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**APPLICATION OF INNOVATIVE NUCLEAR REACTOR
CONCEPTS FOR SEEWATER DESALINATION IN SOUTHERN
EUROPE (EURODESAL)**

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CONTENTS

Executive Summary	4
A. Introduction	4
B. Technical approach	4
C Results obtained	5
D Conclusions	6
Detailed Report.....	8
1. Motivation and Background	9
1.1. Major Objectives	9
2. Technical Approach	10
3. Nuclear reactors and desalination processes	11
3.1. Nuclear reactor systems	11
3.1.1 The French PWR-900.....	11
3.1.2. The AP-600	11
3.1.3. The GT-MHR	12
3.2. Desalination processes.....	13
3.2.1. Multiple effect distillation (MED)	14
3.2.2. Reverse Osmosis (RO)	15
3.2.3. Energy consumption in MED and RO.....	15
4. Nuclear reactor and desalination system coupling and optimisation	16
4.1. Thermal (MED) couplings to PWRs	16
4.1.1. The conventional coupling scheme	16
4.1.2. Research for a MED coupling scheme, utilising waste heat.....	17
4.1.3. MED flash-tank couplings to GT-MHR	19
4.1.4 Other coupling schemes for the GT-MHR	21
4.2. RO Coupling, utilising waste heat (ROph)	22
4.2.1. Preheating of feed-water	22
4.2.2. Ultra-filtration	23
4.2.4. Energy recovery	23
4.2.5. Site specific optimisation	23
4.2.6. Management and control system	24
4.2.7. Experimental verification	24
5. Preliminary safety verification of the coupled systems	25
5.1. Safety barriers.....	25
5.2. Transients and accidents induced by couplings	26
5.2.1. MED coupling	26
2- Modular MED plant system	28
5.2.2. RO coupling.....	28
5.3. Safety considerations for the GT-MHR couplings	28
5.3.1. Radiological protection of users of water produced with the desalination plant, coupled to the GT-MHR.....	29

6.	Economics of desalination systems	30
6.1.	Desalination cost calculations	31
6.2.	Desalination cost results	32
6.2.1.	Results for MED	32
6.2.2.	Results for RO	32
6.2.3.	Results for ROph	33
6.3.	Comparison of nuclear and fossil energy based systems.....	34
6.4.	Comparison of nuclear options with different desalination processes.....	34
6.5.	Desalination with renewable energy based systems	35
6.6.	Summary of economic assessment	36
7.	Conclusions	38
	Acknowledgements	39
	References	40

Executive Summary

A. Introduction

This report summarises our investigations undertaken as part of the EURODESAL project on nuclear desalination, currently being carried out by a consortium of 4 EU, (and one Canadian), Industrials and two leading EU R&D organisations.

Major achievements of the project, as discussed in this report are:

- Coherent demonstration of the technical feasibility of nuclear desalination through the elaboration of high performance coupling schemes for optimum cogeneration of electricity and water and by exploring the unique capabilities of the innovative nuclear reactors and desalination technologies.
- Verification that the integrated system design does not adversely affect nuclear reactor safety.
- Development of codes and methods for an objective economic assessment of the competitiveness and sustainability of proposed options through comparison, in European conditions, with fossil and renewable energy based systems.

B. Technical approach

The project comprises 4 technical work packages (WPs), designed to show the technical and economical feasibility of sea water desalination by selected nuclear reactor concepts, currently under study or development in Europe and the USA.

These WPs are :

- Nuclear Reactor and Desalination System Coupling and Optimisation, (WP1).
- Preliminary Safety Verification of the Coupled Systems, (WP2).
- Fossil and Renewable Energy based systems, (WP3).
- Economics of Desalination Systems, (WP4).

The technical approach implemented in the project is essentially based on the employment of two innovative reactor concepts: the GT-MHR (GT-MHR 1999), and the AP-600 (IAEA, 1996), coupled to selected desalination processes. *To compare the integrated system performances*, an operating 900 MWe French PWR (PWR-900) was also studied as a reference base case. All these nuclear reactors are briefly described in §2.1. For the purposes of comparison, two fossil energy fuelled power plants were also considered: the Gas Turbine Combined Cycle plant (CC-700), producing 700 MWe and the Pulverised Coal plant, producing 600 MWe, (PC-600). For the same reason, approximate first results of desalination costs by renewable energy based systems such as Solar Photovoltaic (SV), Solar Thermal (ST) and Wind (W), have also been included.

Our choice, concerning the desalination processes, has deliberately been confined to the MED (Multiple Effect Distillation) and RO (Reverse Osmosis), in view of their wide utilisation, prospects for further improvements and generally lower costs as compared to other processes. (IAEA, 1992). For comparison, the ROph process has also been included.

ROph is an advanced RO process based on the utilisation of waste heat from the nuclear reactor to preheat the feed-water for RO. This innovation results in significant cost reduction because of the improved permeate flow and the consequent higher water production rates as compared to traditional RO.

C Results obtained

Results obtained so far seem to be quite encouraging. Desalination costs (\$/m³) are summarised in Tables A and B:

Table A

Summary of desalination costs (\$/m³) evaluations for given desalting capacities and for discount rates of 5, 8 and 10%, with MED, RO and ROph processes.

System↓	Capacity (m3/day)	Costs with MED			Cost with RO			Costs with ROph			Cost of Net Saleable Power		
		5%	8%	10%	5%	8%	10%	5%	8%	10%	5%	8%	10%
PWR-900	48000	0,62	0,79	0,91	0,58	0,71	0,81	0,544	0,65	0,727			
	120000	0,54	0,7	0,82	0,51	0,62	0,7	0,487	0,586	0,658	0,023	0,030	0,035
	384000	0,48	0,65	0,77	0,45	0,55	0,63	0,443	0,538	0,608			
AP-600	48000	0,62	0,79	0,92	0,59	0,72	0,82	0,552	0,661	0,742			
	120000	0,55	0,71	0,82	0,52	0,63	0,71	0,495	0,597	0,672	0,026	0,033	0,039
	384000	0,49	0,66	0,78	0,46	0,56	0,64	0,45	0,549	0,623			
CC-700	48000	0,85	0,97	1,05	0,76	0,85	0,76	N/A	N/A	N/A			
	120000	0,77	0,88	0,95	0,67	0,75	0,67	N/A	N/A	N/A	0,055	0,057	0,058
	384000	0,77	0,9	0,99	0,6	0,68	0,6	N/A	N/A	N/A			
PC-600	48000	0,84	0,97	1,07	0,75	0,86	0,94	N/A	N/A	N/A			
	120000	0,76	0,88	0,98	0,66	0,79	0,83	N/A	N/A	N/A	0,058	0,063	0,067
	384000	0,71	0,84	0,94	0,6	0,69	0,77	N/A	N/A	N/A			
PV+ST*	10 000	Min 2.97											
		Max 7.72											
SP	10 000				Min 1.83								
					Max 4.5								
Wind*	10 000				Min 0.51						-		
					Max 1.37								

* On the basis of 1 euro = 0.98 \$; without land acquisition cost and "intermittence" penalty

An idea of the performances of the different integrated systems can be obtained from Table B.

Table B
Performance Characteristics of different integrated systems for a net capacity of
120 000 m³/day

System	Feed Water Required (kg/s)			Energy Consumed (MWth and/or MWe)			Net Saleable Electricity (MWe)		
	MED	RO	ROph	MED	RO	ROph h	MED	RO	ROph
PWR-900	10 409	2 778	3 855	220.6 MWth 7.0 MWe	21.3 MWe	24.6 MWe	925	929.7	926.4
AP-600	10 400	2 778	3 855	220.4 MWth 7.0 MWe	21.3 MWe	24.6	584.6	588.7	585.4
CC700	10 796	2 778	N/A	228.8 MWth 5.7 MWe	21.3 MWe	N/A	591.2	597.4	N/A
PC600	10 796	2 778	N/A	228.8 MWth 5.6 MWe	21.3 MWe	N/A	592.7	598.7	N/A

D Conclusions

The results obtained lead to the following conclusions :

- For PWRs, the most economic coupling scheme is the so called “conventional scheme”, utilising vapour directly extracted from the turbine blades. Coupling an MED plant via the condenser, with a view to utilise waste heat, offers the highest water production possibilities but results in a substantial loss of electrical power. This option may, therefore, be suitable for small or medium sized reactors which provide an optimal water to electricity production ratio.
- The optimal solution for a GT-MHR would be an MED coupling through an intermediate water loop and adopting a heat run-out scheme with 2 temperature steps two lines in parallel). With such a scheme, GT-MHR would produce about 43 000 m³/day of desalted water with virtually “free” heat energy.
- There are no safety problems related to any specific coupling scheme. All couplings investigated maintain the same number of static safety barriers against any radioactive contamination as those in the nuclear plant itself. The only design requirements are that 1)- the desalination feed-water suction line should be place upstream of any waste liquid discharge point and 2)- adequate surveillance and monitoring of any radioactive contamination and or storage of the product water is a necessary condition.
- Modularisation of the desalination plant considerably reduces the feedback impact on nuclear plant safety of any transients originating in the desalination

system in incidental or accidental conditions.

- As regards nuclear desalination economics, all combinations of energy sources and desalination processes show a significant size effect with increased desalination capacities. Thus for example, for the 5% discount rate and MED coupling, when desalination capacity is increased from 48 000 m³/day to 384 000 m³/day, (a factor of 8), the corresponding costs are reduced by about 23% for the PWR-900 or the AP-600, about 15% for the PC and about 9% for the CC
- In a scenario, with low discount rates (5 and 8%) and recommended fuel prices, the two nuclear options (which give analogous results among themselves), coupled to MED, are by far the cheapest, compared to desalination with fossil energy based systems. Thus, for 5% discount rate, the desalination cost from nuclear systems are respectively 37 and 35% lower for a desalination capacity of 48 000 m³/d, as compared to the PC and CC. This difference is about 48 and 60% at higher desalination capacities (e.g. 384 000 m³/d).
- In a scenario, considered to favour the fossil energy based options, (10% discount rate, lower fuel prices) the desalination costs by the PWR-900 and AP-600, coupled to MED are still competitive, although the differences in costs are much lower: about 7 to 15% compared to desalination with CC and PC at low capacity (48 000 m³/d).
- Comparable first result for the GT-MHR (maximum desalted water capacity of 41 000 m³/d), notwithstanding the uncertainties of cost evaluations, show that the difference in desalination costs from GT-MHR and fossil energy based systems could be of the order of 60 to 100%, if it is assumed that heat in the GT-MHR is freely available. Otherwise, the desalination costs from the GT-MHR would be comparable to those by other nuclear options.
- Whatever the energy source, desalted water capacity, or the discount rate, the costs (\$/m³) with the RO system are much lower (12 to 28%) as compared to the MED process. However, the later process produces pure water as compared to product water with about 500 ppm TDS in the RO, (which is acceptable, according to WHO standards for drinking water). Comparison of desalination costs with nuclear and fossil energy sources, coupled to RO and in conditions favouring the fossil energy systems (10% discount rate, low fossil fuel prices) shows that the nuclear options still remain very competitive. Thus the difference in desalination costs, compared to the PC is about 14% lower for the nuclear option at the capacity of 48 000 m³/d. Compared to the CC, at this capacity, the nuclear option gives 7% less desalination cost.
- ROph further reduces the water costs with the nuclear options by about 7 to 15%, as compared to desalination with traditional RO or MED. With design and system optimisation, the costs from ROph could be further reduced.
- Renewable energy based systems such as Solar Thermal (ST) and Solar photovoltaic (PV), give an order of magnitude higher energy and desalination costs even in the most favourable conditions. The desalination costs from Wind, are already competitive for small, isolated communities such as small islands or remote non-electrified communities. Besides, the costs may come down as these technologies mature in time and desalting capacities are increased and when mass production of components is undertaken.

Detailed Report

1. Motivation and Background

It is now generally recognised that sea water desalination is a very attractive and sustainable alternative for the solution of the water shortage problem which will be faced by nearly two thirds of the world population around the time horizon 2020-2030.

However, over the long term, desalination with fossil energy sources would not be very satisfactory: 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 m³/d. If nuclear instead of fossil fuelled options are chosen, then one could avoid about 20 000 000 t/y of CO₂, 200 000 t/y of SO₂, 60 000 t/year of NO_x and 16 000 t/y of other hydrocarbons. A sustainable, non-polluting, solution to energy and water shortages could thus only be provided by nuclear energy and, to a certain extent, by renewable energy systems.

These were the considerations that led to a recent feasibility study on sea water desalination, called EURODESAL project, and carried out under the aegis of the European Commission's 5th Framework Programme by a consortium comprising:

EU and Canadian industrials: ANSALDO (Italy), CANDESAL Technologies (Canada), EMPRESARIOS AGRUPADOS (Spain), FRAMATOME ANP (France), IRRADIARE (Portugal), and

R&D Organizations: CEA (Project Co-ordinator, France) and DINCE, The University of Rome (Italy).

The combined knowledge and experience of these organisations, both in nuclear reactor development and desalination technologies, exceeds by far the individual competence. This knowledge has been used in the project to ensure that the best available technologies and the state of the art R&D are integrated to produce the most competitive product with the highest level of Safety.

1.1. Major Objectives

The basic objective of EURODESAL is to provide a choice of options and technical specifications for a future common European seawater desalination system, using principally nuclear energy. This could be a demonstration plant or a full fledged integrated system based on one or two nuclear reactors coupled to a desalination process. The Project Work Plan was thus designed to achieve the following goals:

- Investigations of high performance coupling schemes for the MED (Multiple Effect Distillation) and RO (Reverse Osmosis) processes, and where possible, utilising the waste heat normally lost to the heat sink.
- System optimisation of the above desalination technologies coupled to the nuclear reactors.
- Verification that the coupling of nuclear reactors to the desalination processes produces contamination free potable water and is without any adverse effects on nuclear reactor operation and safety.
- Consistent and quantitative estimates of achievable power and water costs with

selected nuclear reactors and desalination processes, all operating in the cogeneration mode (simultaneous production of electricity and water); economic comparison of nuclear and fossil fuelled desalination options under different conditions.

2. Technical Approach

The project comprises 4 technical work packages (WPs), designed to show the technical and economical feasibility of sea water desalination by selected nuclear reactor concepts, currently under study or development in Europe and the USA.

These WPs are :

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The technical approach implemented in the project is essentially based on the employment of two innovative reactor concepts: the GT-MHR (GT-MHR 1999), and the AP-600 (IAEA, 1996), coupled to selected desalination processes. *To compare the integrated system performances*, an operating 900 MWe French PWR (PWR-900) was also studied as a reference base case. All these nuclear reactors are briefly described in §2.1

The choice of these reactors is not arbitrary. AP-600 has been studied in detail by ANSALDO (in collaboration with Westinghouse), which is one of the partners of the EURODESAL consortium. Similarly, since December 1995, FRAMATOME, another partner, along with GENERAL ATOMICS, MINATOM, and FUJI ELECTRIC has been working together on the design of the GT-MHR. Furthermore, it should be noted that the GT-MHR and the AP-600 are in the category of small and medium sized reactors (SMR). The deployment of such SMRs is very flexible and appears to be particularly suitable for cogeneration of electricity and water in countries with relatively weaker or non-interconnected electricity grids.

Our choice, concerning the desalination processes, has deliberately been confined to the MED (Multiple Effect Distillation) and RO (Reverse Osmosis), in view of their wide utilisation, prospects for further improvements and generally lower costs as compared to other processes. (IAEA, 1992).

Integrated systems, using different desalination technologies (see §3.2), are substantially different in their design and optimisation objectives. In the distillation system, such as the MED, the objective is to deliver the reject heat at an appropriate temperature without much impact on the power production level. In PWRs, this requires steam bleeding at different stages of the turbine, which naturally leads to some loss of electric power. MED systems coupled to PWRs will thus be those operating at the lowest possible temperatures. In the case of the GT-MHR, heat is available at 80 to 105°C, compared to ~ 35°C (in normal operation) at the turbine outlet for PWRs. Emphasis is, therefore, placed on coupling schemes for the GT-MHR, which effectively use higher temperatures for increased water production.

In the RO process, the objective is to minimise the electric power consumption.

The most crucial point is the economic performances of the integrated nuclear systems.

It is for this reason that detailed and coherent comparisons have been made with desalination by fossil energy based systems such as the pulverised coal (PC) and the gas turbine, combined cycle (CC). For the same reason, comparison with renewable energy based desalination systems has also been considered.

3. Nuclear reactors and desalination processes

3.1. Nuclear reactor systems

3.1.1 The French PWR-900

In 1969, France opted for the enriched uranium, light water cooled and moderated nuclear reactor systems. Since then the French Nuclear Power Programme has continued steadily. Nuclear power actually generates 76.6 % of the total electricity in France. Thirty four units of the standardized, 900 MWe PWR are actually in operation in addition to twenty four 1300 MWe and four 1450 MWe units.

The PWR-900 is quite well known and was chosen as the reference base case in view of its considerably lower costs resulting mainly from the series construction of standardised units.

Essentially, the reactor comprises of a single walled, steel lined containment building, which houses the reactor vessel and the primary system with three coolant loops. The turbine hall, shared by one or two pairs of units on the site is either oriented tangentially (CP1 models) or radially (CP2 models). For each unit, the Hall houses a turbo-generator set with one high pressure and three low pressure cylinders (CP1) or with one high pressure and two low pressure cylinders (CP2).



Figure 1: Schematic diagram of the PWR-900
1: Pressure vessel; 2: Steam generator; 3: Primary pump; 4: Pressuriser

3.1.2. The AP-600

The Westinghouse AP-600 is an advanced 600 MWe 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 pressuriser.

The major innovative plant 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

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.

The features of the AP-600 passive safety systems include passive safety injection (CMT and IRWST), passive residual heat removal (PRHR), automatic depressurisation system (ADS) and passive containment cooling (PCCS).

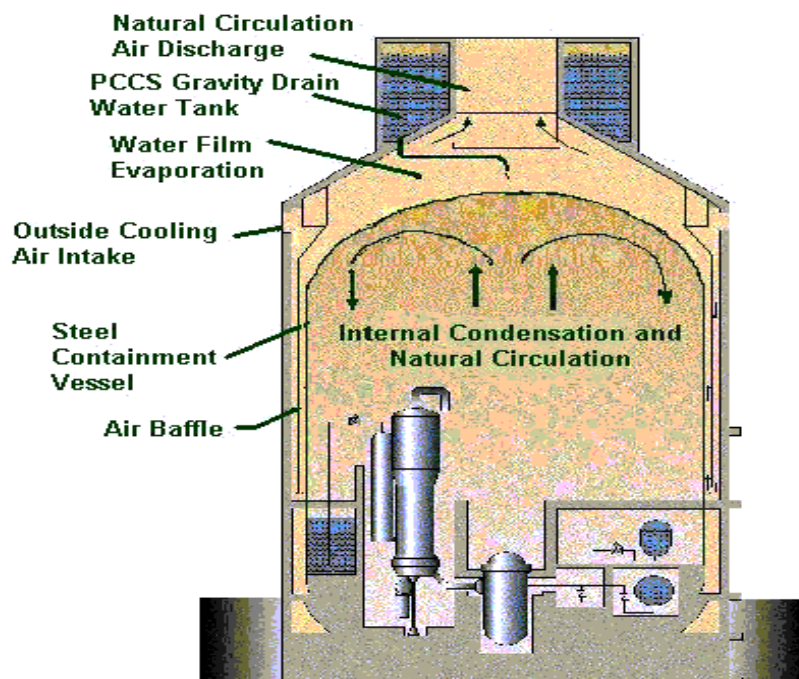


Figure 2: Schematic layout of the AP-600 nuclear Island

3.1.3. The GT-MHR

The Gas Turbine - Modular Helium Reactor (GT-MHR), is a meltdown-proof, helium-cooled reactor, developed to meet the need for safe and economical nuclear-generated electricity and process heat. The reactor is characterised by inert helium coolant, graphite as the core structural material and refractory-coated particle fuel which retains fission products at very high temperatures. In the GT-MHR, the high temperature helium

coolant directly drives a gas turbine coupled to an electric generator. (Figure 3).

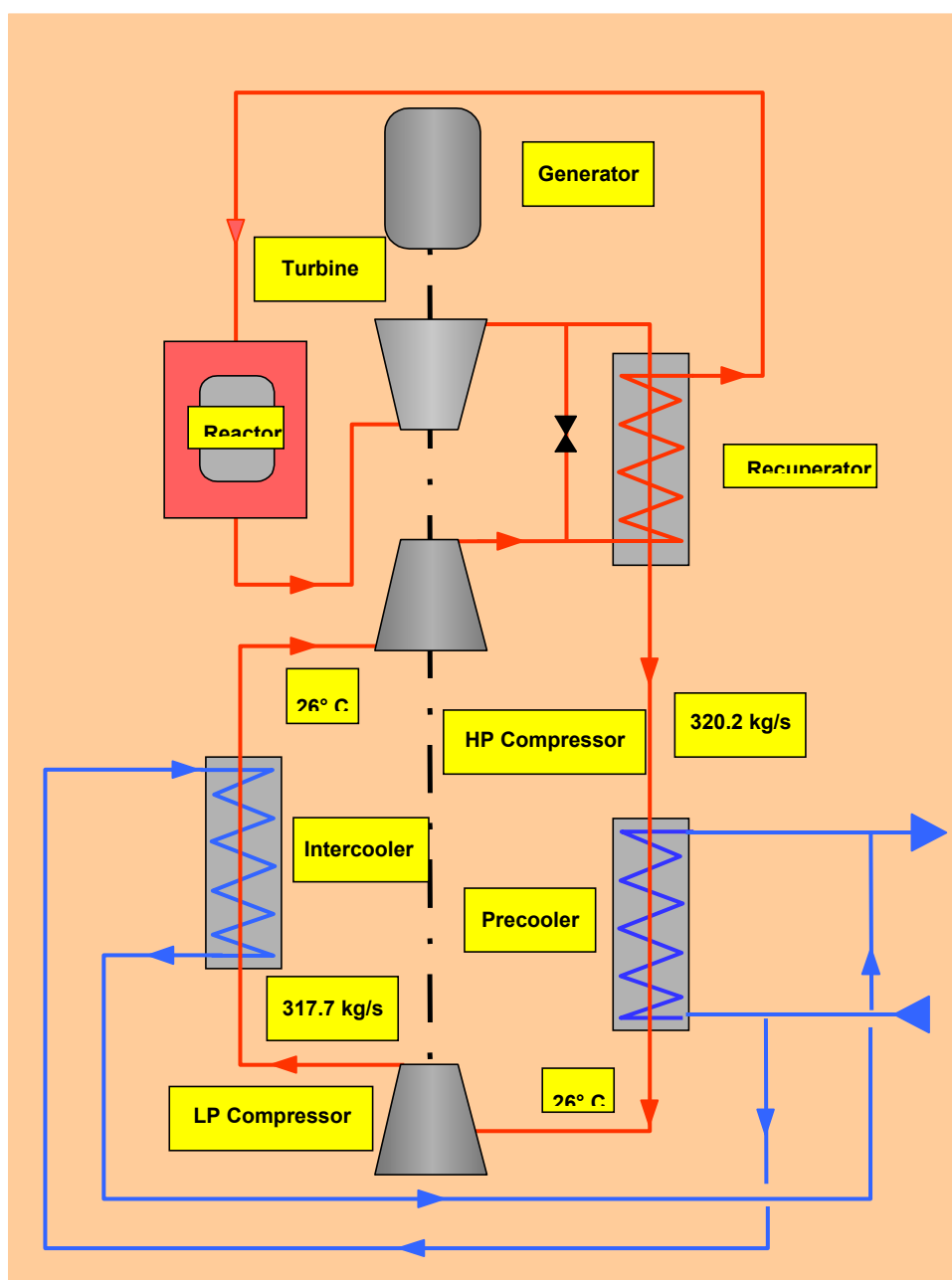


Figure 3: GT-MHR power conversion system

The efficiency of the system is about 48%. A typical GT-MHR module, rated at 600 MWth thus yields a net output of about 285 MWe. This system permits sequential construction of modules to match the user's growth requirements.

3.2. 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.

In distillation processes, (Khan, 1986) 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).

RO is a membrane process (Buros, 1990) which requires only mechanical (electrical) energy for its operation.

3.2.1. Multiple effect distillation (MED)

Figure 4 shows the schematic flow diagram of an MED process, using horizontal tube evaporators. 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.

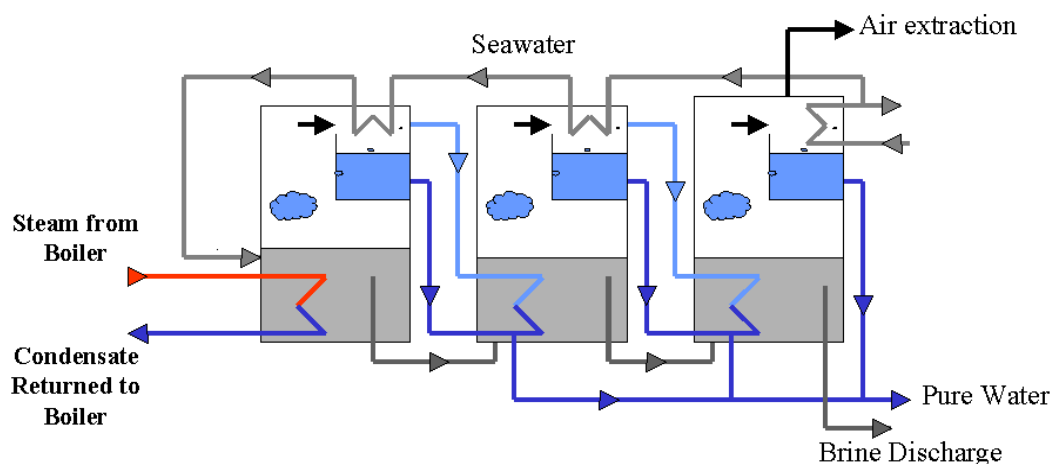


Figure 4: Schematic diagram of an MED system

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 vertical tube evaporation process (VTE).

The main differences between LT-HTME plants and 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 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.

3.2.2. Reverse Osmosis (RO)

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. sea water). Reverse osmosis 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 5). This pressure difference must be higher than the osmotic pressure between the solution and the pure water.

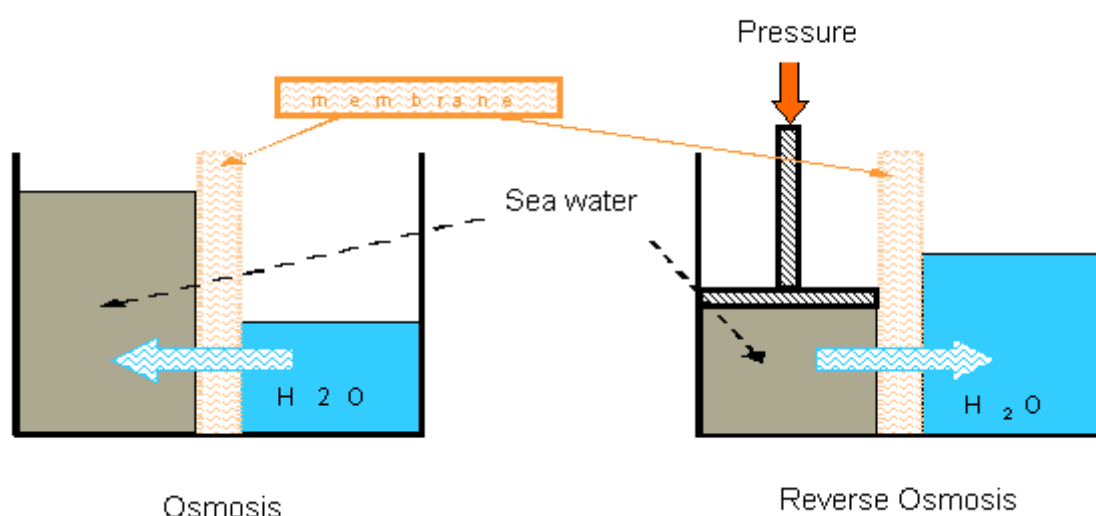


Figure 5: Osmosis and reverse osmosis processes

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 in the case of spiral wound and up to 2 in the case of hollow fibre modules.

3.2.3. Energy consumption in MED and RO

Desalination is an energy intensive process. For the MED plant, 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 desalted water for these two processes is a function of many variables: heating fluid temperature and flow rate, seawater temperature, desalination plant capacity etc. Indicative values are given in Table 1. MSF (Multi-stage Flash) is another distillation process.

Table 1

Average energy consumption in desalination processes

Process	Specific Heat Consumption $\text{kW}_{\text{th}}\cdot\text{h}/\text{m}^3$	Specific Electricity Consumption $\text{kW}_{\text{e}}\cdot\text{h}/\text{m}^3$
MED	50	3*
MSF	100	3
RO	-	4.5

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

It can be shown that typically, in order to produce about 290 000 m^3/day , MED process would require about 520 MW_{th} and 13 MWe. To produce the same amount of water, RO would require about 54 MWe.

4. Nuclear reactor and desalination system coupling and optimisation

Two of the most critical issues, facing nuclear desalination as a commercially viable technology, are energy utilisation and the cost of water production. In addition to conventional coupling schemes, (based on either the steam bleeding from the turbine, as in the MED process, or the direct utilisation of electrical energy as in the RO process), EURODESAL recognised that improvements in the efficiency of energy utilisation could be achieved by taking advantage of the waste heat from nuclear reactors which is normally evacuated to the heat sink. This section describes the potential of such an application both for the MED and the RO processes. Traditional MED and RO schemes have also been studied for comparison purposes.

4.1. Thermal (MED) couplings to PWRs

4.1.1. The conventional coupling scheme

In this coupling scheme, schematically illustrated in Figure 6, 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.

Results of thermodynamic calculations for PWR900 are given in Table 2. As the thermal power used will be the same for the AP-600 and since the efficiencies of the PWR-900 and AP-600 are the same, the results are also valid for the later type of reactor. 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 2 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 .

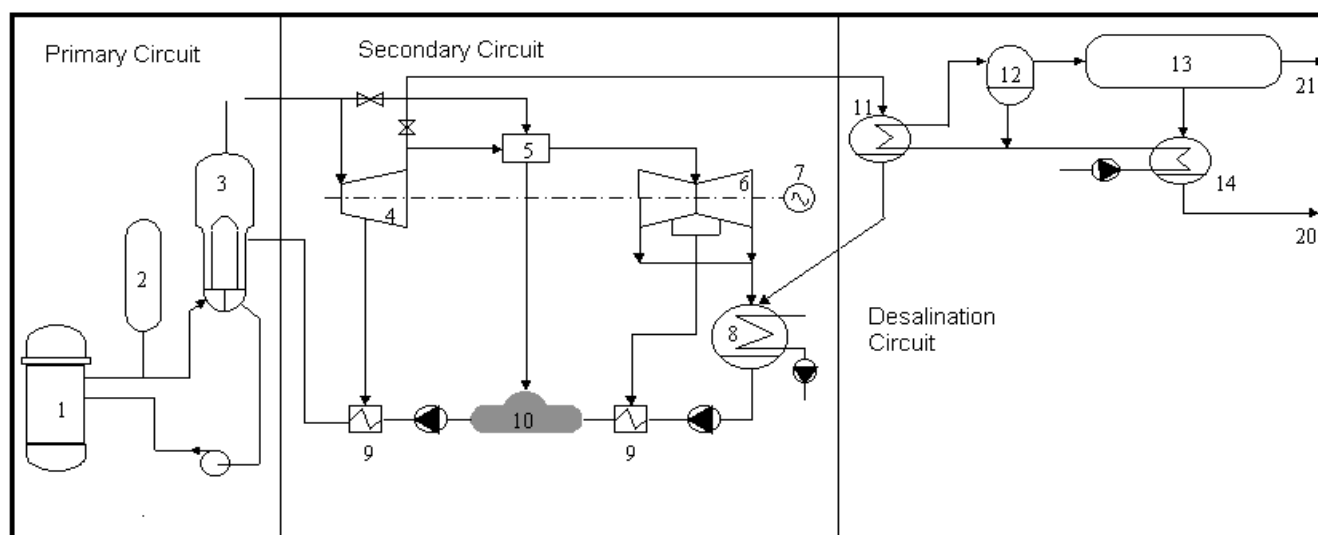


Figure 6: Conventional coupling of a nuclear reactor to a MED plant.

1: Reactor core, 2: Pressuriser; 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: Sea-water heater; 12: Flash tank, 13: MED plant, 14: MED output condenser, 20: Fresh water out, 21: Brine out-fall

Table 2

Water production in the conventional MED coupling to a PWR

Production Capacity (m ³ /day)	Thermal Power Used (MWth)	Initial Vapour Flow Rate (Kg/s)	Lost Shaft Power (MWe)
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

4.1.2. Research for a MED coupling scheme, utilising waste heat

In PWRs, nearly two thirds of the total thermal power is evacuated to the heat sink via the condenser. The basic idea behind the new coupling of the MED process to a given PWR was to make use of this energy. Since in most PWRs, the temperature in the condenser is about 33 to 40 °C, (corresponding to the vapour temperature from the last stage of the turbine), no meaningful desalination can be performed. It is for this reason that we have proposed increasing the condenser temperature (and pressure). Thermodynamic characteristics of the condensers in PWR-900 and the AP-600 under these new conditions are presented in Table 4. (Caruso et al, 2002). In this table, a minimum value of 0.22 bar has been considered in order to obtain in the condenser a temperature suitable for an efficient desalination process. The highest value (0.4 bar, 80°C) has been chosen to avoid an excessive loss of power in the turbine at high

temperatures and to avoid corrosion and scaling effects in the MED system.

Table 3
Nominal conditions in PWR condensers

	PWR-900	AP-600
Pressure (bar)	0.055	0.085
Temperature (°C)	34.8	42.6
Coolant flow rate (m ³ /s)	37.7	25.1
Coolant ΔT (°C)	12	12
Thermal power to Condenser (MW _{th})	1866	1244
Total Plant Electrical power (MW _e)	919	675

Table 4
Modified thermodynamic conditions in the condensers at higher temperatures

Pressure, (bar)	0.22	0.3	0.4
Temperature, (°C)	62.2	67.1	80
PWR-900			
Lost shaft power, (MW _e)	148	220	310
Thermal power to condenser (MW _{th})	2006	2070	2155
Coolant flow rate, (kg/s)	40120	41400	43100
AP-600			
Plant electrical power, (MW _e)	607	567	517
Thermal power to condenser (MW _{th})	1313	1353	1403
Coolant flow rate, (kg/s)	26260	27060	28060

The principle of this coupling scheme is similar to that in Figure 6. The only difference is that the vapour to the main condenser is input from a point at higher temperature rather than from the last stage of the turbine. In this case, one need not provide for the separate seawater heater as in the conventional scheme.

A make-up flow to the flash-tank loop is the sea water or the pre-heated sea water from MED, depending on the operating temperatures of the scheme. The double barrier is assured by the steam generator and the condenser tubes.

Results for PWR-900 and AP-600 are presented in Table 5. The coolant flow rate has been calculated for a constant temperature increase in the condenser (12°C) in all the conditions.

Table 5

Results of the MED coupling via condenser			
Condenser pressure, bar	0.22	0.3	0.4
Condenser temperature, °C	62.2	67.1	75.9
flash-tank temperature, °C	49.5	54.5	63.2
Number of MED Effects	6	8	11
PWR-900			
Water production, (m ³ /day)	394810	500959	696127
GOR	6.37	7.96	10.23
AP-600			
Water production, (m ³ /day)	258418	327438	453209
GOR	6.37	7.96	10.23

It is observed that, compared to the nominal conditions, coupling through the condenser results in a significant decrease of turbine efficiency since the electrical production, in the PWR-900 for example, has been reduced by 148 MWe at condenser temperatures of 62°C (0.22 bar), as opposed to about 93 MWe in the conventional scheme, using the direct vapour extraction from the turbine. The electrical power is naturally further reduced as condenser temperatures are increased. The only interest of the condenser coupling is thus the increased thermal power available for desalination and consequently much greater water production levels.

4.1.3. MED flash-tank couplings to GT-MHR

The coupling of the GT-MHR with a MED desalination plant is analogous to couplings adopted above for PWRs, but an intermediate heat transformer is required to satisfy the safety requirement of "minimum two barriers plus pressure reversal" between the reactor and the desalination plant.

Figure 9 shows the proposed general scheme (Lecomte, 2002). Heat is transferred from the pre-cooler (170.5 MW) and the intercooler (131.5 MW) through two water loops in parallel. In the first loop water reaches a temperature of 120°C, while in the second one a temperature of about 96°C is obtained. From a simple heat balance, the two flow rates are quite similar and a mixing temperature of about 108°C may be supposed.

The lowest water temperature must be lower than 22°C, to cool helium at 26°C for the compressor. Therefore, in the heat transformer unit, assuming a minimum ΔT of 2°C, the coolant temperature range is between 106°C and 22°C, assuming 20°C as input sea water temperature.

The helium cycle in the GT-MHR allows two possibilities regarding the output temperature of the hot water: 1)- a high temperature option which would require heat exchangers with large surfaces (because of small temperature difference between the two fluids) and reduced coolant flow rate and 2)- a low temperature option which, because of the high temperature difference between the two fluids, would require smaller heat exchanger surfaces but with increased flow rates.

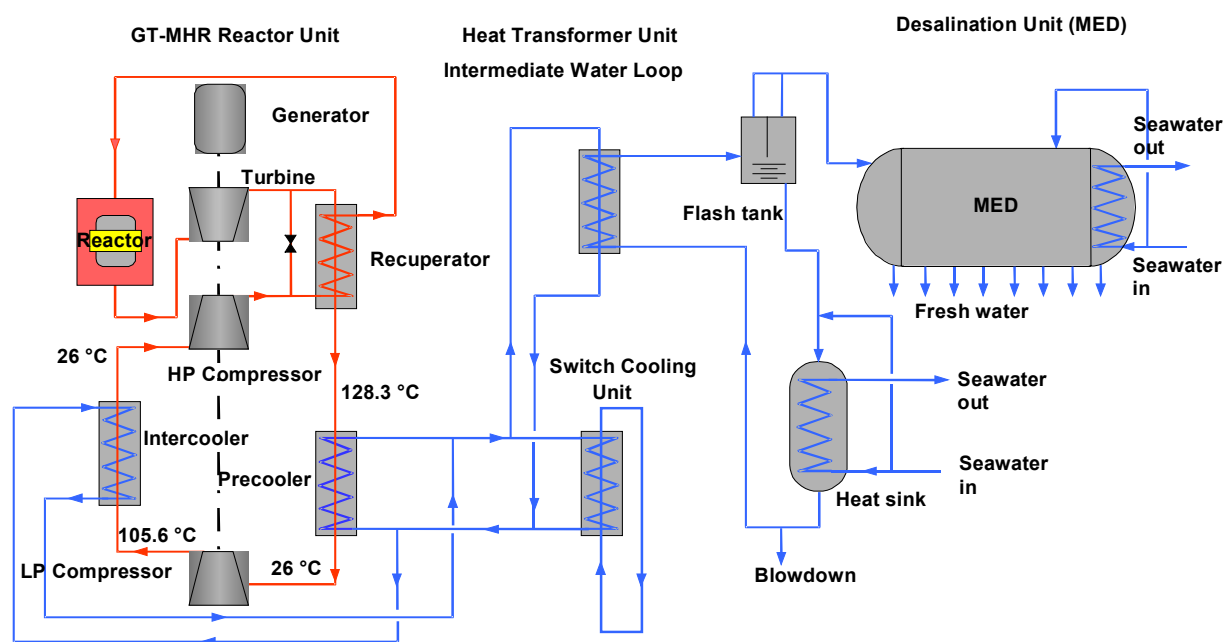


Figure 7: Coupling of the GT-MHR to MED via a flash-tank

Table 6 summarises the results of these two schemes.

Table 6
GT-MHR coupling with a flash-tank

Coolant temperatures, high/low	°C	106/22	80/22
Coolant flow rate (60000 ppm)	kg/s	895.4	1313.9
Flash-tank temperature	°C	69.5	52
Steam produced	kg/s	57.1	61.6
Make-up flow rate	kg/s	180.2	194.7
Rejected flow rate	kg/s	123.1	133.0
Heat rejected in the heat sink	MW	155.7	145.81
Total heat rejected	MW	166.2	157.2
N° of MED effects	-	14	7
Distillate production.	m ³ /day	61508	38306
GOR	-	12.48	7.19
H.P.	kJ/kg	210.37	360.75

4.1.4 Other coupling schemes for the GT-MHR

Two configurations have been analysed in a study by FRAMATOME and CEA (Bandelier, 2000): a base, low temperature, scheme with the coolant temperature from 80°C to 50°C (Figure 9) and the "Heat run-out " configuration, (Figure 8), where two or three MED lines have been considered in parallel with temperature steps, for example, of 80 to 65 and 65 to 50°C, or 80 to 70, 70 to 60 and 60 to 50 °C. Results are presented in table 7.

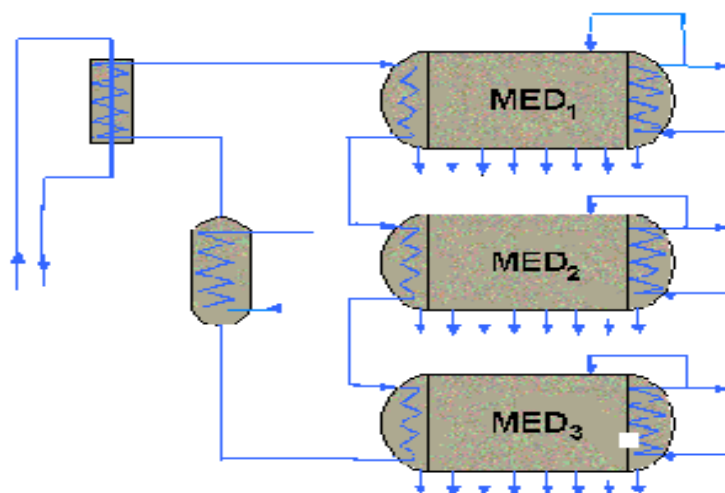


Figure 8: Principle of the Heat Run-out scheme for GT-MHR

Table 7 clearly shows that the Heat Run-Out scheme provides a larger amount of distillate (more than a factor of 1.5). However, in this scheme, the gain in distillate production from two to three MED lines is about 9 % and probably lower than the increment of costs for the construction of three desalination plants, even if they are smaller than in the previous two-plants scheme. Specific desalination costs from the heat run-out scheme may therefore be the same as those from the base scheme. However, it is possible to envisage Heat Run-Out schemes with only one line and a periodic re-injection of hot water. This may lead to much lower specific desalination costs. (Bandelier, 2000).

Table 7
GT-MHR coupling with an intermediate-loop; low temperature configuration

Plant	Input/output Temperatures (°C)	Production (m ³ /d)	MED Effects
Base scheme			
Line 1	80/50	30000	6
Total		30000	
Heat Run-Out scheme with 2 MED lines in parallel			
Line 1	80/65	27888	12
line 2	65/50	15000	6
Total		42888	
Heat Run-Out scheme with 3 MED lines in parallel			
Line 1	80/70	21360	14
Line 2	70/60	15840	10
Line 3	60/50	10008	6
Total		47208	

4.2. RO Coupling, utilising waste heat (ROph)

CANDESAL has developed an advanced reverse osmosis (RO) desalination system that emphasizes a non-traditional approach to system design and operation (Humphries et al, 2002). 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 optimisation and automatic real-time plant management systems. These features are described in the following sections.

4.2.1. Preheating of feed-water

The waste heat normally discharged from water cooled reactors through the condenser cooling system can also be used as “preheated” feed-water into the RO system. This preheating improves the feed-water viscosity and membrane permeability thereby increasing the relative potable water production for a given plant size and energy consumption, with corresponding reduction in the unit cost of water production. This is illustrated in Figure 11 for a fixed feed-water flow rate.

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..

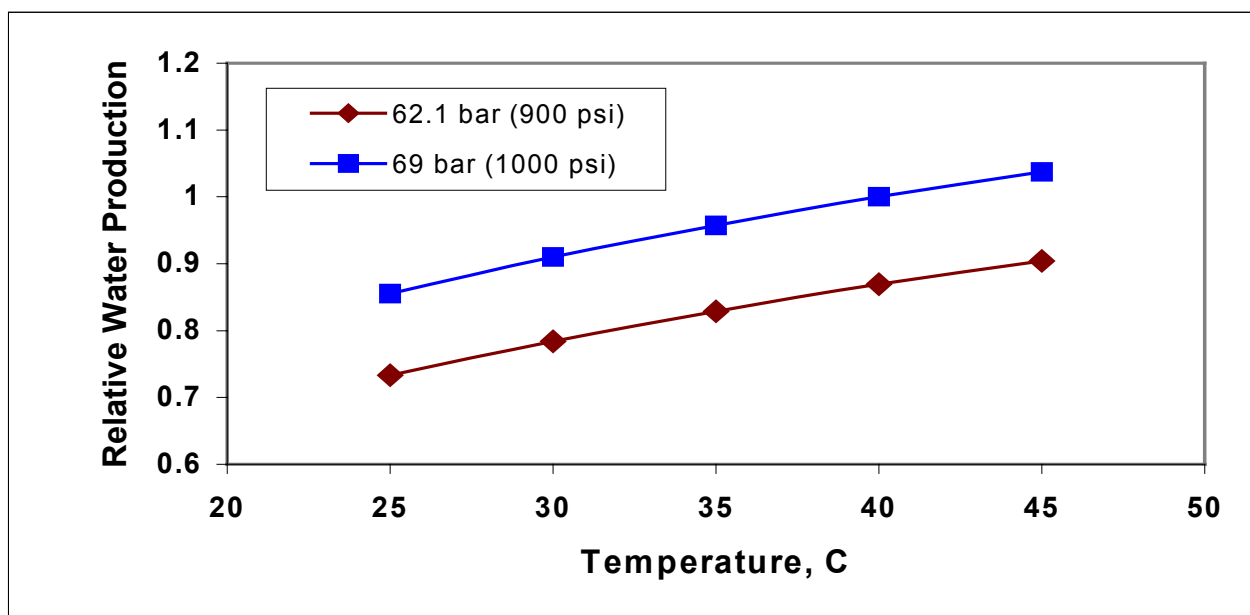


Figure 9: Normalised water production as a function of RO feed-water temperature and Pressure

4.2.2. Operation at high feed-water pressures

High pressure operation is another key feature of this advanced design concept. While many RO system designers and membrane manufacturers themselves will advocate use of lower pressures to save energy costs in water production, operation at higher pressures leads to significant water production increases. This effect is also illustrated in Figure 9, which shows increased water production at increasing pressures as well as temperatures. Studies have shown that the apparent increase in pumping costs due to

the higher pressure is offset by increased water production and is ameliorated further by the use of energy recovery.

Similarly, as the feed pressure increases, with all other factors remaining the same, the TDS (concentration of total dissolved solids) of the product water decreases, as shown in Figure 10. This compensates for the increase in feed-water salinity with its temperature.

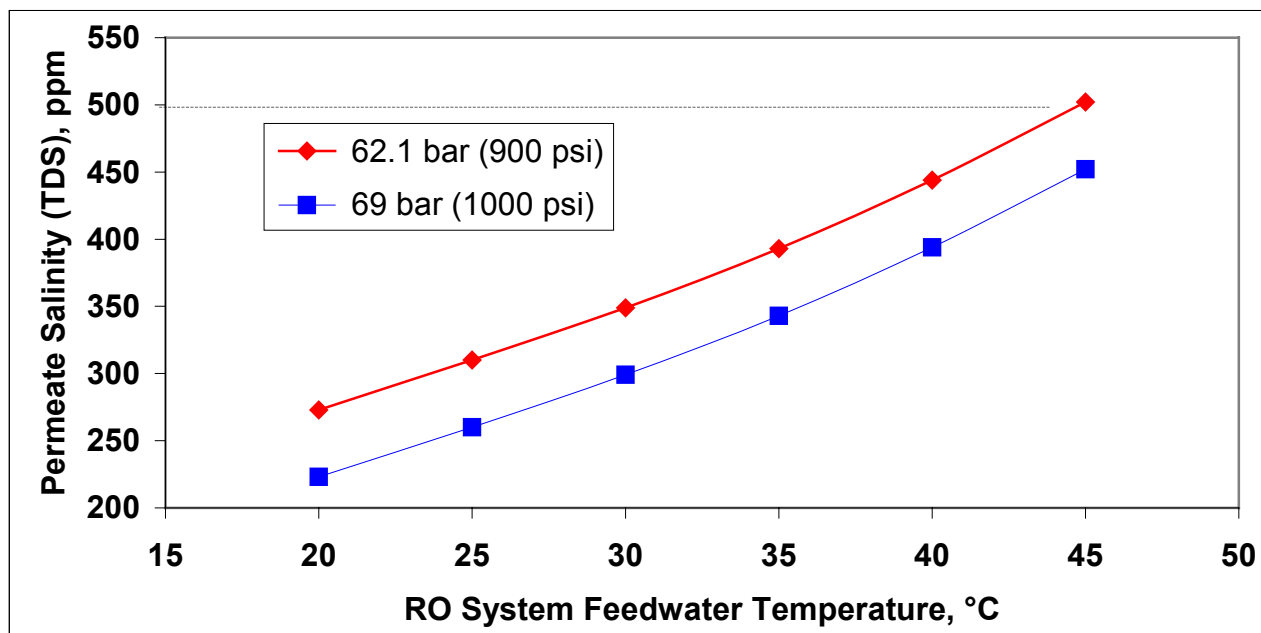


Figure 10. Effect of pressure and temperature on product water salinity

4.2.2. Ultra-filtration

Another key feature is the use of ultra-filtration (UF) pre-treatment of the feed-water rather than the extensive use of mechanical filtration and chemicals. Chemical pre-treatment is not only a major cost in the operation of an RO plant, it is also a source of environmental pollutants. Through the use of UF membranes, the system uses a minimal amount of chemical pre-treatment and thus lowers the cost of water production, and the associated environmental burden, significantly over time. A second and equally important benefit of UF pre-treatment is the broadening of the acceptable performance envelopes for the RO membranes that accrues with the use of very clean feed water that has not been subject to chlorination, has a very low silt density and turbidity, and is virus and bacteria free.

4.2.4. Energy recovery

Energy recovery is used in the system design to take advantage of energy that would otherwise be lost by the direct rejection of the high pressure brine. Significant progress has been made in energy recovery systems in recent years and it is expected that progress in this area will continue to reduce the cost and raise the efficiency of these systems. Today there are a number of these products on the market that could be incorporated in a plant to increase the level of cost saving.

4.2.5. Site specific optimisation

The importance of site-specific optimisation cannot be over-emphasized and is a key component in this advanced RO system design. Many factors influence the ultimate cost of the product water and need to be considered when designing a plant. This stresses the importance of considering all of a site's characteristics when developing and

optimising a plant design, (e.g. the make-up of the feed-water, the availability of waste heat, seasonal and other variations in feed-water quality and temperature, the owner's specific needs with respect to water production minimums and maximums, system management requirements, and so on).

4.2.6. Management and control system

Perhaps one of the most important aspects of the design of an advanced RO desalination plant, where minimum life cycle water costs are the goal, is the design and configuration of the Management and Control System. Not only does the Management and Control System removes the task of the general determination of optimal operation conditions for the plant from the operators, it also, by being a real time system monitor, allows for the minute by minute adjustment of the system operating parameters to optimally accommodate varying conditions in the feed stream. This real-time capability is especially important on large plants (above 100,000 m³/day) located on river estuaries and other locations where tidal action causes very large changes in the diurnal levels of dissolved solids, turbidity and silt density.

4.2.7. Experimental verification

Demonstration testing has been carried out using a trailer mounted system producing up to 150 m³/d of potable water. The facility was commissioned and functional testing was carried out in the spring of 2001. Experimental data on performance characteristics under varying conditions of temperature and pressure were obtained during the summer of 2001. The experimental program has addressed feed water temperature in the range 20 °C through 45 °C over a pressure range of up to 69 bar.

Experimental results from the demonstration testing (Figure 11) are behaving as expected based on analytical performance models, validating the advanced design concept and confirming that the performance improvements indicated by the analyses can be achieved in operating systems.

Further demonstration testing is planned in the context of the forthcoming EURODESAL Demo project, using a 1000 m³/d containerised system, currently under design, coupled to an existing nuclear power reactor.

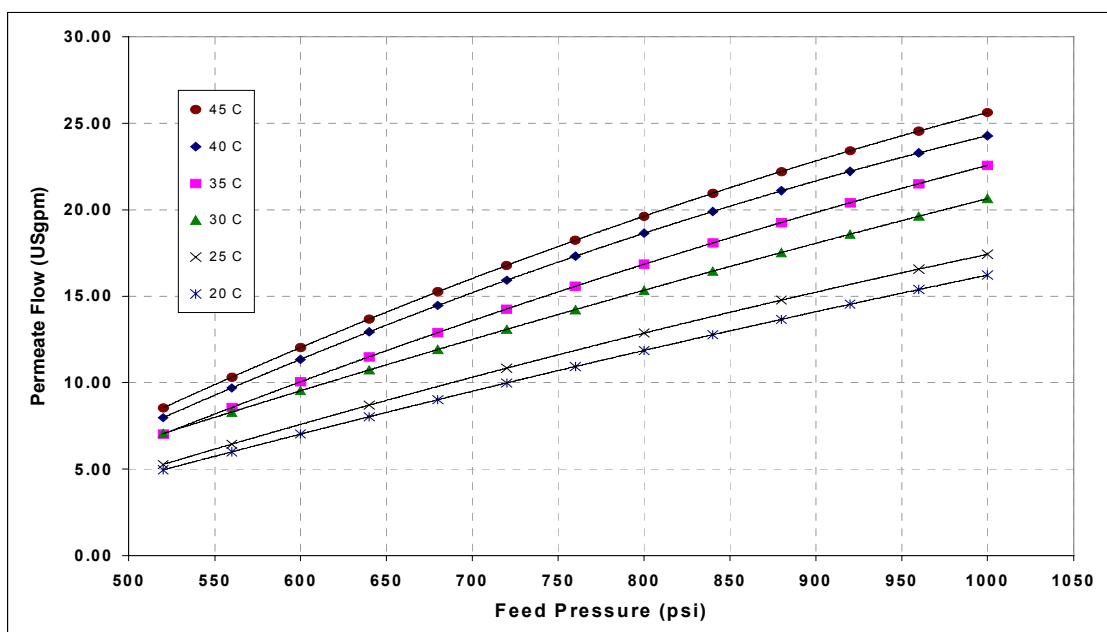


Figure 11: Permeate flow as a function of feed-water pressure at various temperatures

5. Preliminary safety verification of the coupled systems

The overall safety issues associated with an integrated nuclear desalination facility are primarily those associated with the nuclear plant itself. Since these aspects are already taken care of in specific reactor safety studies, this section will only address those specific safety issues caused by the coupling between a reactor system and a desalination plant. These issues are related to:

1. The potential for the transfer of radioactive materials from the nuclear plant to the desalination system during normal operation or as a result of an incident or accident. This issue involves an evaluation of the adequacy of the adopted containment-confinement boundaries in terms of number of barriers and their effectiveness.
2. The potential for more severe reactor system transients induced by transients in the desalination plant, either during normal operation or as a result of an accident.

The safety impact of these issues is strongly dependent on the adopted coupling scheme. Safety verification was therefore made by ANSALDO (Alessandroni et al, 2002) for the coupling schemes discussed above: MED, RO and RO with preheating. AP-600 reactor was considered as the reference nuclear plant. Conclusions are however applicable to other reactor types:

5.1. Safety barriers

The fact of coupling the nuclear reactor to any of the above mentioned processes does not reduce the number of safety barriers as compared to the standard nuclear plant configuration. Thus the usual barriers are maintained in all cases: fuel matrix, fuel cladding, primary circuit and the reactor containment system. In the case of coupling through the condenser, an additional non-grad safety barrier are the main condenser tubes.

In normal operation, the main condenser is at a lower pressure compared to its environment. There is thus no leakage of the secondary side steam outside the condenser.

Nevertheless, the integration of the nuclear plant with the desalination system can lead to a modification of the radioactive exposure pathways. This is due to the possibility that radioactive materials could be released to the potable water – and not to the sea or to the river – through the interface boundary between the nuclear facility and the desalination system, e.g. main condenser or main condenser cooling water. Potential radioactive releases can be a consequence of normal operation routine releases – i.e. normal operating leakage at interface boundary - or accident events.

Radioactive releases to potable water can be prevented by a combination of design and operational provisions as discussed below.

1)- Leakages during normal operations can be precluded by assuring a leak-tight boundary and by maintaining a dynamic barrier, i.e. higher pressure on the process side (as compared to the reactor side) at the interface boundary for both the coupling schemes. In this case routine radioactive releases at the interface boundary are expected to be negligible. For MED coupling scheme, the dynamic barrier is obtained maintaining the cooling loop at higher pressure using a lamination valve, according to the scheme presented in Figure 12.

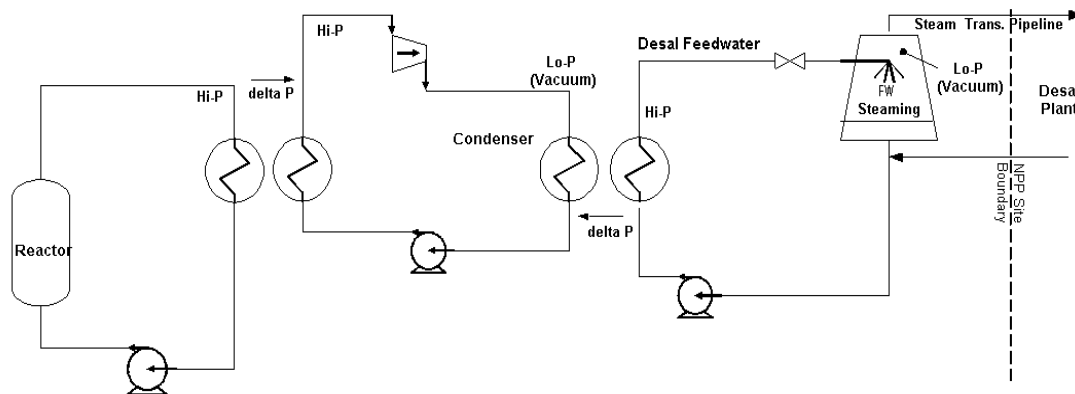


Figure 12: MED coupling with pressure reversal at the main condenser

It is also important that the feed-water suction line be placed upstream of any waste liquid release discharge point located in the main condenser cooling water stream.

2)- In case of accident conditions at the nuclear plant which can result in an increase of the secondary side contamination or a loss of vacuum in the condenser - including condenser tube rupture – the desalination plant has to be put in shut-down condition in order to prevent a potential contamination of the potable water.

This protective action permits the “standard” exposure pathways associated with the reactor accident situations to be re-established.

3)-The water produced by the desalination system could be stored and monitored for radiological contamination before its distribution.

5.2. Transients and accidents induced by couplings

5.2.1. MED coupling

The partial or total unavailability of the MED system, which provides the unique heat sink for the nuclear facility, can result in a partial or total loss of heat sink with consequent possible turbine trip and reactor trip. This is analogous to a typical class 2 transient event in Safety Analysis.

Major causes of the transient are:

- loss of condenser vacuum,
- main condenser tube leakage,
- loss of re-circulating cooling water flow; this cause is usually negligible due to component redundancies (pumps and electrical power) provided in the main condenser cooling water system.

The transient induced by the unavailability of the desalination plant is not expected to be more severe than the analysed transient. However, the transient frequency could change as a consequence of the connection with the desalination plant.

Two effects on transient frequency are anticipated:

- The cooling loop can process highly salted cooling water or salt free cooling water according to the scheme adopted. It should be recalled that the salt content in the cooling water can increase the erosion-corrosion problems at the main condenser tubes with consequent increase of the frequency of condenser leakage or pipe break events. A choice of appropriate material can avoid corrosion problems in the

condenser tubes but would slightly increase costs.

- The desalination plant is a more complex system compared with a typical main condenser cooling circuit; this characteristic can increase the frequency of the loss of heat sink transient due to a failure in the desalination facility.

The change in the event frequency may affect the Plant Design Transients and the Probabilistic Risk Assessment (PRA) results (Initiating Event Frequencies). On the contrary, the accident analysis event categorization does not change because the transient is already classified as a frequent abnormal event (Class 2 Event).

The impact on Plant Design Transients – reference transients for system component mechanical design - essentially depends on the transient's frequency to be assumed in component design. The AP-600 standard design considers two Reactor Trips per Year (from all causes) with the reactor at full power.

The frequency of the Loss of Condenser Initiating Event (IE) – from all causes – as assumed in the AP-600 PRA, is equal to 0.112 events per year. The IE results in a reactor trip produced by the loss of the plant normal heat sink due to a Loss of Condenser Vacuum (dominant cause) or a Condenser Leakage event.

The value assumed in the PRA is consistent with PWR values reported in the NRC document NUREG CR3862 as shown in the following table:

Table 8
Transient frequencies in PWRs

Transient	EPRI-PWR Transient Category	Frequency event/yr
Loss of Condenser Vacuum (Causes: hardware failure or human Errors)	25	0.14.
Condenser Leakage	27	0.04

On the basis of the above, it is reasonable to limit the reactor trip due to MED unavailability to 0.1 events per year, i.e. equivalent to the frequency of the dominant cause (loss of condenser vacuum). In this manner the overall frequency of a reactor trip due to a loss of condenser heat sink will be roughly doubled ($f_{\text{loss of condenser}} = 0.2$ event/yr).

$$f_{\text{loss of condenser}} = f_{\text{loss of condenser vacuum}} + f_{\text{MEDunavailability}} + f_{\text{Condenser tube leakage}}$$

In order to achieve the 0.1 event/year goal and possibly further reducing it, the MED coupling scheme has to cope with the following two design requirements:

1- Transportation pipeline from nuclear site to MED site should carry water instead of steam.

Transportation of steam at a temperature below 100°C requires a large diameter pipeline maintained at a significant sub-atmospheric pressure. This solution reduces the overall availability of the MED system and renders the achievement of the transient frequency goal more difficult.

The proposed solution is to transport cooling water from the nuclear site to the flash tank located at the MED system site (Figure 13).

2- Modular MED plant system

The MED plant should include sufficient number of modules (typically 10-11) to ensure that a loss (unavailability) of one module – due to a planned shutdown or an accident event - does not induce a reactor trip but only a load reduction acceptable for the nuclear plant (acceptable load reduction $\leq 10\%$).

Each module should integrate its own steam feeding system, i.e. lamination valve and flask tank. In this case, also a loss of vacuum in a module does not result in a reactor trip.

This requirement is consistent with the present technology which is based on module standardized plant.

The scheme in Figure 13 shows how the coupling configuration can be modified to satisfy the above stated requirements.

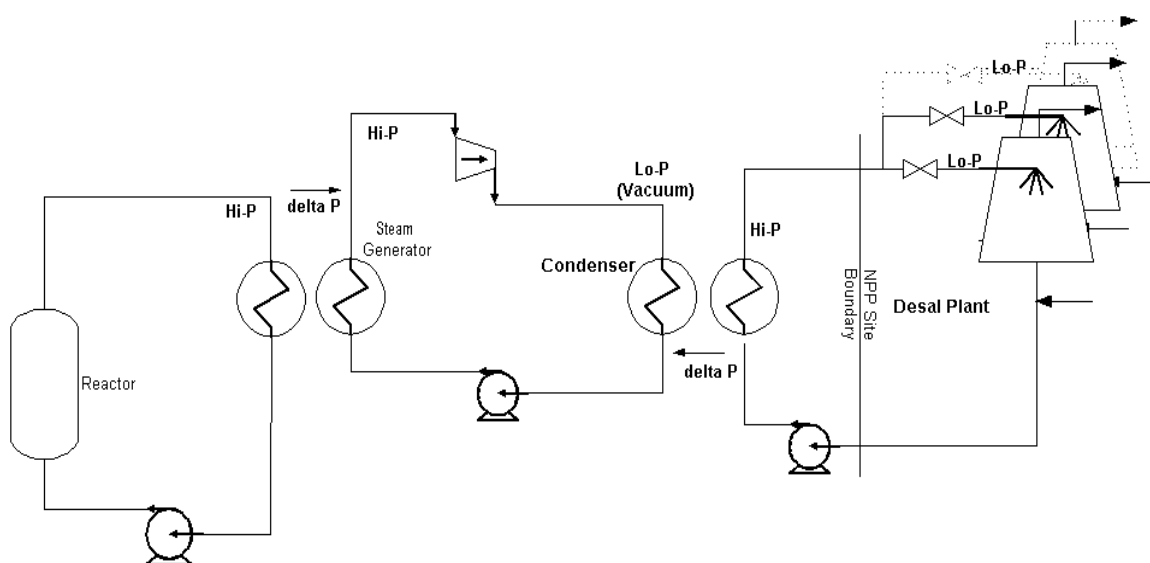


Figure 13: Modular MED couplings via the condenser

5.2.2. RO coupling

The sudden cessation of the demand of the electricity by the RO system creates a loss of electrical load. However, the amount of electric energy used by this desalination process is only a small fraction of the electric energy generated by the nuclear plant. In fact, the energy required for the production of 10 000 m³/day – which is the reference daily capacity of a RO module - is about 0.25% of the energy produced by the a 600 MWe nuclear plant.

Therefore the nuclear plant is able to tolerate a shutdown of several RO modules – if powered directly from the nuclear plant - without the need for reactor trip. Based on reference data the AP-600 would accept a shutdown of up to 40 RO modules, which can furnish a maximum of 400 000 m³/day of potable water.

5.3. Safety considerations for the GT-MHR couplings

Safety aspects regarding the GT-MHR coupling to RO or to an MED plant, as investigated by DINCE (Naviglio and Caruso, 2002), follow the trends presented above:

Since the inter-cooler system and the pre-cooler system do not play a function relevant

to safety for the GT-MHR, we can state that, in principle, no relevant, direct safety effect may be envisaged, if the function of the final heat sink for the inter-cooler and/or of the pre-cooler system is fully or partially fulfilled by the brine heater of a MED desalination plant.

The possibility that part or all of the heat to be released through the inter-cooler and/or the pre-cooler be utilised by a MED desalination plant does not affect, in principle, the safety level of the GT-MHR.

Obviously, the following requirements should be incorporated in the design of a coupled system for cogeneration of electricity and water:

- The desalination system should be designed so that the maximum percentage of the inter-cooler (/pre-cooler) thermal power, that may undergo a sudden change during transient or accidental conditions, is limited (i.e. not higher than some 10%). This implies an upper limit in the thermal power that a single MED module may absorb.
- Even if a large, traditional-design, desalination plant is connected to the GT-MHR a redundant cooling system, sized for 100% of the thermal power absorbed by the desalination plant, should be included.
- The size of the additional, back-up cooling system could be reduced in the case of a high-reliability design of the MED plant. However, since the design standards of current MED systems are not comparable with the nuclear power plant design standards, it does not seem economically logical to interfere with the design criteria of the MED plant. A redundancy of the final heat sink appears therefore to be more suitable.

5.3.1. Radiological protection of users of water produced with the desalination plant, coupled to the GT-MHR

In this regard, it should be recalled that a final safety analysis of a GT-MHR plant has not yet been carried out and no information is therefore available on the radiological impact of such a plant on the surrounding environment.

Nevertheless if we refer to the results of the analysis carried out by DOE for a MHTGR, no special hazard can be recognised, especially if one takes into account the differences in the features of GT-MHR with respect to MHTGRs. Therefore, no special limitation for the coupling of a desalination plant with a GT-MHR may be envisaged.

A second issue concerns the possible release of radioactivity from the GT-MHR to the desalination plant, through the coupling itself between the two plants.

In the case of a GT-MHR being cooled totally or partially by a MED desalination plant, there is a physical interface between the two plants and a path for possible radioactive migration may be identified.

The pressure of the inter-cooler/pre-cooler circuit must be as low as possible in order to limit the introduction of water into the helium filled vessels in accidental scenarios, and this is a positive feature in the view of creating dynamic barriers to the migration of radioactive matters towards the desalination effects.

At least one intermediate, high pressure, loop should be foreseen between the inter-cooler/pre-cooler systems and the MED plant, operating at a pressure both higher than the pressure of the inter-cooler/pre-cooler circuits and higher than the pressure in the first effect of the MED plant.

Fast-closing fail-safe valves will have to guarantee the closure of the loop in case of radioactivity monitored within it.

It is suggested that additional analysis and research be made regarding:

- suitable design of the circuits connecting functionally the inter-cooler/pre-cooler circuits and the MED plant,
- migration of tritium through metallic containment boundaries and the study of systems/devices able to avoid totally the contamination of desalinated water because of tritium migration.

6. Economics of desalination systems

Power costs calculations were principally made with the CEA code system, SEMER (Nisan, et al, 2002). These were input in the IAEA code, DEEP/V2 (Gowin and Konishi, 1999) to obtain the desalination related costs. Details are presented in (Nisan and Volpi, 2002).

Input parameters for the power cost evaluations of the two nuclear options (AP-600 and PWR-900) with SEMER are given in Table 9.

Table 9
Input parameters used for PWR-900 and AP-600 costs evaluations

Item	Unit	PWR-900	AP-600
Date of Estimation	2001		
Net thermal efficiency		0.33	0.33
Average discharge burn-up	GWd/t	45	42
Construction lead time	y	5	4
Economic life	y	60	60
Plant availability	%	0.87	0.9
Interest/Discount rate	%	5, 8, 10	5, 8, 10
Monthly labour costs	\$/m	3571	3571

Similarly, fossil fuelled power plant costs estimations were also made by selecting the corresponding fossil energy based models in the SEMER library. The input parameters are given in Table 10.

Two important points need to be mentioned here:

- Fossil fuel prices used in the calculations are basically those recommended by the French Ministry of Industry (DIGEC) or by international organisations such as OECD, IAEA etc. Reference base case fossil prices were thus respectively 50 and 60 \$/t for the coal fired plant and 30 \$/bbl for the combined cycle, gas fired plant.
- We have, however, also made studies for much lower fuel prices (respectively 40 \$/t for the PC and 20 \$/bbl for the CC). These, combined with a discount rate of 10%, simulate the scenario, favouring fossil energy options, (S_F), in many countries. The other costs naturally represent what might be considered as conditions favouring the nuclear option (S_N).

Table 10
Input parameters used for FPP cost evaluations

Item	Unit	PC600	CC700
Date of estimation	2001		
Net electrical output	MWe	620	700
Net thermal efficiency		0.39	0.51
N° of units (nth of a kind)		1	1
Power plant availability		0.90	0.90
Construction lead time	y	3	2
Economic life	y	30	25
Interest/Discount rate	%	5, 8, 10	
Labour cost	\$/m	2571	2485
Fuel Cost, PC	\$/t	40,50,60	
Fuel Cost, CC	\$/bbl		20, 30
Transport cost	\$/t, (or \$/bbl)	35	(0.5)
Desulphurisation cost	\$/t	100	N/A
Add. transportation cost	\$/t	15	N/A

6.1. Desalination cost calculations

This study was basically carried out with the purpose of making cost comparisons between nuclear and fossil energy sources, with selected desalination processes such as the MED, RO and RO with preheating (with a special version of the DEEP code, developed by CANDESAL), and for particular geographic areas and economic conditions.

The main parameters, used as input in DEEP, are presented in Table 11. Power plant related costs are those calculated by SEMER.

Table 11
Input parameters for desalination cost evaluation

Parameter	PWR-900	AP-600	PC600	CC700
Net power output (MWe)	951	610	620	700
Thermal efficiency (%)	33	33	39	51
Number of units	1	1	1	1
Planned outage	0.13	0.10	0.10	0.10
Unplanned outage	0.11	0.11	0.11	0.11
Plant economic life (y)	60	60	30	25
Specific construction cost (\$/kW)	1263	1579	1336	565
Const. lead time (months)	60	48	36	24
Discount/Interest rate (%)	5 - 8 and 10			
Specific O&M cost (\$/MW·h)	6.8	8.1	3.9	3.1
Specific decom. cost (\$/MW·h) for DR=5,8,10%	1.48, 2.44, 3.18	1.75, 2.83, 3.66	N/A	N/A
Air inlet temperature (°C)	N/A	N/A	N/A	25
Fossil fuel cost (\$/t or \$/bbl)	N/A	N/A	40, 50, 60	20, 30

6.2. Desalination cost results

6.2.1. Results for MED

These are graphically illustrated in Figures 14 and 15 for the MED process, coupled to the nuclear power plants and the fossil fuelled plants. Results are shown without the backup heat source effect.

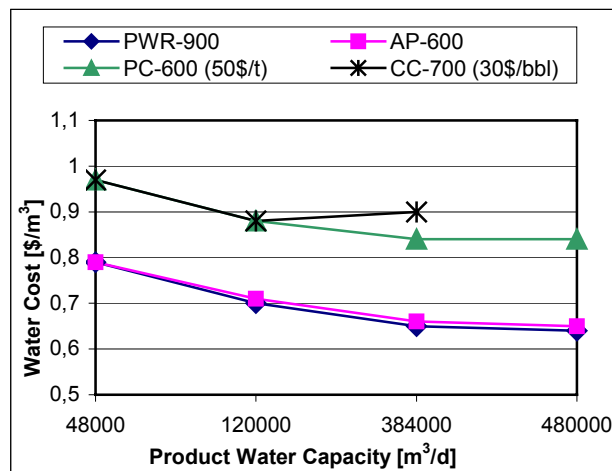
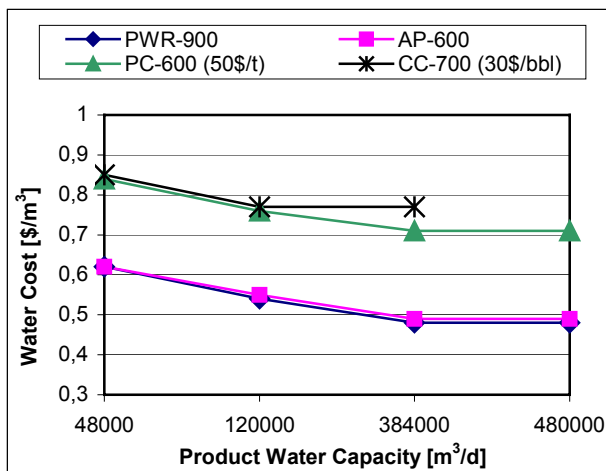


Figure 14: Results with MED: discount rate= 5%; Figure 15: Results with MED: discount rate = 8%;

- The results confirm the expected **size effect**. As desalination capacity is increased, desalination costs are reduced, independent of the type of power plant. This is shown in figures 15 and 16. Thus for example, for 5% discount rate, when desalination capacity is increased from a relatively «low» capacity of 48 000 m³/day to a «high» capacity of 384 000 m³/day, (a factor of 8), the corresponding costs are reduced by about 23% for the PWR-900 or the AP-600, about 15% for the PC and about 9% for the CC.
- The two nuclear plants, with almost the same water costs, are by far the cheapest options for desalted water production. At 5% discount rate, and compared to the PC and CC plants, the nuclear options are respectively about 37 and 35% lower at the low capacity. At the high capacity, corresponding values are 48 and 60%.

6.2.2. Results for RO

These are presented in Figures 16 and 17, which show about the same tendencies as the MED case :

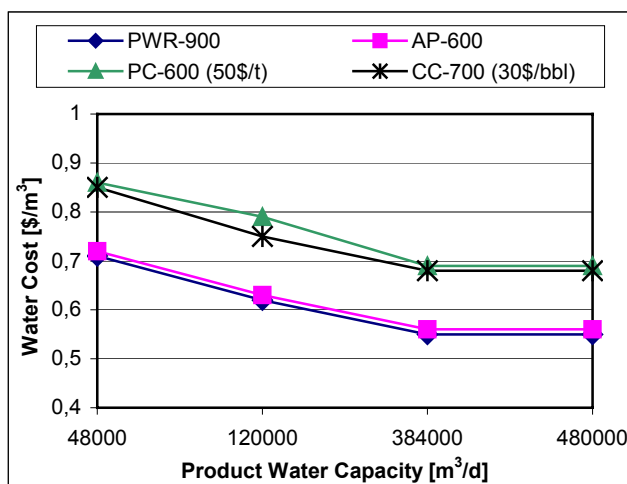
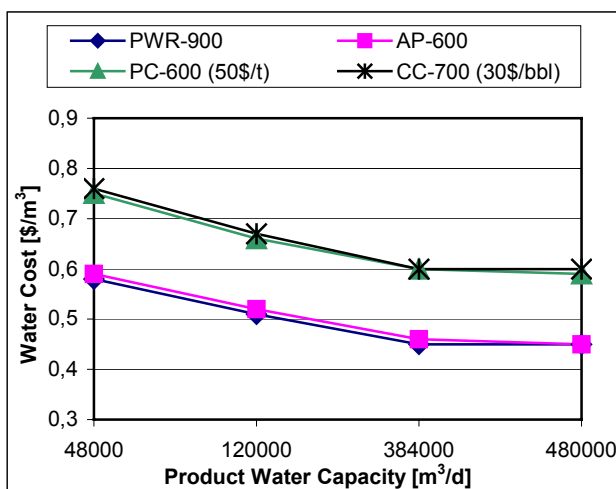


Figure 16: Results with RO; discount rate= 5%

Figure 17: Results with RO; discount rate= 8%

- Overall desalination costs are significantly lower than the MED process for any water capacity or discount rate. Thus, for 5% discount rate and the CC case, at the lowest capacity (48 000 m³/d), the relative difference between RO and MED costs is about 12%. For the high capacity (384 000 m³/d) this difference is about 28%. Similar conclusions can be inferred for other energy sources.

- The economics and the choice of one or the other desalination process would be determined not only by these differences but also by the usage that one hopes to make of the product water. The RO process satisfies WHO standard easily and provides drinking water with about 500 ppm residual salinity, which adds a good taste to it. The MED process provides pure water which can satisfy any standards. Such a water can be directly used in industrial processes, but will have to be « post treated » to give an acceptable taste to the water for drinking.

- Results of a Sensitivity Study with TDS=41000 ppm, designed to simulate the southern Mediterranean region, show that the overall effect of increased salinity, compared to the results in Figures 16 and 17, is a slight increase in desalination costs for all energy sources.

6.2.3. Results for ROph

The desalination costs calculations for RO, with the preheating of the feed water were performed with a special version of the DEEP code, developed by CANDESAL. This version currently works for only nuclear options. Results are presented in Figure 18 for 5, 8 and 10% discount rates.

It is observed that ROph, indeed, is the least expensive solution in terms of specific desalination costs : for the 5% discount rate, ROph gives water costs about 2 to 7% lower than the traditional RO at high and low capacities. It should be recalled that this gain is without design and system optimisation.

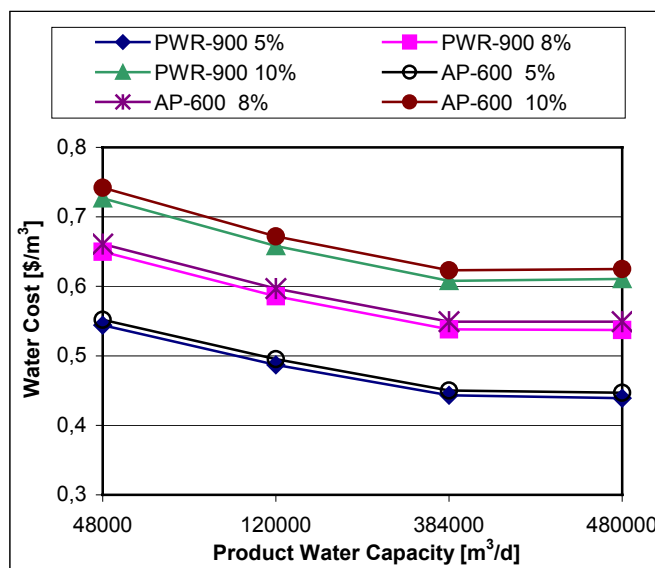


Figure 18: Desalination with ROph and nuclear power plants for different discount rates.

6.3. Comparison of nuclear and fossil energy based systems

It was shown in figures 14 and 15 (or 16 and 17) above, that for standard recommended fuel costs for the PC (50 and 60 \$/t) and the CC (30\$/bbl), the nuclear desalination options were significantly cheaper. We consider the standard fuel prices combined with discount rates of 5 and 8% as the scenario which may intrinsically favour the nuclear option, (the S_N scenario).

For objective comparison of nuclear versus fossil options, we also made calculations for the case in which the fuel prices were low (40 \$/t for PC and 20 \$/bbl for CC) and the discount rate was 10%. Clearly, this scenario would rather favour the fossil energy based desalination option, (the S_F scenario). Results of calculations are given in Figure 19 for both MED and RO.

A quick inspection of this figure shows that although the large differences between the water costs by nuclear and fossil options have been reduced, the nuclear option remains still competitive as compared to the CC or PC. Thus in the lowest capacity and the MED case, the difference between nuclear (PWR-900) and the PC is about 15%. For CC, this difference is about 7%. For the higher capacity case, the nuclear option is respectively about 16 and 20% lower than the CC and PC options.

Similar conclusions can be drawn in the RO case. Thus the difference in desalination costs, compared to the PC is about 14% lower for the nuclear option at the capacity of 48 000 m³/d and for a discount rate of 10%. Compared to the CC, at this capacity, the nuclear option gives 7% less desalination cost. For the high capacity, (384 000 m³/d), the nuclear option is respectively 17 and 9% lower, compared to the desalination costs with the PC and CC.

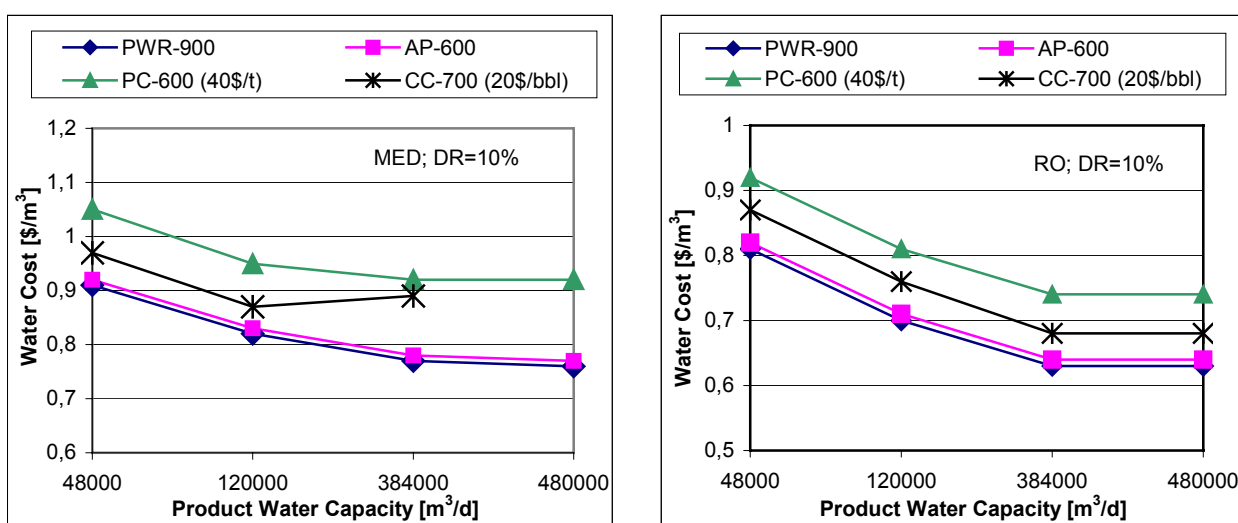


Figure 19: Comparison of nuclear and fossil options for desalination with MED and RO; low fossil fuel prices and discount rate=10%

6.4. Comparison of nuclear options with different desalination processes

The water costs from the MED, RO and ROph are compared in Figure 20 for 5 % discount rate and for the PWR-900. This figure confirms, that the desalination cost with ROph is 14% lower than that with the MED, at low capacity. This difference is 7% when compared to the desalination cost with traditional RO.

At high capacities, desalination cost with ROph is 8% lower compared to that with MED. It is only 2% lower compared to traditional RO. It is noted that these results are without

taking into account the benefits of design and system optimisation, which would increase the differences between traditional RO and ROph. These differences also increase as discount rates are increased.

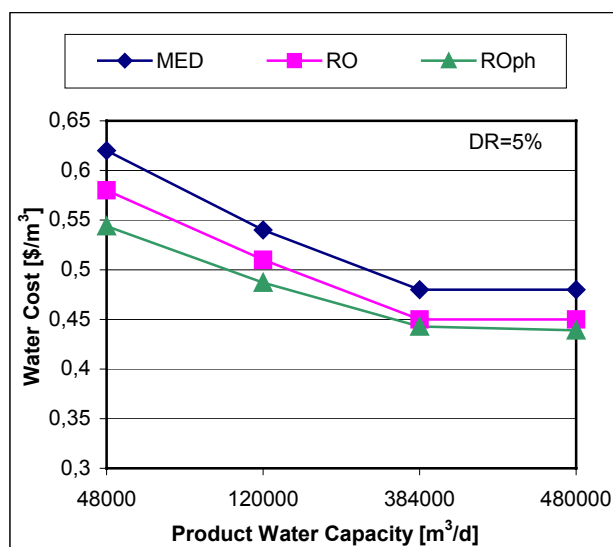


Figure 20: Desalination costs with MED, RO, ROph, coupled to PWR-900

6.5. Desalination with renewable energy based systems

With nuclear energy, renewable energy based systems for electricity, and for desalination, appear to have the greatest potential for carbon-free sustainable development.

Renewable energy systems have been handicapped in the past by their intrinsic low power density and intermittent nature. Proposed solutions have had thus systematically rather very high costs.

With the continuous innovations made in this field, which have already led to considerable cost reductions, it seemed logical to us to include the renewable energy source based desalination in our comparative studies.

We do not yet dispose of adequate models in SEMER or in DEEP to treat the case of renewable energy sources. Evaluations are being made separately, using some partial results in the published literature (Riberio, 1996, and Templitz-Sembitsky, 2000) for Solar Thermal (ST) and Solar Photo-voltaic (PV), and Wind (W) energy based systems coupled to MED and RO processes. First results, IRRADIARE, 2002) are presented in Table 12.

Table 12
Cost of the m³ of water produced

System	Amort. + M&O (\$ / m³)		Energy (\$ / m³)		Total (\$ / m³)*	
	Min	max	min	max	min	max

	Amort. + M&O (\$ / m ³)		Energy (\$ / m ³)		Total (\$ / m ³)*	
MED + ST + SP	0.27	0.81	2.69	6.91	2.97	7.72
RO + SP	0.31	0.85	1.52	3.65	1.83	4.5
RO + W	0.31	0.85	0.20	0.52	0.51	1.37

* 1 euro = 0.98 \$; without land acquisition cost and "intermittence" penalty

This table shows that, despite very favourable assumed conditions (large sized plants benefiting from the size effect, availabilities of the same order of magnitude as other energy sources, exclusion of land acquisition costs etc.), the desalination costs remain still an order of magnitude higher than the fossil or nuclear energy based systems, except for desalination by the wind energy whose costs approaches that of nuclear or fossil fuelled systems. **However, when account is taken of the land acquisition costs and of the intermittent nature of renewable energies (through interim storage of the water produced), these costs could be about two to three times higher.**

6.6. Summary of economic assessment

In order to facilitate a quick comparison of the desalination costs, all the results of desalination costs with nuclear (AP-600 and PWR-900), fossil (PC-600 and CC-700) and renewable (ST, PV and W) energy based systems, coupled to desalination processes (MED, RO and ROph), are summarised in Table 13.

Table 13

Summary of desalination costs (\$/m³) evaluations for given desalting capacities and for discount rates of 5, 8 and 10%.

Capacity		Costs with MED			Cost with RO			Costs with ROph			Cost of Net Saleable Power		
System↓	(m3/day)	5%	8%	10%	5%	8%	10%	5%	8%	10%	5%	8%	10%
PWR-900	48000	0,62	0,79	0,91	0,58	0,71	0,81	0,544	0,65	0,727			
	120000	0,54	0,7	0,82	0,51	0,62	0,7	0,487	0,586	0,658	0,023	0,030	0,035
	384000	0,48	0,65	0,77	0,45	0,55	0,63	0,443	0,538	0,608			
AP-600	48000	0,62	0,79	0,92	0,59	0,72	0,82	0,552	0,661	0,742			
	120000	0,55	0,71	0,82	0,52	0,63	0,71	0,495	0,597	0,672	0,026	0,033	0,039
	384000	0,49	0,66	0,78	0,46	0,56	0,64	0,45	0,549	0,623			
CC-700	48000	0,85	0,97	1,05	0,76	0,85	0,76	N/A	N/A	N/A			
	120000	0,77	0,88	0,95	0,67	0,75	0,67	N/A	N/A	N/A	0,055	0,057	0,058
	384000	0,77	0,9	0,99	0,6	0,68	0,6	N/A	N/A	N/A			
PC-600	48000	0,84	0,97	1,07	0,75	0,86	0,94	N/A	N/A	N/A			
	120000	0,76	0,88	0,98	0,66	0,79	0,83	N/A	N/A	N/A	0,058	0,063	0,067

	384000	0,71	0,84	0,94	0.6	0,69	0,77	N/A	N/A	N/A
PV+ST*	10 000	Min 2.97 Max 7.72								
SP	10 000				Min 1.83 Max 4.5					
Wind*	10 000				Min 0.51 Max 1.37			-	-	

* On the basis of 1 euro = 0.98 \$; without land acquisition cost and "intermittence" penalty

An idea of the performances of the different integrated systems can be obtained from Table 14.

Table 14
Performance Characteristics of different integrated systems for a net capacity of 120 000 m³/day

System	Feed Water Required (kg/s)			Energy Consumed (MWth and/or MWe)			Net Saleable Electricity (MWe)		
	MED	RO	ROph	MED	RO	ROph	MED	RO	ROph
PWR-900	10 409	2 778	3 855	220.6 MWth 7.0 MWe	21.3 MWe	24.6 MWe	925	929.7	926.4
AP-600	10 400	2 778	3 855	220.4 MWth 7.0 MWe	21.3 MWe	24.6	584.6	588.7	585.4
CC700	10 796	2 778	N/A	228.8 MWth 5.7 MWe	21.3 MWe	N/A	591.2	597.4	N/A

PC600	10 796	2 778	N/A	228.8 MWth 5.6 MWe	21.3 MWe	N/A	592.7	598.7	N/A
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7. Conclusions

This report summarises our recent investigations as regards the technical and economical assessment of desalination, under the EURODESAL project, currently being carried out by a consortium of European and Canadian industrials and R&D organisations.

Detailed results are presented for two nuclear systems (the PWR-900 and the AP-600, respectively representing an existing large sized plant and an innovative medium sized plant), two fossil energy based systems (Pulverised coal, PC600, and Gas turbine combined cycle plant, CC700). These energy sources are coupled to three desalination processes : the Multiple Effect Distillation (MED), the Reverse Osmosis (RO) and the innovative Reverse Osmosis, with feed water preheating (ROph). The nuclear reactor GT-MHR has also been considered but its economic evaluation has not yet been completed. However, some results from a preliminary independent study have been included in the discussion. Similarly, a first comparison has also been made to evaluate the interest of renewable energy based systems for low capacity desalination.

The results obtained lead to the following conclusions :

- For PWRs, the most economic coupling scheme is the so called “conventional scheme”, utilising vapour directly extracted from the turbine blades. Coupling an MED plant via the condenser, with a view to utilise waste heat, offers the highest water production possibilities but results in a substantial loss of electrical power. This option may, therefore, be suitable for small or medium sized reactors which provide an optimal water to electricity production ratio.
- The optimal solution for a GT-MHR would be an MED coupling through an intermediate water loop and adopting a heat run-out scheme with 2 temperature steps (two lines in parallel). With such a scheme, GT-MHR would produce about 43 000 m³/day of desalted water with virtually “free” heat energy.
- There are no safety problems related to any specific coupling scheme. All couplings investigated maintain the same number of static safety barriers against any radioactive contamination as those in the nuclear plant itself. The only design requirements are that 1)- the desalination feed-water suction line should be placed upstream of any waste liquid discharge point and 2)- adequate surveillance and monitoring of any radioactive contamination and/or storage of the product water is a necessary condition.
- Modularisation of the desalination plant considerably reduces the feedback impact on nuclear plant safety of any transients originating in the desalination system in incidental or accidental conditions.
- As regards nuclear desalination economics, all combinations of energy sources and desalination processes show a significant size effect with increased desalination capacities. Thus for example, for the 5% discount rate and MED coupling, when desalination capacity is increased from 48 000 m³/day to 384 000 m³/day, (a factor of 8), the corresponding costs are reduced by about 23% for the

PWR-900 or the AP-600, about 15% for the PC and about 9% for the CC

- In a scenario, with low discount rates (5 and 8%) and recommended fuel prices, the two nuclear options (which give analogous results among themselves), coupled to MED, are by far the cheapest, compared to desalination with fossil energy based systems. Thus, for 5% discount rate, the desalination cost from nuclear systems are respectively 37 and 35% lower for a desalination capacity of 48 000 m³/d, as compared to the PC and CC. This difference is about 48 and 60% at higher desalination capacities (e.g. 384 000 m³/d).
- In a scenario, considered to favour the fossil energy based options, (10% discount rate, lower fuel prices) the desalination costs by the PWR-900 and AP-600, coupled to MED are still competitive, although the differences in costs are much lower: about 7 to 15% compared to desalination with CC and PC at low capacity (48 000 m³/d).
- Comparable first result for the GT-MHR (maximum desalted water capacity of 41 000 m³/d), notwithstanding the uncertainties of cost evaluations, show that the difference in desalination costs from GT-MHR and fossil energy based systems could be of the order of 60 to 100%, if it is assumed that heat in the GT-MHR is freely available. Otherwise, the desalination costs from the GT-MHR would be comparable to those by other nuclear options.
- Whatever the energy source, desalted water capacity, or the discount rate, the costs (\$/m³) with the RO system are much lower (12 to 28%) as compared to the MED process. However, the later process produces pure water as compared to product water with about 500 ppm TDS in the RO, (which is acceptable, according to WHO standards for drinking water). Comparison of desalination costs with nuclear and fossil energy sources, coupled to RO and in conditions favouring the fossil energy systems (10% discount rate, low fossil fuel prices) shows that the nuclear options still remain very competitive. Thus the difference in desalination costs, compared to the PC is about 14% lower for the nuclear option at the capacity of 48 000 m³/d. Compared to the CC, at this capacity, the nuclear option gives 7% less desalination cost.
- ROph further reduces the water costs with the nuclear options by about 7 to 15%, as compared to desalination with traditional RO or MED. With design and system optimisation, the costs from ROph could be further reduced.
- Renewable energy based systems such as Solar Thermal (ST) and Solar photovoltaic (PV), give an order of magnitude higher energy and desalination costs even in the most favourable conditions. The desalination costs from Wind, are already competitive for small, isolated communities such as small islands or remote non-electrified communities. Besides, the costs may come down as these technologies mature in time and desalting capacities are increased and when mass production of components is undertaken.

Acknowledgements

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References

- Alessandroni, C., Cinotti, L., Mini, G., Nisan, S., 2002
Safety Aspects of Nuclear Desalination with Innovative Systems ; the
EURODESAL Project. ICAPP Meeting, Hollywood, Florida USA, (June 10-13)
- Bandelier, Ph., 2000
Production of Fresh water using the waste heat from a GT-MHR
(Internal CEA/GRETH Note, N°00/693)
- Buros, O.K., 1990
"The desalting ABC's", Research Department, Saline Water Conversion
Corporation of Riyadh, (Saudi Arabia).
- Caruso, G., Naviglio, A., Nisan, S., Asuar, O., Bielak, B., Humphries, J.R.,
Martins, N., 2002 Optimal Coupling of a Thermal Reactor and a Thermal
Desalination Plant.
ICAPP Meeting, Hollywood, Florida USA (June 10-13)
- Gowin, P., Konishi, T., 1999
Nuclear Desalination - IAEA Activities and Economic Evaluation for Southern
Europe, Desalination **126**, 301
- GT-MHR, 1999
International GT-MHR Project Design Review,
St. Germain-en-Laye (France), (June 28-30)
- IAEA, 1996,
AP-600 reactor System Description and Development Status
TECDOC N° 881
- IAEA, 1992,
Technical and Economic Evaluation of potable water Production through
Desalination of Seawater by Using Nuclear Energy and Other Means
TECDOC N° 666
- Humphries, J.R., Davies, K., Ackert, J., 2002
An Advanced Reverse Osmosis Technology for Applications in Nuclear
Installations
ICAPP Meeting, Hollywood, Florida, USA (June 10-13)
- Khan, A. H., 1986
Desalination Processes and Multistage Flash Distillation Practice" Elsevier
- Lecompte, M., Bandelier, Ph., Bielak, B., 2002
Int. Conf. On nuclear desalination, Marrakech, (October 16-18)
- Naviglio, A., Caruso, G., 2002
Preliminary Safety Assessment of the Coupling of a GT-MHR with a Desalination
Plant. EURODESAL report
- Nisan, S., Rouyer, J.L., Marcetteau, P., Duflo, D., 2002
SEMER: A simple code for the economic evaluation of nuclear and fossil energy
based power production systems. (To appear).
- Riberio, J., 1996
Desalination Technology, Survey and Prospects
Fian Report, IPTS-European Commission Joint Research Centre, EUR
1643-EN,
- Templitz-Sembitsky, W., 2000
The Use of Renewable Energies For Sea Water Desalination- A Brief
Assessment Technical Information, W16e, GATE Information Service, Germany.

