

However, a 30% variation in total plant production capacity leads to a reduction of only 0.3% in water cost.

By increasing the total water plant availability by 30%, the water cost reduces to 18%. Water cost increases by the same amount when water plant base cost is increased by 30%.

Further harmonisation in the case studies was made possible by the availability of DEEP-3 files from three studies (Argentina, Egypt and France). To get a general idea of water costs in these three countries, calculations were made with the following main assumptions:

- Currency reference year = 2006
- Initial year of operation = 2020
- Interest rate= discount rate = 8%
- Power plant life time = 40 years
- Feed water salinity = 38 500 ppm
- Feed temperature = 21°C
- Water plant life time = 25 years
- Water plant construction lead time = 16 months
- Water plant nominal capacity = 48 000 m^3/day
- Optional unit size = 12 000 m^3/day
- Base unit cost = 900 \$/m^3

TABLE 23. HOMOGENISED DEEP-3 CALCULATIONS

	Water cost in \$/m^3	
	PWR + RO	PWR + MED
Argentina	0.738	
Egypt	0.727	0.886
France	0.611	0.887

The results, summarized in Table 23, show that:

- PWR + RO costs vary from 0.611 to 0.738 \$/m^3, depending upon the power costs of the PWR.
- At least in two cases, the PWR + MED costs are nearly the same, about 0.88 \$/m^3.
- Under these conditions, desalted water cost from RO is from 16 to 31% lower than from the MED plant.

5. DEPLOYMENT OF NUCLEAR ENERGY, FINANCING AND SOCIO-ENVIRONMENTAL ASPECTS

5.1. THE DEPLOYMENT OF NUCLEAR ENERGY IN DEVELOPING COUNTRIES

In addition to high capital requirements, and the requirement that importing countries adhere to the rigorous application of the non-proliferation regime, the main policy issues in deploying nuclear reactors or nuclear desalination systems are the following:

- Engagement and planning

For a large number of DCs, nuclear energy remains, and will continue to do so for some time, a new and advanced technology. As such, its introduction would impose severe constraints on the local technical and industrial infrastructures.

Since a nuclear program necessitates high investment in capital, resources and manpower, it is essential that a concerned DC give a strong commitment to the pursuit of continued and intense efforts as regards the deployment of the nuclear program. The government should prepare long-term plans for nuclear energy and water development, as well as the associated financial and economic plans. An isolated nuclear reactor, without complete integration in the local energy policy can rapidly become an extremely dangerous and costly adventure.

- Safety considerations

In many countries with a new nuclear power program, the safety and regulatory aspects concerning the protection of the public and the environment are not fully understood by the government, designated operator and the industry.

For most governmental leaders, the only difference between the conventional fossil fuelled plant and the nuclear plant is the replacement of conventional heat source by a nuclear heat source. Tasks, such as the procedures for authorisation and inspection of a nuclear installation are thus delegated to "regional inspectors" of conventional power plants whereas the safety reports and procedures are only read and approved by some university professors.

This lack of understanding often leads to inadequate budget allocations to create a really independent safety authority with the consequent problems of incomplete procedures, absence of reference and control documents, absence on any quality assurance, defective components and industrial processes etc.

- Local grid characteristics

The safe and economic operation of a nuclear reactor requires an off site source of electrical energy with a sufficient capacity for the start-up and shutdown of the reactor. Similarly, the local grid must have stable characteristics and large enough capacity for distribution of the load.

In a number of DCs, the capacity of the grid always lags behind the demand. There are important load-fluctuations because of the absence or insufficiency of control equipment and protective systems.

Before considering the deployment of any nuclear plant, the DC and the exporting country/organisation must have satisfactory answers to the following:

- What is the optimum size of the nuclear plant, compatible with the load of the system? (Generally, the reactor power should be about 10% of the total grid capacity).
- What are the required mitigation measures concerning the mutual interaction between the nuclear reactor and the dynamics of the electrical grid?
- Regulation of nuclear activities.
- Qualified manpower.

The availability of qualified manpower in developing countries is a fundamental necessity for the safe operation and maintenance of the nuclear installation. Since no compromise in this respect is even thinkable, it is of primordial importance that the personnel acquire required competence through study and training.

These studies and training are habitually undertaken in the exporting country. This requires time and it is costly. However, it is absolutely necessary that the training be not confined to the creation of only scientists but extended to the levels of engineers, technicians and even industrial draughtsmen/women.

- Investment requirements

Indeed, the major issue of financing nuclear plants is the raising of large capital funds under the optimal combination of the following conditions: low interest rate, long durations for debt repayments and maximum utilisation of the local currency. Nuclear plants have high initial investment costs but low fuel costs although the initial investment can be reduced to a certain extent by the choice of so called small and medium sized reactor systems, (SMRs).

Seawater desalination plants and their accompanying facilities such as water storage, transport and distribution systems are also capital-intensive installations. It is estimated that, for medium sized reactor of 600 MW(e), combined with a desalination system to produce 50 000 m^3/day of potable water, the initial investment can reach the order of US $1300 million.

However, the desalination component would be of the order of US $50 million, i.e. less than 4% of the total plant cost.

The main problem in financing integrated nuclear desalination system is thus essentially the financing of the associated nuclear reactor.

- Electricity and water prices

National policies should be established so as to protect the owner from the effects of fluctuations in local and international currencies. If a plant is constructed on the basis of foreign financing arrangements, as is most likely in developing countries, electricity and water pricing should be adjusted to compensate for the fluctuations in currencies used for financing the project. This will minimize the effects of fluctuations in the market prices.

- Basic financing and contracting approaches

The magnitude of the investment and the constraints to financing underscore the need to explore financing for a nuclear desalination project from all possible sources, both local and foreign. Examples of international financing sources include:

- Public sector export credits.
- Supplier's credits and financing arrangements through commercial banks, guaranteed by export credit guarantee agencies and by multilateral development and financing institutions.
- Bilateral financing sources.
- Private international markets for commercial loans and international bonds.

The financing of local costs is one of the most difficult problems for power projects in many countries. Domestic funds should be used to finance, as much as possible, the total project costs but in any event the local portion of these costs. Difficulties in financing local costs arise from shortages of utility and government funds and constraints in local capital markets, especially in developing countries. A well functioning domestic capital market is particularly important for organizing local financing.

5.2 FINANCING OF NUCLEAR DESALINATION PROJECTS

The deployment of nuclear energy in most emerging and developing countries (DCs) continues to be rather stagnant (except in China and India) for numerous and very complex reasons. Among these the most important one is the considerable difficulties that such countries encounter in finding adequate financing of the nuclear projects. Two main factors appear to be the root cause of this problem:

- The relatively high investment cost of nuclear reactors and the associated uncertainties and risks [17].
- Relatively longer constructions lead times, which have varied in the past from 6 to 14 years in some countries. A construction lead-time of about 6 years is considered normal for a first of a kind reactor. Delays beyond this period are in particular related to the additional investment that a given country has to make: construction of roads and adequate transport, development of large enough ports to receive heavy material, development of infrastructures, preparation of the site including facilities for the personnel etc. For a construction period of 8 years and 7% discount rate these additional investments may represent from 30 to 40% of the total investment cost.

5.2.1. Financing arrangements

A nuclear desalination project is only viable if financing is assured. This might constitute a major constraint to countries poor in capital and financial resources or where many different investment requirements compete for the available resources. Because of the relatively large investment requirements of a nuclear desalination plant, its financing should be viewed within the framework of the country's overall electricity and water supply and even within the country's overall economy if it represents a sizeable addition.

If the buyer has difficulty in obtaining suitable financing on his own, he may request financed offers in the bid specifications. The reactor, power plant or desalination plant vendors might offer some partial financing to directly finance their supplies. The vendors might have access to their national export financing institutes, whose objective is to facilitate exports, and consequently may offer preferential terms. There is a common interest between the vendor and his national financing institute to promote the sale.

The financing arrangements have to be negotiated directly between the buyer and the financing institute. The vendor will usually provide assistance. This could be of fundamental importance for obtaining loans on the best possible terms. Financial institutes are usually reluctant to commit themselves before a supply contract is finalized between the buyer and the vendor. However, if the acceptability of the bids is subject to being accompanied by a financing offer, the financial institute(s) might issue conditional letter(s) of intent.

5.2.2. Public private partnerships

One option for the efficient implementation of a nuclear desalination project is to involve the private sector, either through inducting stand-alone projects, financed, constructed and operated by a private sector partner, or through some wider partnership with the private sector.

Tight budgets, lower aid availability, and other investment priorities mean that water projects must compete for scarce government financial resources. Therefore, private sector investment can provide a much-needed source of funding for the water sector. In addition, private sector-government partnerships can provide other benefits such as advanced technology, improved operational performance, and more efficient commercial operations.

There are various approaches to promote private sector participation in the water sector. These include service contracts, management contracts, operations and management services, leases, system-wide concessions, asset divestitures and Build-Own-Operate/Transfer (BOOT) structures for new infrastructure. In selecting the most appropriate approach, governments must assess their specific infrastructure and operations requirements, as well as an overall strategy for partnering with the private sector.

Thus, the private sector is widely participating in desalination projects but not yet in nuclear power projects, because of their specific aspects needing the direct control and monitoring from governments. Suitable public private partnerships need then to be established for nuclear desalination projects, which allocate responsibilities between public and private sector, taking into account the specific characteristics of nuclear field.

5.2.3. Financing options

The financing of nuclear power projects in developing countries involves complex issues that need to be fully understood and dealt with by all the parties involved. Consideration should be given to the principal characteristics specific to NPPs, as well as to the overall complexities of such projects and how these complexities affect their financing. It is essential that every effort be made by all parties involved in the development of a NPP to reduce the uncertainties linked to such large investments and long project times, in order to improve the overall climate for the financing of these projects in developing countries.

The special circumstances for financing nuclear power projects in developing countries are: long construction times, large capital requirements on terms, which are extraordinary with other projects, and the likelihood of cost overruns. In addition to these considerations, public acceptance of nuclear power has also become an important concern; particularly because of safety, waste disposal and non-proliferation issues.

Conventional options for financing power generation projects in developing countries have included financing through a utility's own resources, national budgets, local commercial banks and foreign multilateral and bilateral sources, usually to cover foreign exchange costs. Most developing countries often lack foreign exchange and the ability to mobilize resources in their domestic capital markets. Industrialized countries able and willing to export components and services for power generation systems have made a number of arrangements to assist developing countries in financing their projects.

To supplement national financing schemes, multilateral financing institutions were created after World War II to assist developing countries in mobilizing financial resources for economic development. The World Bank Group is one such institution. The efforts of the World Bank have been supported by the establishment of regional development banks in Africa, Asia, Europe and Latin America, and of the European Bank for Reconstitution and Development. While multilateral sources have made a major contribution to financing development, they have not yet participated in the funding of nuclear power projects.

It is to be recalled here that current World Bank policy is not to finance any nuclear projects. There is thus need to prepare a clear and concise argumentation for such projects giving concrete proofs that the choice of the nuclear option is indeed a valid one and that all the associated risks and problems, as discussed above, are fully dealt with.

Successful financing arrangements depend on the thorough use of a full range of expertise and on learning from experience. If the national budget or a sponsor's equity and cash flow can accommodate the implementation of a project, there will be no problem in financing the project. If a country launching a nuclear power project, or expanding it, is creditworthy, it can be helped through granting of export credits and can procure funds by international borrowing. If the capital market is relatively developed in the host country, local financing may be easier. The reality, however, has proved to be different.

In general, as long as the debt servicing by a given developing country is a cause of concern, lenders, exporters and the governments of developed countries will remain hesitant to finance nuclear power projects, owing to their high degree of uncertainty with respect to costs and schedules. In view of the need for more foreign exchange in most developing countries and the difficult situation in the international financing environment for lending to a developing country for a nuclear power project, additional approaches and complementary mechanisms must be explored. Developing countries are turning increasingly to more innovative financing options. These include non-recourse, or limited recourse, financing techniques for mobilizing additional external financial resources.

5.2.4. The financing mechanisms

The main financing schemes for large projects are:

- Project financing;
- Leasing,
- Build-Operate-Transfer (BOT).

Among these schemes, the first two approaches were proposed for TUNDESAL project. They are based on the same principle: instead of financing the local utility (STEG), the project sponsor will create an independent structure called TUNDESAL company, which is responsible of project's financing, construction, operation and maintenance. This principle is called "project finance". The difference between the two schemes is the nature and the share of each financing source in the global investment needs.

The second approach although being based on the "project financing" principle, integrates the leasing approach: instead of buying all the project facilities, a part of them will be procured on a leasing basis.

Detailed calculations have led to the results summarized in Table 29.

TABLE 29. SURPLUS GENERATED FOR THE PROJECT'S SPONSORS

Year	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
Surplus 1	105	107	109	112	114	117	119	122	124	149	188	190	193	200	202
Surplus 2	137	140	142	145	148	151	153	156	158	177	199	202	205	211	141

The surplus 1 corresponds to the surplus generated through the first financing mechanism;

The surplus 2 corresponds to the surplus generated through the second financing mechanism.

We note that till the year 10, the second scheme (with leasing) seems to be more advantageous because the revenues generated are higher than those of the first mechanism (without leasing). After the year 10, where a great part of the debt (90%) is reimbursed, the first scheme will be more interesting.

At the end of the year 15, the facilities leased in the scheme 2 will be bought by the TUNDESAL company, which explains a lower surplus. From the year 16, the both schemes will generate the same surplus, since the loans will be fully repaid and the annual charges due to the leasing will disappear. The operating incomes will then be allocated in the form of dividends to the shareholders and profits for the sponsors.

So far, no BOT approach has been used for nuclear projects.

5.3 SOCIO-ECONOMIC AND ENVIRONMENTAL BENEFITS OF NUCLEAR POWER

The socio-environmental aspects of nuclear desalination need greater attention for its large-scale adoption. Setting up of desalination plants at nuclear reactor sites, for providing the much needed freshwater to public, will no doubt add to the social acceptance of nuclear energy.

The foremost challenge facing nuclear desalination is that those countries suffering from scarcity of water are, generally speaking, not the holders of nuclear technology and of the infrastructure for product water distribution. The utilisation of nuclear energy in those countries will require infrastructure building and other institutional arrangements for financing, liability, safeguards, security. It will also require preparation for the fuel cycle including upstream and downstream. The concept of multi-national fuel cycle centres, as is proposed by IAEA, could be used to assure a supply of nuclear material to legitimate would-be users under control of sensitive parts of the nuclear fuel cycle.

The design of nuclear desalination plants normally concerns with various safety related aspects. The possibility of radioactive contamination of product water, however, is a very important issue to be considered for the nuclear desalination plants. The dissemination of data from the existing co-generation facilities in many countries would go a long way to alleviate this concern and improve the public perception for the nuclear desalination plants. Sharing of relevant information in this area from Member States involved in nuclear desalination and co-generation facilities will be very useful.

Studies are reported on the significant reduction in water costs if the carbon tax were included in future when nuclear energy is also considered under clean development mechanism (CDM). The environmental impact assessment of nuclear powered desalination systems as reported in recent literature; also indicate their advantages over fossil fuel based energy sources. These would result in enhanced acceptance of the nuclear desalination plants.

REFERENCES

[1] A. MACOUN, Alleviating Water Shortages – Lessons from the Middle East, The International Desalination and Water Reuse Quarterly, Vol. 10/2 (2000).

[2] INTERNATIONAL ATOMIC ENERGY AGENCY, Use of Nuclear Reactors for Seawater Desalination, IAEA-TECDOC-574, IAEA, Vienna (1990).

[3] INTERNATIONAL ATOMIC ENERGY AGENCY, Optimization of the Coupling of Nuclear Reactors and Desalination Systems, IAEA-TECDOC-1444, IAEA, Vienna (2005).

[4] M.D. CARELLI, et al., "IRIS reactor design overview and status update", Proc., ICAP'05 Conference, Seoul, Republic of Korea (2005).

[5] M. LECOMTE, J.-C. GAUTHIER, Ph. BILLOT, The FRAMATOME-ANP near term concept and its longer term development perspective, 13th ICONE Conference, Beijing, China (2005).

[6] S. NISAN, G. CARUSO, J.-R. HUMPHRIES, G. MINI, A. NAVIGILIO, B. BIELAK, O. ASUAR ALONSO, N. MARTINS, L. VOLPI, Seawater desalination with nuclear and other energy sources; Nuclear Engineering & Design, 221**,** 251–275 (2003).

[7] S. NISAN, S. DARDOUR, Y. DUMONT, N. REGUIGUI, Inter-regional collaborative nuclear desalination studies by France and Tunisia, Int. J. Nuclear desalination, Vol. 1,No. 3, 308–324 (2004).

[8] T.M. PANKRATZ, Advances in desalination technologies, Nuclear desalination: Challenges and options; International Conference Marrakech, Morocco (2001).

[9] INTERNATIONAL ATOMIC ENERGY AGENCY, Desalination Economic Evaluation Program (DEEP 3.0) User's Manual, Computer Manual Series No. 19, IAEA, Vienna (2006).

[10] M. METHNANI, Recent model developments for the Desalination Economic Evaluation Program DEEP, International Desalination Association Congress, Singapore (2005).

[11] S. NISAN, B. COMMERCON, S. DARDOUR, A new method for the treatment of a reverse osmosis process with preheating of the feed water, Desalination, 182, 485–49 (2005).

[12] S. DARDOUR, S. NISAN, F. CHARBIT, Utilisation of waste heat from GT-MHR and PBMR type of reactors for nuclear desalination, EUROMED 2006 Conference, Montpellier, France (2006).

[13] GT-MHR CONSORTIUM, International GT-MHR Project Design Review, St Germain-en-Laye, France (1999).

[14] J.R. HUMPHRIES, K. DAVIES, J. ACKERT, An advanced reverse osmosis technology for applications in nuclear installations, ICAPP Meeting, Hollywood, Florida, USA (2002).

[15] J. Le DIRACH, S. NISAN, C. POLETIKO, Extraction of strategic materials from the concentrated brine rejected by integrated nuclear desalination systems, Desalination, 182, (2005) 451–462.

[16] MASSACHUSETTS INSTITUTE OF TECHNOLOGY, MIT Report, The future of nuclear energy (2003).

[17] N. BOUZGIEMDA, S. NISAN, M. ALBOUY, Financing of nuclear desalination projects in developing countries, EUROMED 2006 Conference, Montpellier, France (2006).

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