The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific and
Cultural Organization

IAEA
International Atomic Energy Agency

2141-21

Joint ICTP-IAEA Workshop on Nuclear Reaction Data for Advanced Reactor Technologies

3 - 14 May 2010

Nuclear Desalination

KHAMIS I.

IAEA
Vienna
AUSTRIA

Strada Costiera 11, 34151 Trieste, Italy - Tel.+39 040 2240 111; Fax +39 040 224 163 - sci_info@ictp.it

Nuclear Desalination

I. Khamis

Department of Nuclear Energy, IAEA

Contents

- Introduction
- Aspects of nuclear desalination
- Summary of IAEA activities
- Conclusion

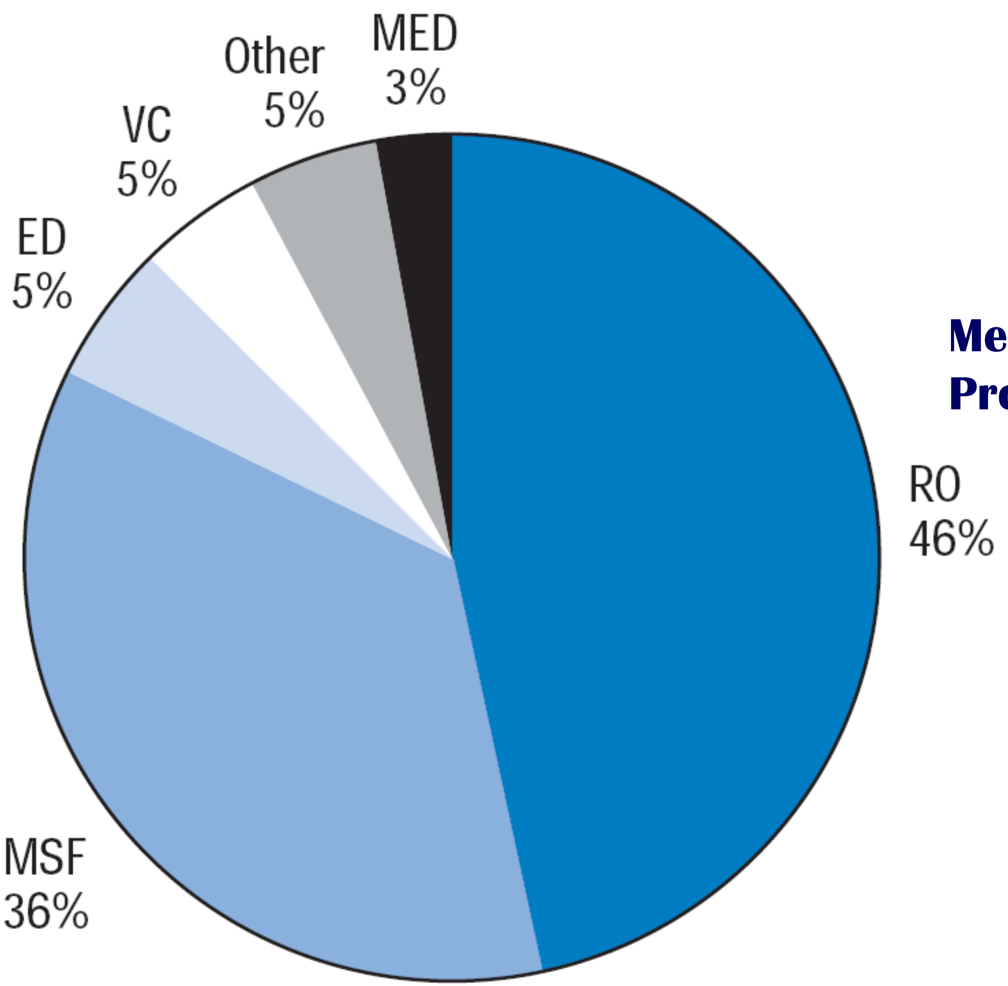
Growing interest in desalination systems

- **Desalination capacity is growing exponentially**
- **Current estimates are 60 million cubic meters of water production per day**

+ 60 Newcomer

- **50% Gulf region**
- **17% N. America**
- **10% Asia**
- **8% N. Africa**
- **7% Europe**
- **1% Australia**

Desalination Technologies

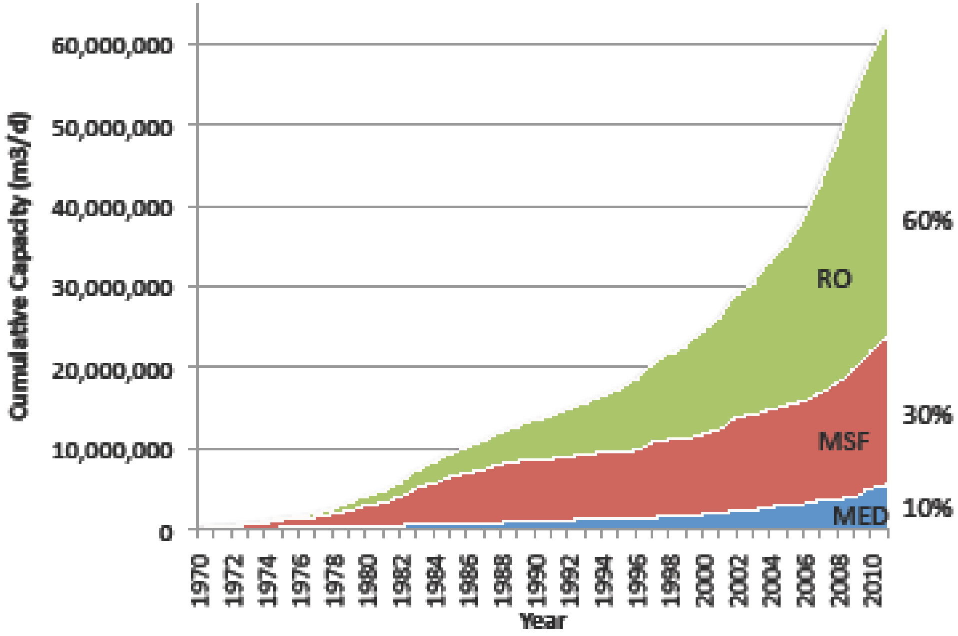


Membrane Processes 51%

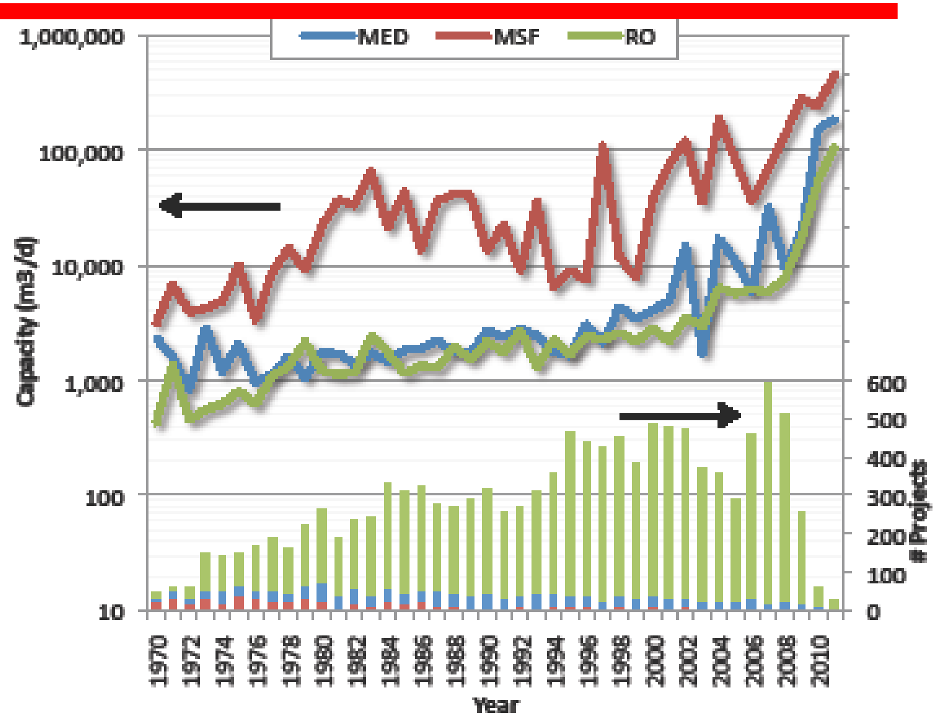
Distillation Processes 49%

Source: Wangnick/GWI. 2005.

Current trends of Desalination



Cumulative contracted capacity



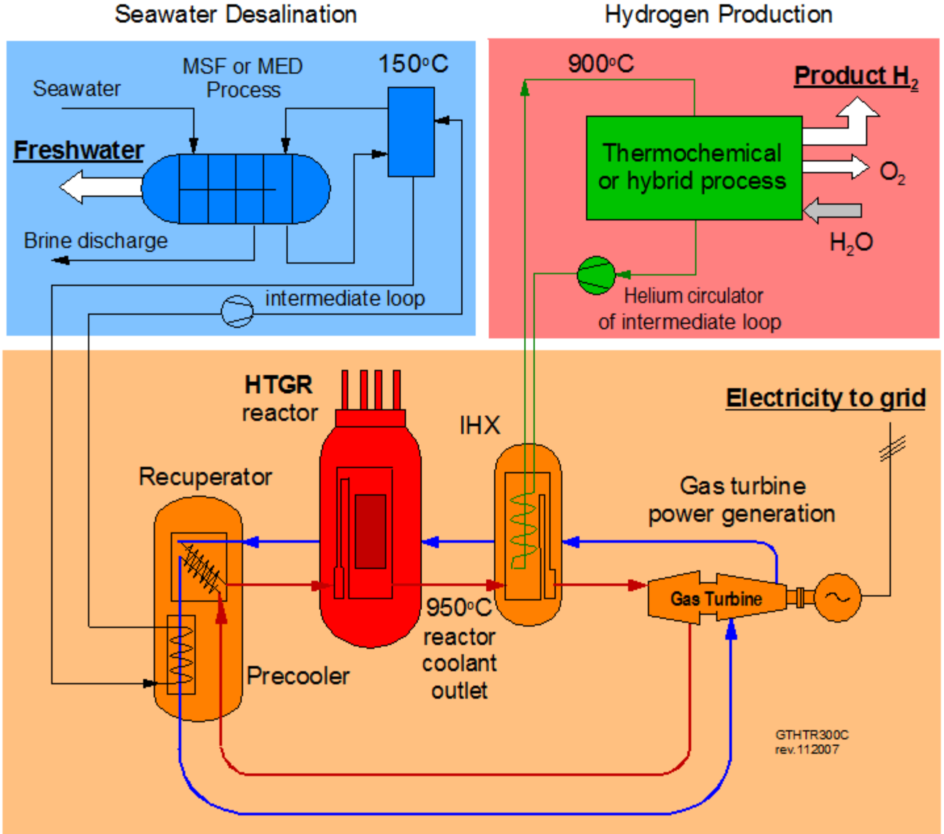
Average capacity per project and number of projects contracted for each type of desalination plant

Nuclear desalination is an inevitable option to alleviate:

- ***Need for water,***
  - ***Environmental impacts,***
    - ***High oil prices.***

Preferred option?

✓Cogeneration



✓Small & Medium Reactors

99% of the industrial users need power less than 300 MWth

Characteristics of the Nuclear Desalination

✓Sound technically and economically

✓Available experience:

- **No. of reactors:** 13
- **No. of countries with experience:** 4
- **Tot. reactor-years:** 250

Evaporators at Aktau, Kazakhstan

✓*Innovations* to make ND more viable

Nuclear Desalination Experience

Plant name	Location	Gross power [MW(e)]	Water capacity [m³/d]	Reactor type/ Desal. process
Shevchenko	Aktau, Kazakhstan	150	80000 – 145000	FBR/MSF&MED
Ikata-1,2	Ehime, Japan	566	2000	LWR/MSF
Ikata-3	Ehime, Japan	890	2000	LWR/RO
Ohi-1,2	Fukui, Japan	2 x 1175	3900	LWR/MSF
Ohi-3,4	Fukui, Japan	1 x 1180	2600	LWR/RO
Genkai-4	Fukuoka, Japan	1180	1000	LWR/RO
Genkai-3,4	Fukuoka, Japan	2 x 1180	1000	LWR/MED
Takahama-3,4	Fukui, Japan	2 x 870	1000	LWR/RO
NDDP	Kalpakkam, India	2 x 170	1800	PHWR/RO
Diablo Canyon	San Luis Obispo, USA	2 x 1100	2180	LWR/RO

Public acceptance of nuclear desalination

- safety

- public health

-environmental impacts

Safety of Nuclear Desalination

Safety level of ND

Safety issues of ND are similar to NPP

- Safety: mainly dependent of nuclear plant, the design of coupling technology, and transient interactions between the two plants.

- Additional **specific safety considerations** for the coupling schemes between the reactor and the desalination plant (DP):

- Issues related to environment, shared resources, and siting…etc.

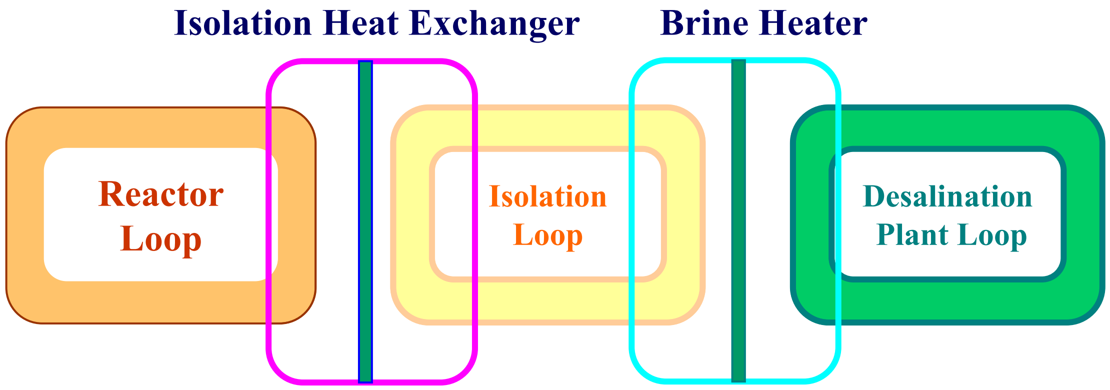
Safety in nuclear desalination

Usual safety barriers are:

- Fuel matrix
- Fuel cladding
- Primary circuit
- Reactor containment system

• Coupling through ***additional HX*** i.e. increase in the number of usual safety barriers that are standard in a NPP.

COUPLING



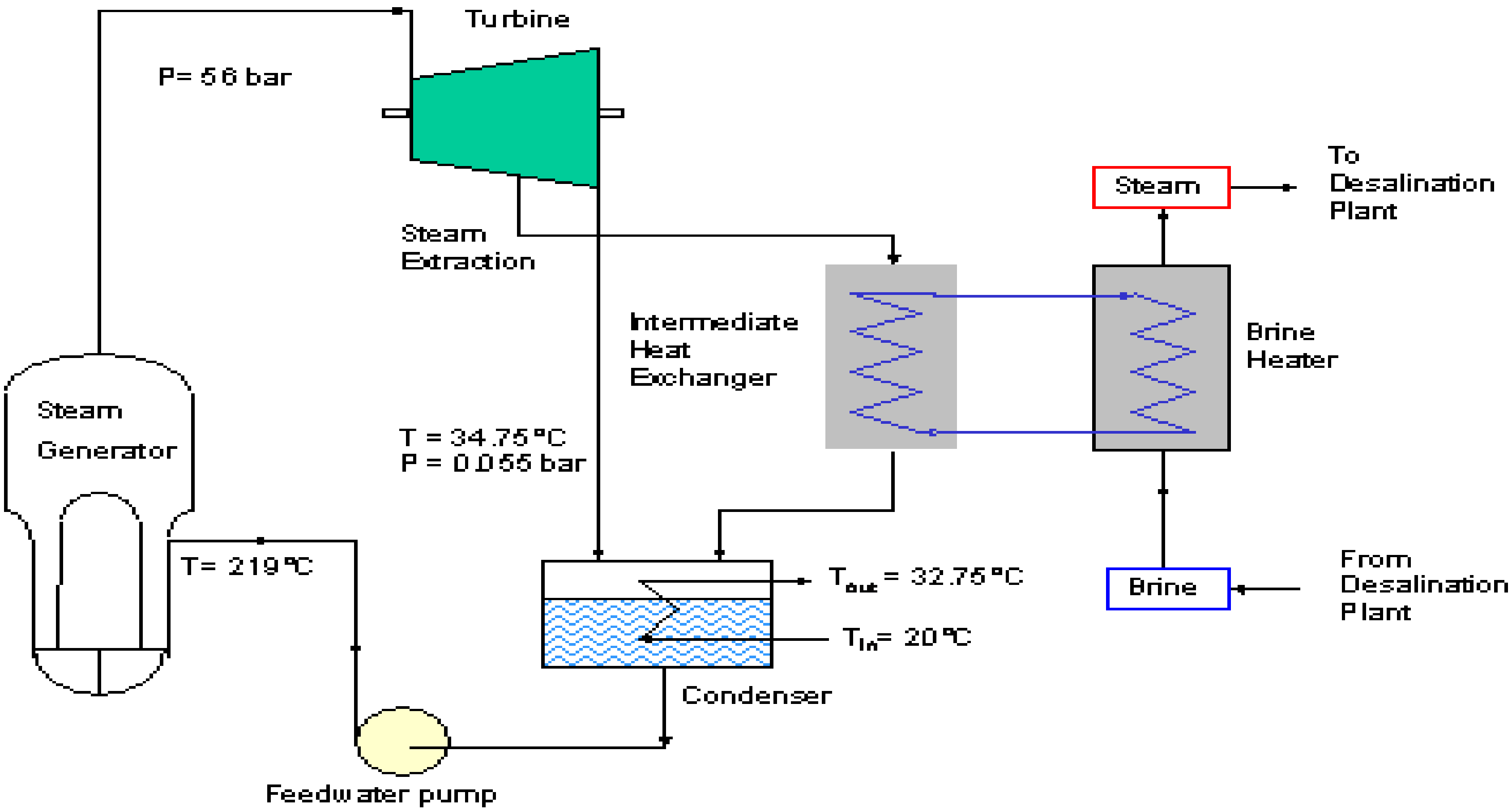
Coupling dictates **specific safety considerations** :

- **Prevent the transfer of radioactive materials from NPP to DP**
- **Minimize the impact of thermal desalination system on the nuclear reactor**

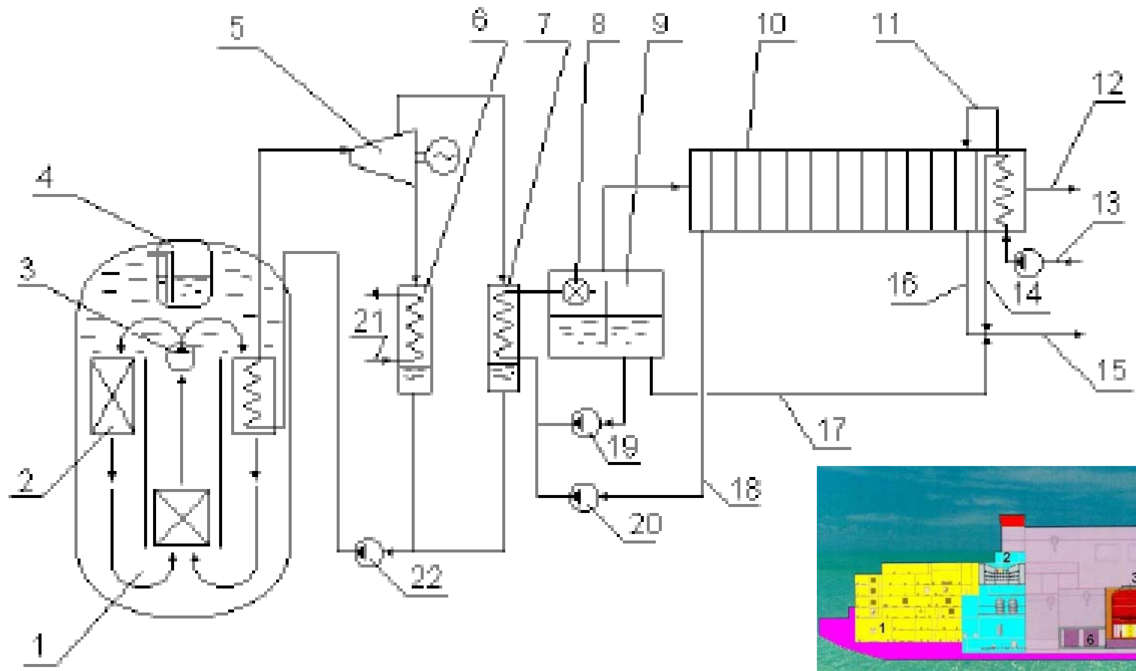
Provision for coupling

- Existing and planned nuclear power stations could be used to produce fresh water using the surplus of
  - Waste heat
    - MED desalination plants
      - GT-MHR, through a flash tank using intercoolers reject heat
      - HRT, using steam extractions
      - PWR, using low pressure steam extraction
      - AP1000, using condenser reject heat
      - FPU, using condenser reject heat
    - through MSF desalination plants
      - BWR, through a flash tank using turbine steam extractions
  - Electricity
    - though RO desalination plants
      - Any plant (e.g., CANDU-6)
  - A combination of heat and electricity
      - PHWR: steam extraction to MSF and electricity to RO

Coupling PWR with MED



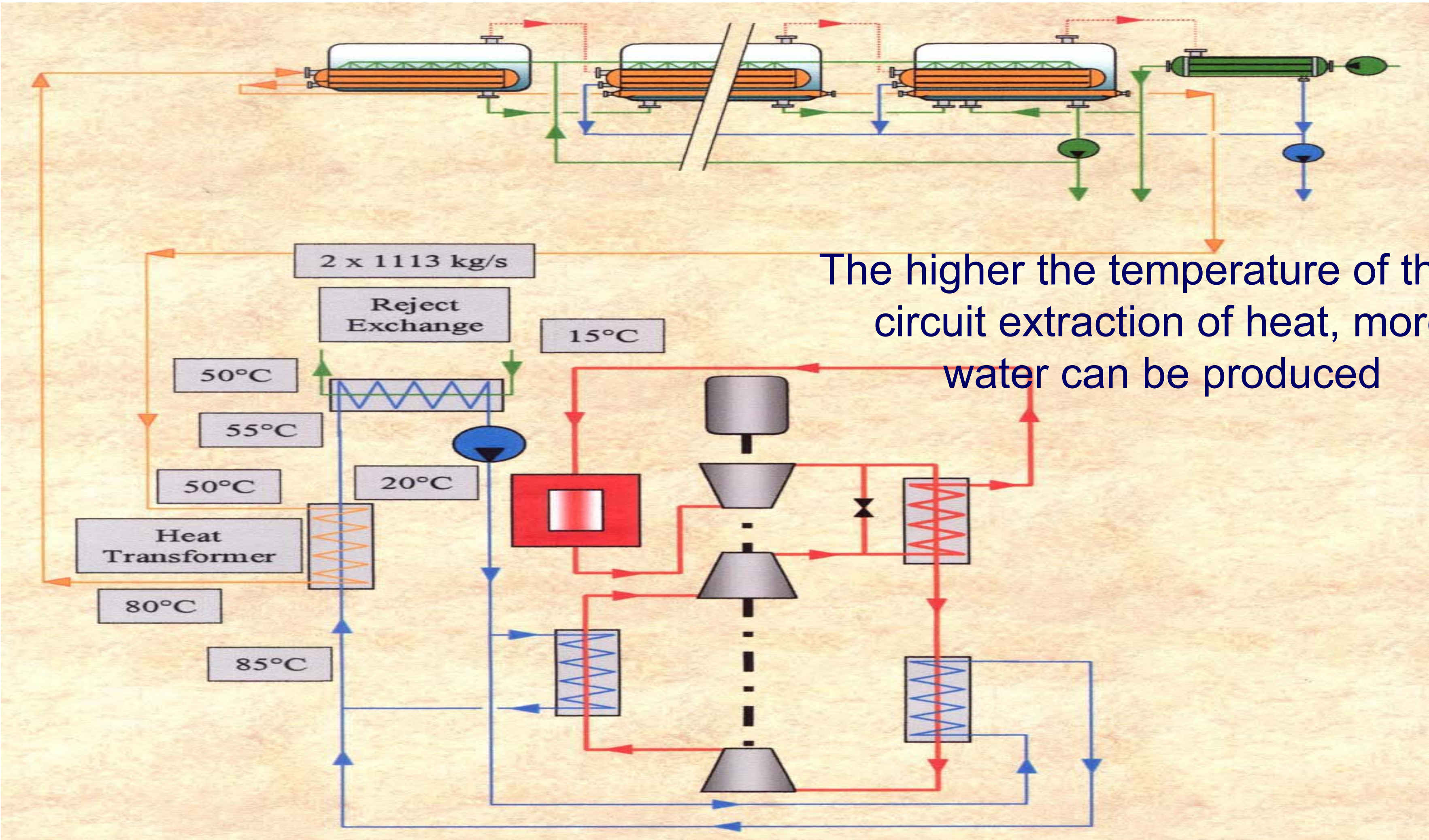
Coupling of Floating Power unit FPU and MED



1 – nuclear reactor; 2 – steam generator; 3 – primary pump; 4 – pressurizer; 5 – turbogenerator; 6 – turbine condenser; 7 – condenser-heat exchanger of distillation plant; 8 – throttle; 9 – flash tank; 10 – multi effect distillation plant; 11 – feed makeup; 12 – product water; 13 – seawater intake; 14 – reject cooling water; 15 – brine outfall; 16 – brine discharge; 17 – flash tank blowdown; 18 – preheated water makeup; 19 – intermediate recirculation pump; 20 – makeup pump; 21 – cooling seawater; 22 – feed pump

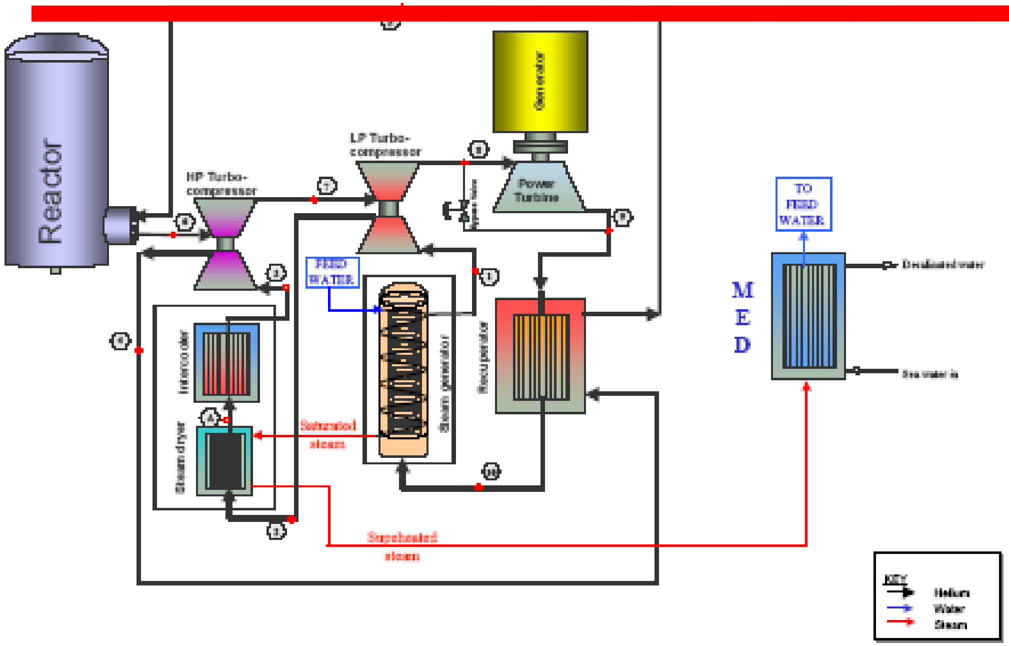
*Floating Power Unit, Modular Reactor Russian pressurized water of 2 x 150 MW

Coupling of the GT-MHR to MED



The higher the temperature of the circuit extraction of heat, more water can be produced

HTR – MED (Spain)



HTR / Desalination Process Coupling Scheme

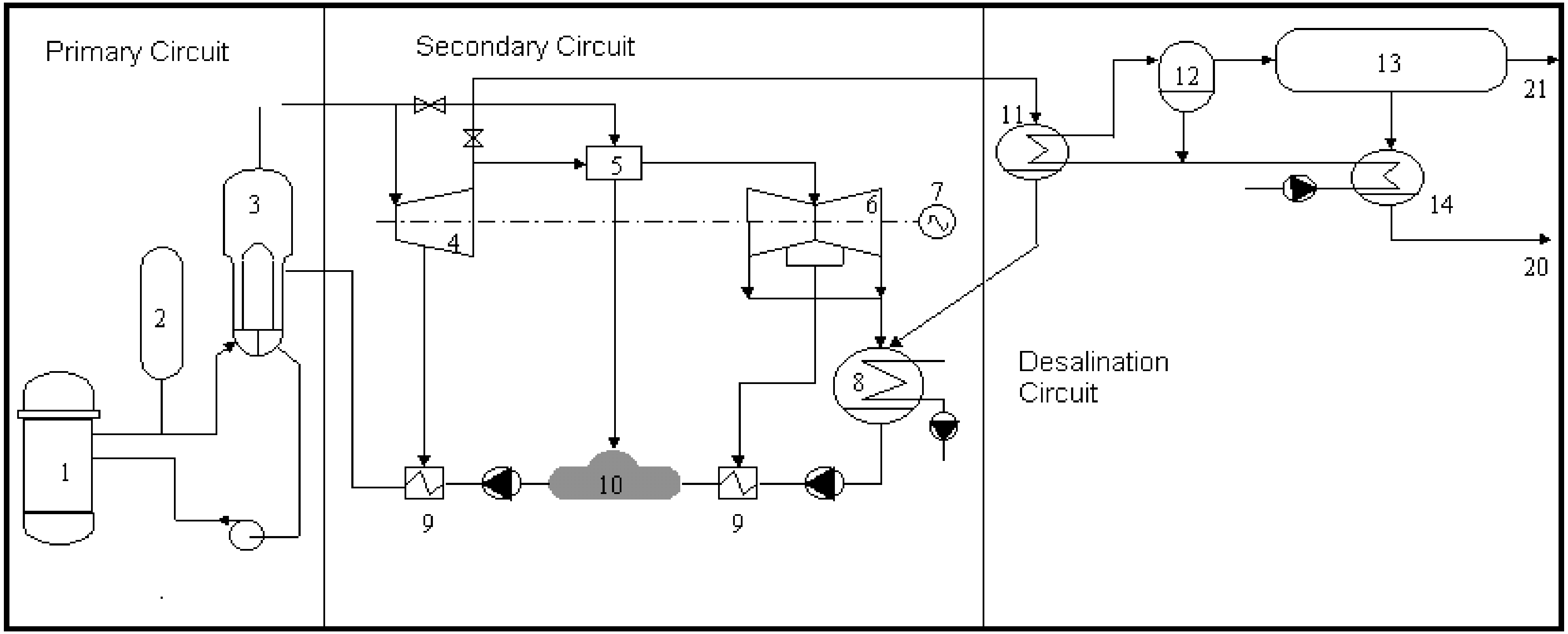
HTR coupled to MED Results (similar results for MSF)			
Steam interface data HTR to MED	35.8 kg/s	70ºC	0.3 bar
Desalinated water produced	27200 m^3/day (~ 90 Hm^3/year)		
Electric power produced	122 MWe		

Proposed Scheme

1 HTR unit coupled with MED or MSF plant

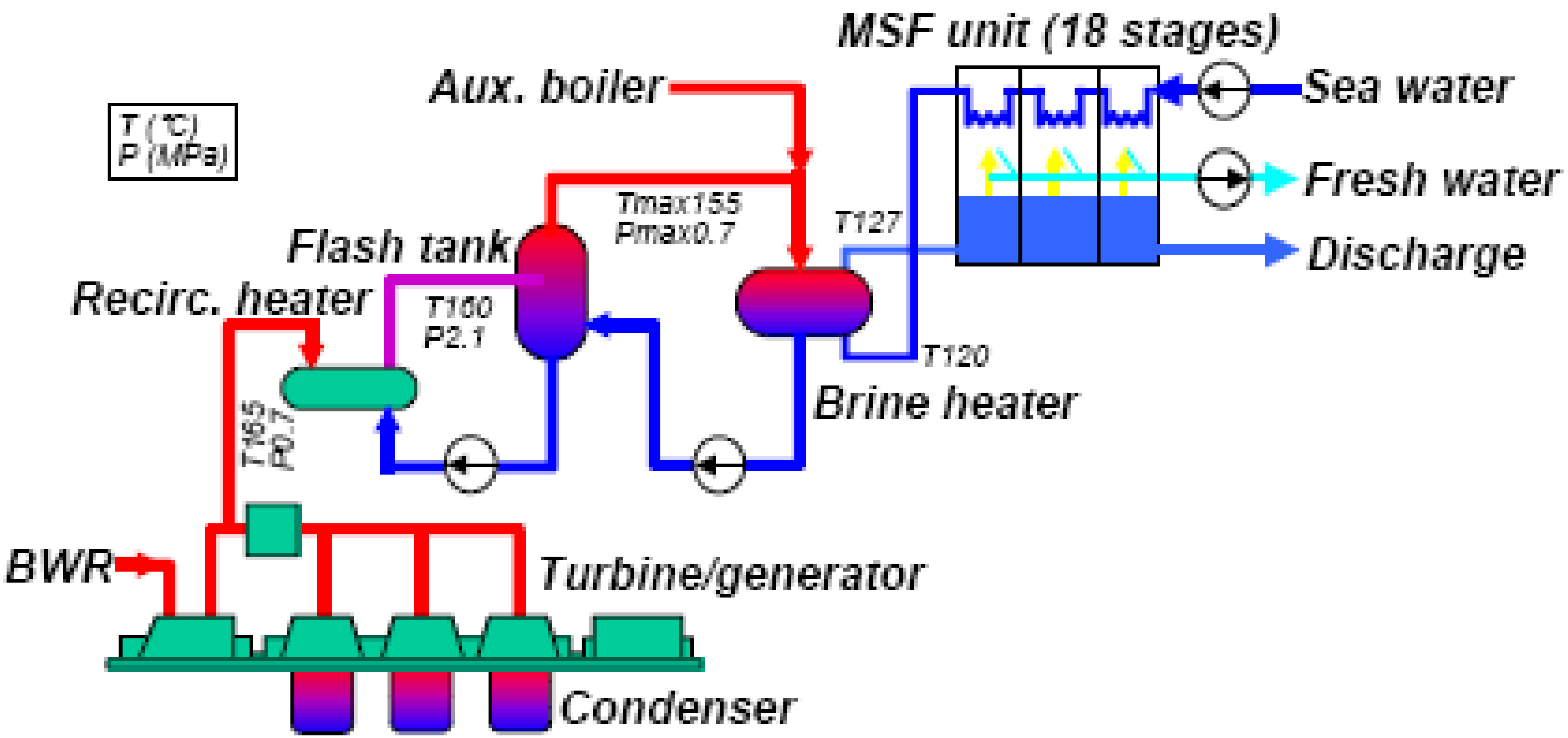
- Typical water and electricity demand for a middle-sized town (population ≈ 50.000)
- Water production and efficiency improves using excess of electricity for RO plant

AP1000 to MED through the condenser

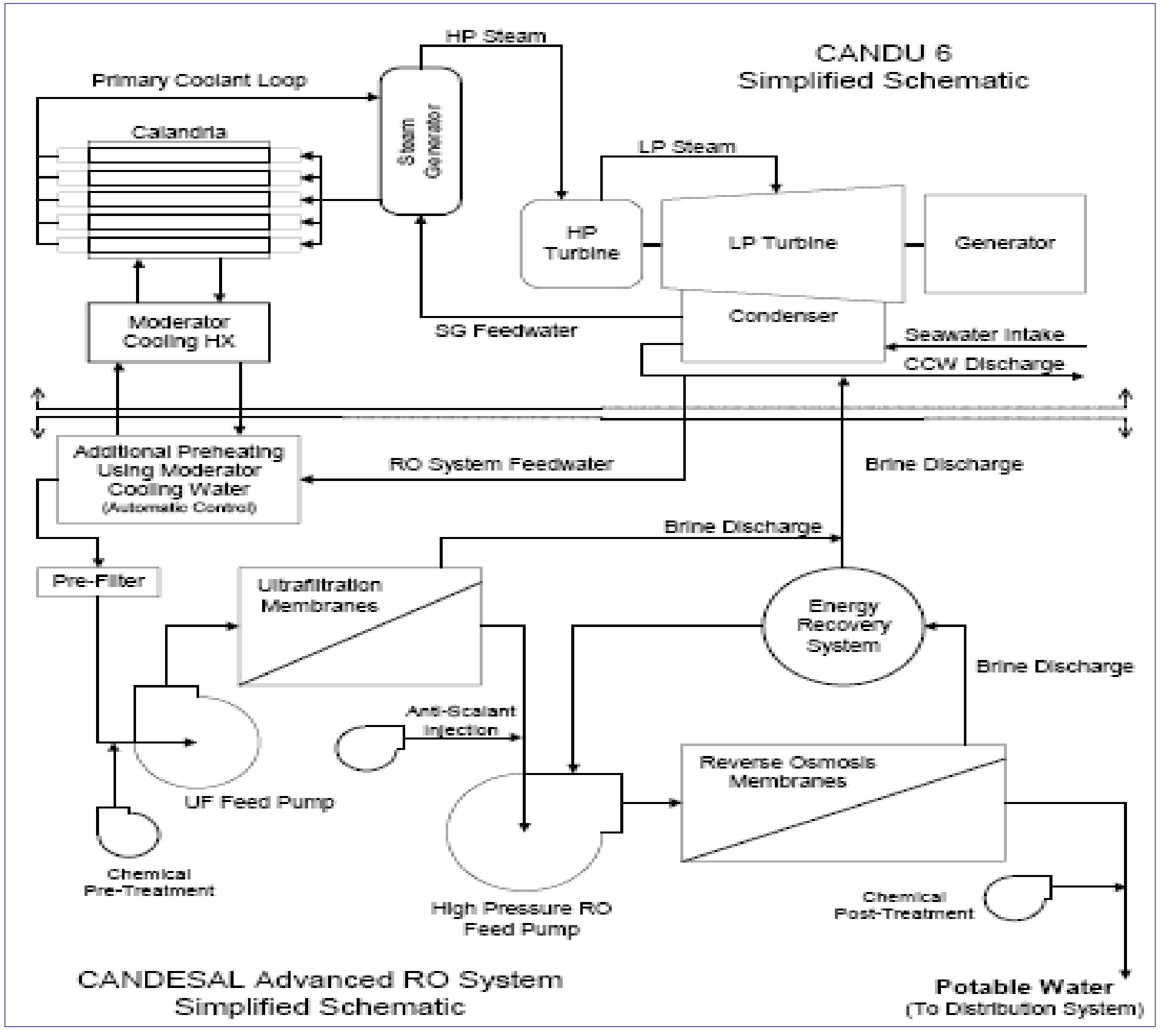


The higher the pressure in the condenser, the greater amount of water can be produced, but power generation is reduced.

BWR coupled to MSF (*Japan)*

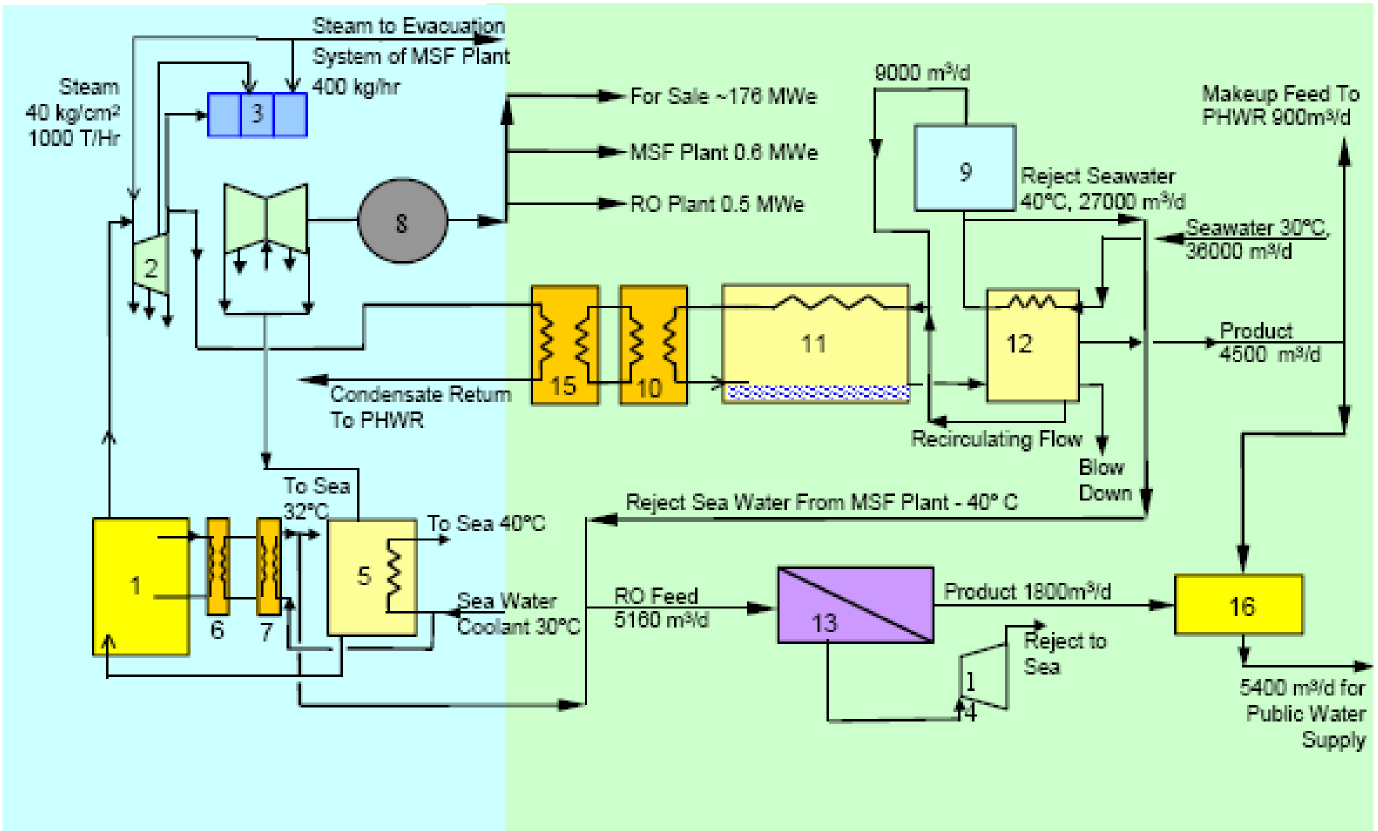


Coupling CANDU-6 * and RO



* Canadian Reactor of 600 MW pressurized water moderated by heavy water

Coupling PHWR* with MSF- RO (Kalpakkam, India)



* Indian Reactor of 170 MW pressurized water moderated by heavy water

Water quality and monitoring

WHO Guideline for Drinking-Water Quality (Vol. 1, Chapter 9, page198, 2004)

Recommended annual dose limit from radionuclides present in the drinking water = **0.1 mSv/year**

This limit is based on:

- Estimated lifetime risk of stochastic health effect: 10E-5
- Average global background radiation exposures : 2.4

Populations in areas with 10 times naturally high background radiation are without any health consequences

Water quality and monitoring

ALLOWED TRITIUM LEVELS IN DRINKING WATER

Country	Tritium limit (Bq/l)
Finland	30000
Australia	76103
Canada	7000
EU	100
Kazakhstan	7700
Switzerland	10000
United States	740
WHO	10000

Water quality and monitoring

- ***Desalinated water quality:*** in compliance with national and international regulations (WHO)
- ***Radiological limits for drinking water:*** based on consumption of ~2 litres per day
- ***Standards:*** according to the ALARA principle
- ***Monitoring*** for radioactivity and conductivity: batch monitoring, intermediate loop and product stream water.

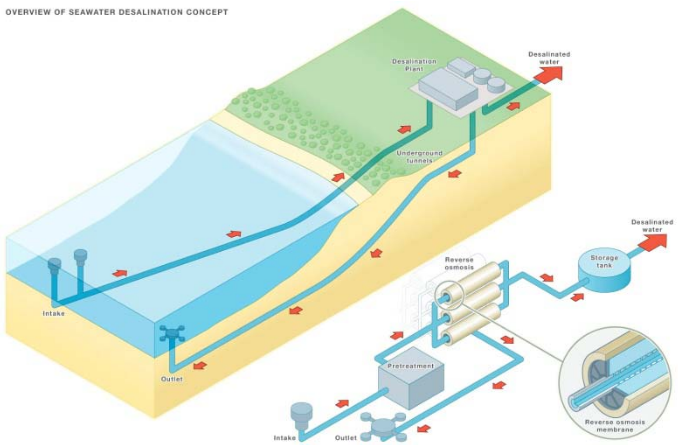
Environmental Issues

- **Marine**
- **Coastal**
- **Atmospheric**
- **Socio-economic**

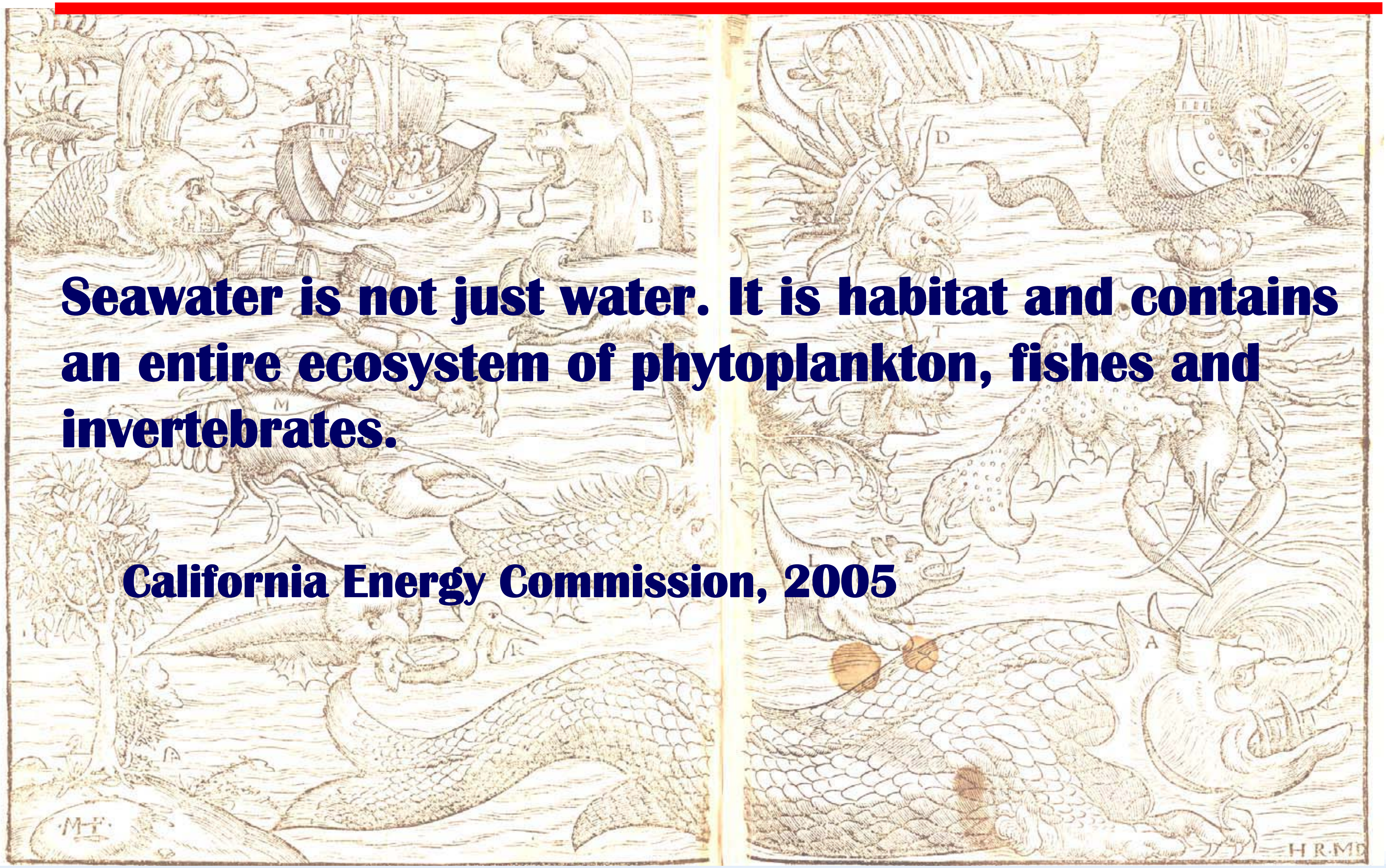
’60s artist's rendering of a nuclear desalination plant. Source: ORNL

Co-location reduces impacts

Desalination's impact is complex



Marine impacts



Seawater is not just water. It is habitat and contains an entire ecosystem of phytoplankton, fishes and invertebrates.

California Energy Commission, 2005

Source: S. Münster, *Cosmography*. 1598.

Water consumption in NPPs

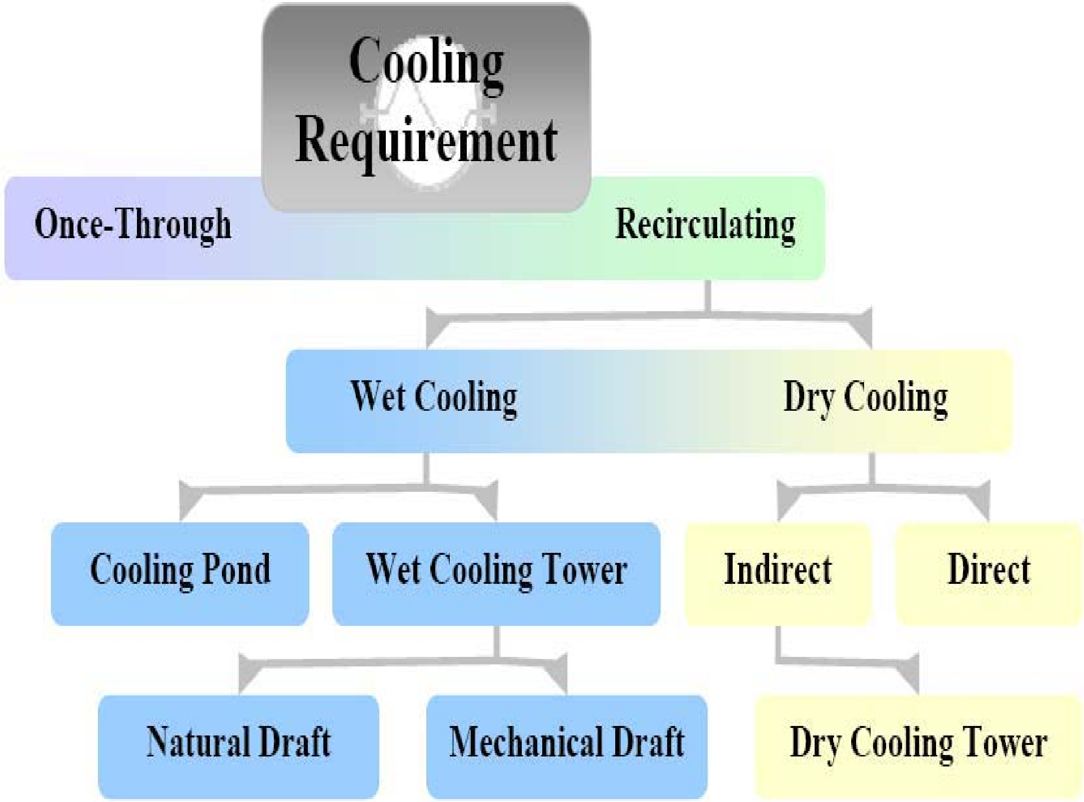
Drinking water		Industry		Irrigation		Electricity production	
$10^6 m^3$	%	$10^6 m^3$	%	$10^6 m^3$	%	$10^6 m^3$	%
5966	**18**	**3575**	**11**	**4391**	**14**	**18531**	**57**

RNDE-Ifen data 2002

River water used	water evaporated in the cooling towers	electricity produced	water taken vs electricity produced	Water evaporated vs electricity produced
16.5 billions m^3	0.5 billions m^3	294 billions kWh	**56 liters/kWh**	**1.7 liter/kWh**

2005 EDF data

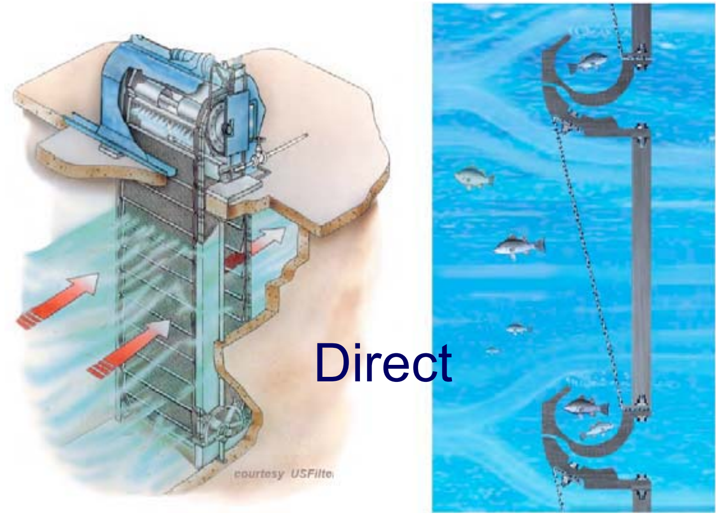
Cooling systems for Power plants



	OTC	Cooling towers
Nuclear	95 – 230	3 – 4
Fossil	76 – 190	2
NG/Oil CC	29 - 76	1

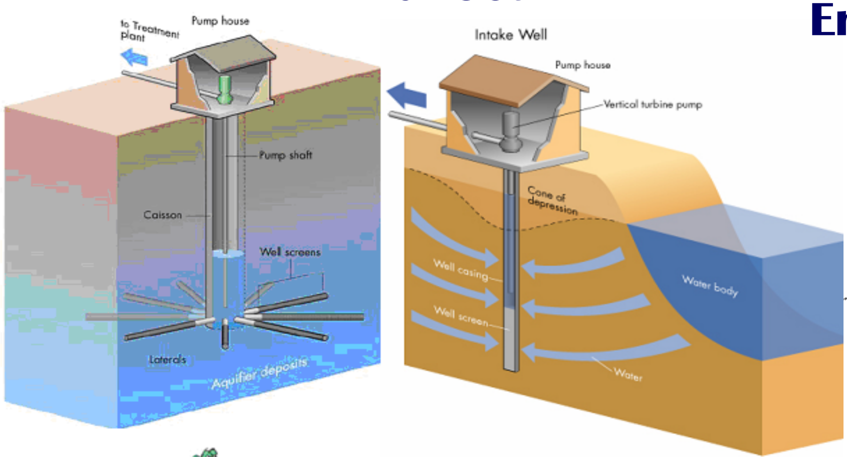
Direct and Indirect Intake systems

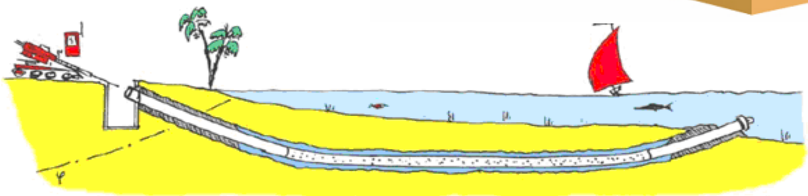
Once-through cooling requirements for Nuclear is the highest



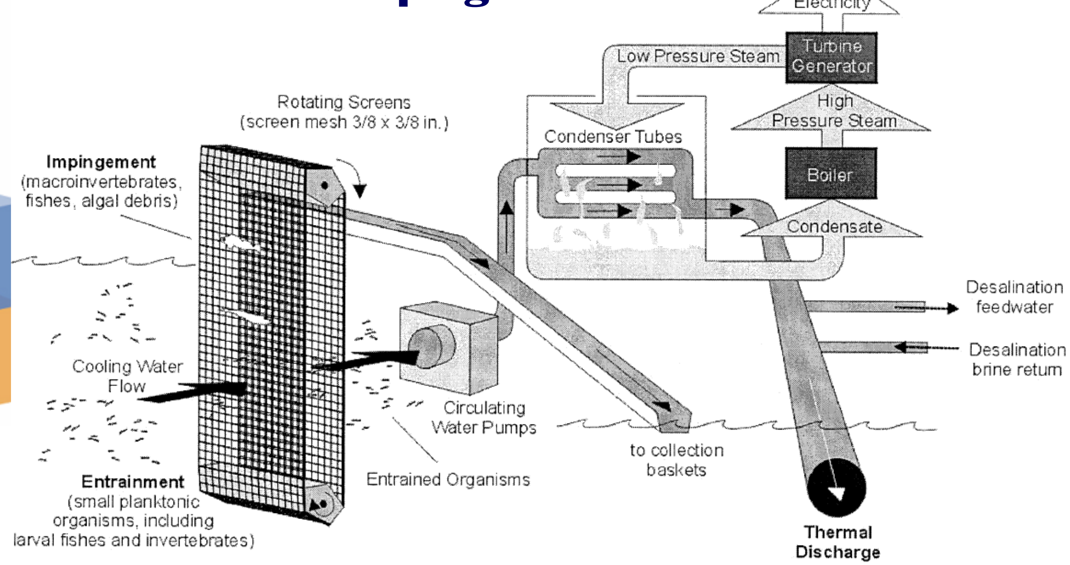
Direct

Indirect

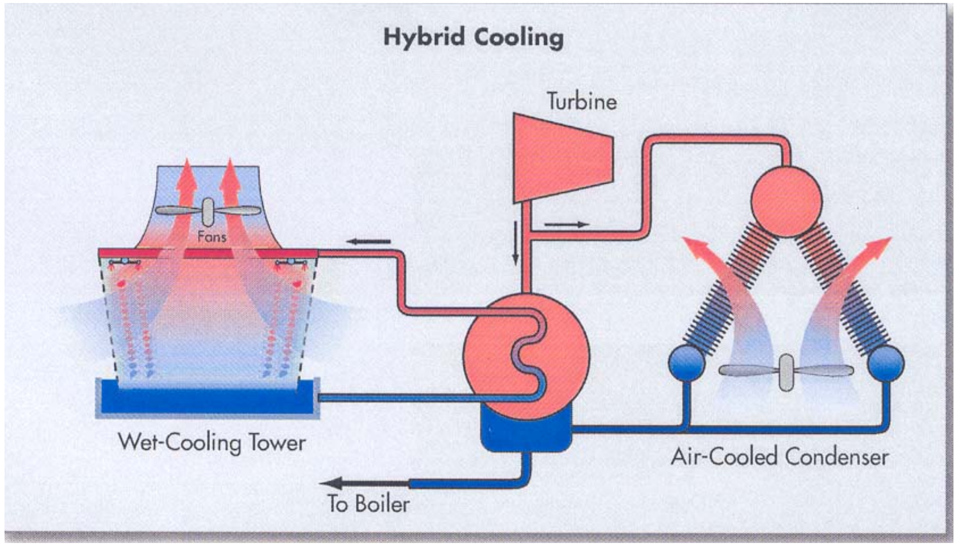




Entrainment and impingement



Mitigation recommendation

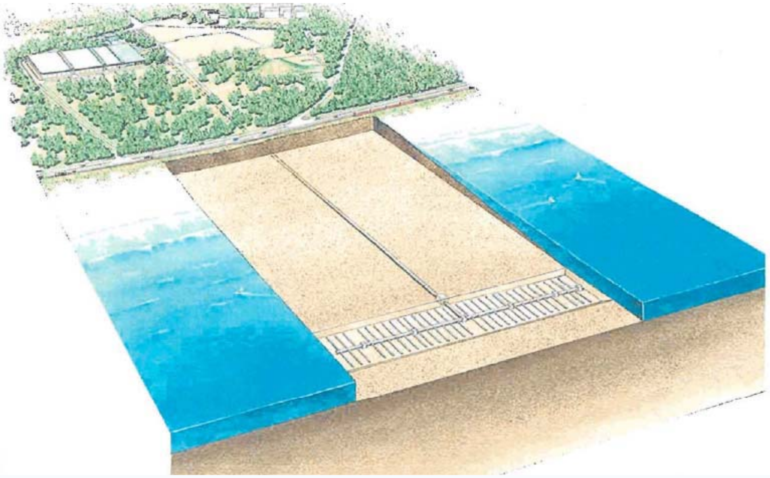


Dry- and/or wet-cooling for Nuclear, and

Source: Barker, 2007

Indirect intake systems for desalination, or

Intake from areas with low biological activity



Source: Fukuoka District Waterworks Agency

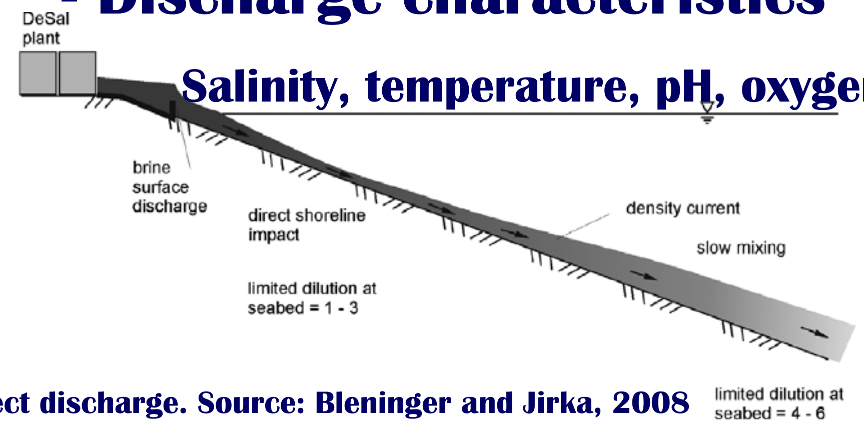
Discharge

- Regulations

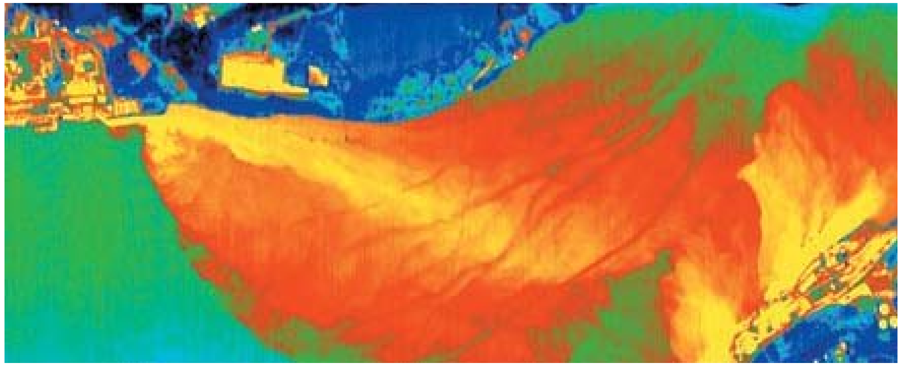
US Clean Water Act Section 403(c), Barcelona Convention, IAEA Safety Guide No. NS-G-3.2

- Discharge characteristics

Salinity, temperature, pH, oxygen content, toxicity



Direct discharge. Source: Bleninger and Jirka, 2008



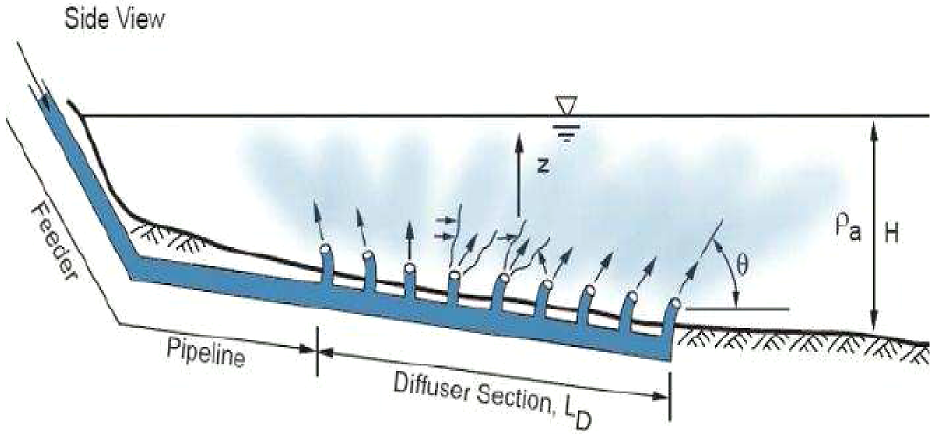
Thermal discharge. Source: IGER Archive Collection, 1988

Mitigation recommendations

Commercial use of the discharged brine

(recovery of valuable trace metals)

Dilution with multi-port diffusers in biologically insensitive areas…



Discharge diffusers. Source: USEPA 1991

…and environmentally sound intakes!

In Conclusion for Marine Impacts

- **All energy options are similar**
- **Mitigation schemes are easily installed**
- **Once-through cooling has to be abandoned**

Coastal Impact

- Land use and visual impacts
- Aquifer contamination
- Construction impact
- Noise impact

Land Use

Method	Area needed for a 1GW power plant
Solar (photo voltaic)	20 – 50 km^2
Windmill	50 – 150 km^2
Biomass (including bio-alcohol/oil)	4000 – 6000 km^2
Nuclear	1 - 4 km^2

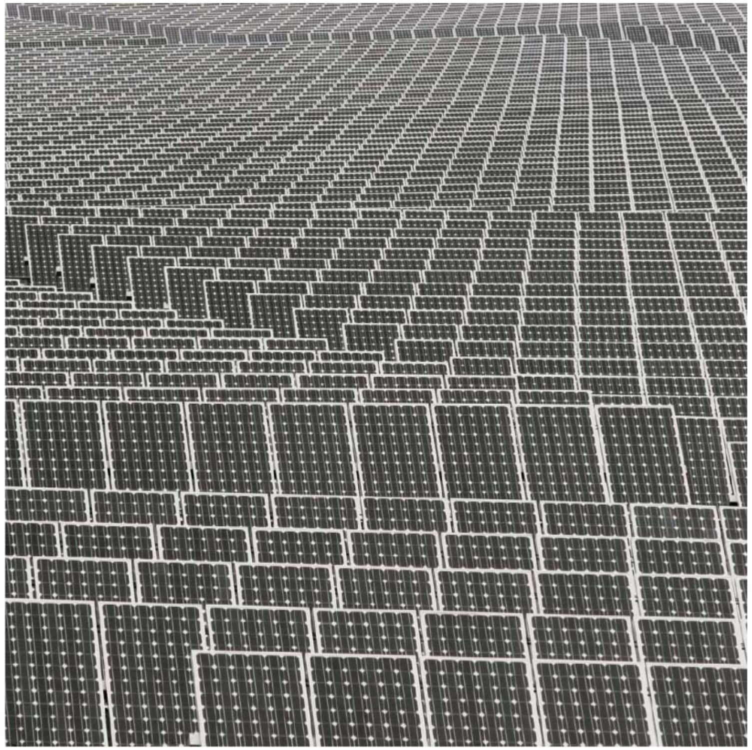
Source: IAEA; WEC, 2007

Desalination facilities of 100 000 m3/day would require 0.2 km^2

Visual Impacts

Paluel (F) nuclear power plant

Serpa (P) solar power plant



Palm Springs (US) wind farm

In conclusion for Coastal Impacts

- **Nuclear Desalination**
  - **is best for large water production**
  - **economy of scale is a big advantage**
- **Coastal impact for large-capacities nuclear desalination is lower than any other option**

Atmospheric Impacts

Carbon Dioxide Release

- for 100,000 m3/day desalination plant

Power Source	CO_2 Released (tons)
Coal	200 to 900
Natural Gas	100 to 200
Wind	0.02 to 0.2
Nuclear	0.02 to 0.2

Socio-economic Impacts

Water is Power

&

Power is Development

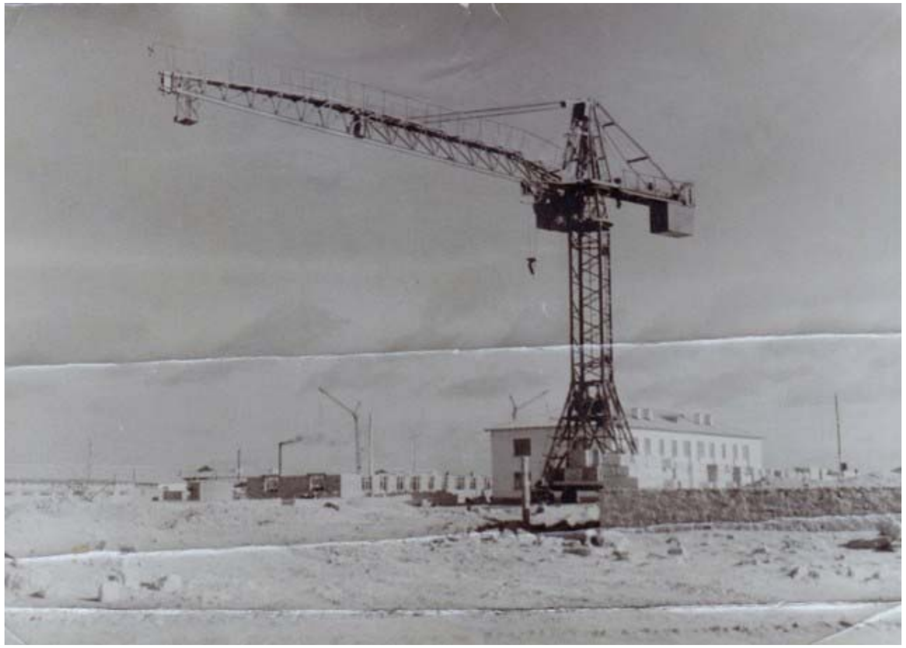
&

Development is Security

Development stimulus

- energy availability

- water availability



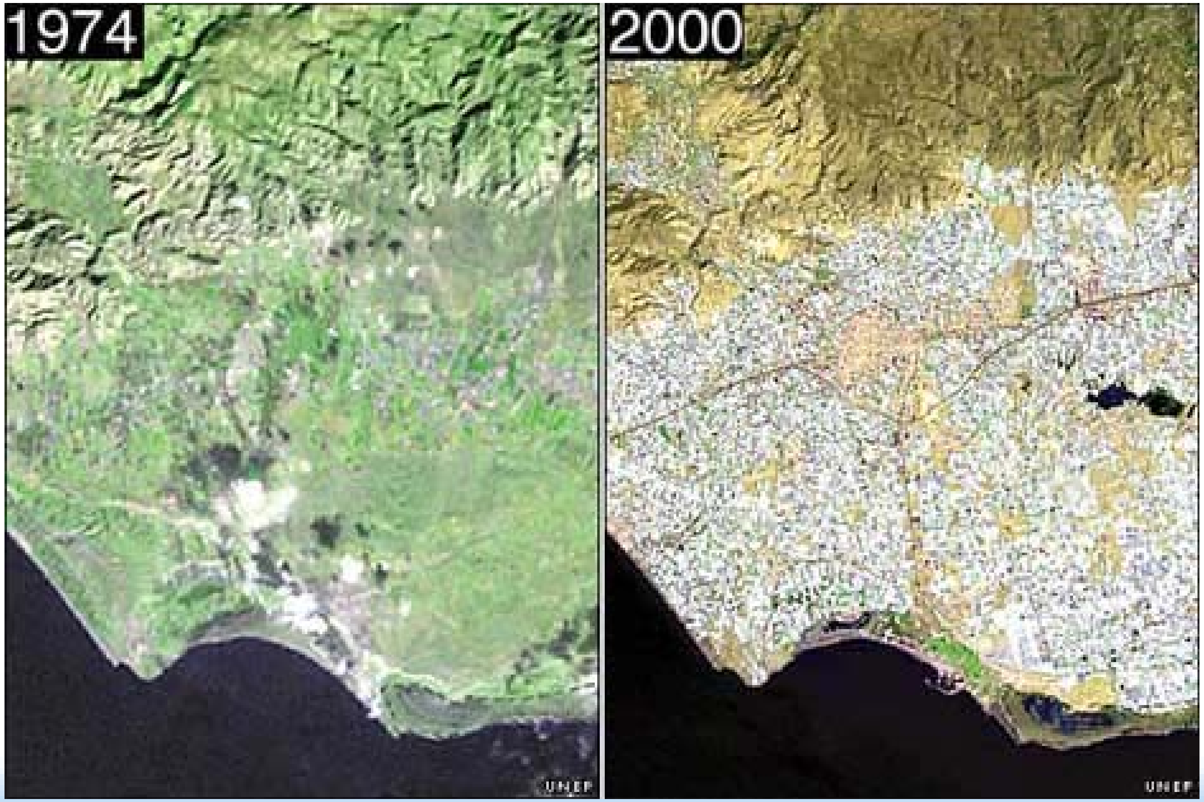
Aqtau, 1961

Aqtau, 1975

Changes in the land use, development of new industries

- population relocation, social disturbance

- environmental justice



Source: UNEP

Economics of nuclear desalination

- Results are site specific.
- Nuclear desalination costs:
  - RO: 0.5 to 0.94 $/m3
  - MED: 0.6 to 0.96 $/m3
  - MSF: 1.18 to 1.48 $/m3
- Comparing to prices of oil:

All nuclear options are economically competitive.

Economic target of nuclear desalination costs:

0.4-0.6US$/m^3 depending on the region

Economics of Nuclear Desalination

- MSF costs systematically higher than RO or MED
- RO economically favorable for less stringent drinking standards (e.g. WHO, <1000 ppm TDS)
- Costs higher with smaller reactors ("economy of scale" effect)
- RO and MED costs are, in general, comparable

Incentives of Nuclear desalination

PBMR_Reject heat (from pre-cooler and intercooler) → 220 MW_{th} at 70 C

↓

Clean and fresh desalinated water

15 000 – 30 000 m3/day of

↓

55 000 – 600 000 person

Incentives of Nuclear desalination-cont.

To produce 130 000 m3/day of desalinated water using 1000 MWe PWR

Total revenue **(Cogeneration 90% electricity +10% water)** :

- **Electricity: 6771.6 M$**
- **Water: 888.59 M$**
- **Total: 7660 M$**

Using MED

Total revenue from 100% for **electricity alone**: **7166.8 M$**

Net benefit of ND: 493.2 M$ ~ 7% more

Incentives of Nuclear desalination-cont.

Using RO even better:

- **Increased availability (more water)**
- **No lost shaft power as in MED**
- **Considerable fraction of energy will be recovered.**

Revenue:

-From electricity: 7026.72 M$

-From Water: 672 M$

→ Total: 7700 M$

Net benefit: 532 M$~ 7.5% more

IAEA Activities on Nuclear Desalination

IAEA activities on Nuclear Desalination ND

Objective: Support demonstration of nuclear seawater desalination:

- Activities to demonstrate that ND is viable (CRPs, Forums, publications...etc).
- Provide tools:
  - ➢Desalination Economic Evaluation Programme DEEP
  - ➢Toolkit on nuclear desalination
- Support to Member States through Technical Cooperation (TC).

IAEA Coordinated Research Projects (CRP)

CRP: **Optimization of the Coupling of Nuclear Reactors and Desalination Systems**. 1998-2003.

- It encompassed research and development programmes in the interested Member States pursuing coupling of nuclear reactors with desalination systems in the following fields:
- Nuclear reactor design,
- Optimization of thermal coupling,
- Performance improvement of desalination systems
- Prospects of advanced desalination technologies for the application of nuclear desalination.
- The results of this CRP were published as IAEA-TECDOC-1444 (2005)

Coordinated Research Projects

CRP: **Economic Research on, and Assessment of, Selected Nuclear Desalination Projects and Case Studies"**

- Launched in 2002 on and completed in 2006
- It is to contribute to the IAEA's efforts to enhance prospects for the demonstration, and eventually, for the successful implementation of nuclear desalination in Member States.
- The objective of the CRP is;
  - To evaluate economic aspects and to investigate the competitiveness of nuclear desalination under specific conditions
  - To identify innovative techniques leading to further cost reduction of nuclear desalination and to refine economic assessment methods and tools.
- The results of this CRP were published as IAEA-TECDOC-1561 (2007)

Coordinated Research Projects

CRP: **Advances in Nuclear Process Heat Applications**”

- It is to contribute to the IAEA’s efforts to investigate the prospects of using waste heat generated in High Temperature Reactors.
- The objective of the CRP is;
  - To evaluate the potential of all advanced reactor designs in process heat applications.
- The CRP is launched in 2007, completed in 2009 and future IAEA-TECDOC under compilation.

Coordinated Research Projects

A new CRP started in 2009 on

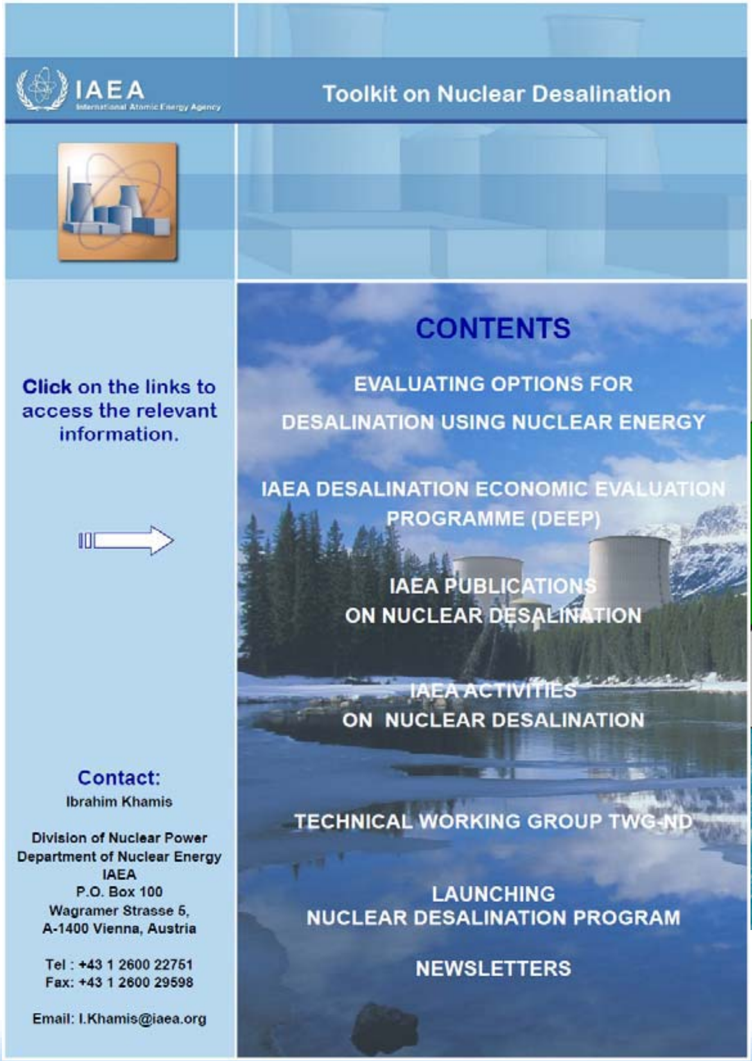
"New Technologies for Seawater Desalination using Nuclear Energy"

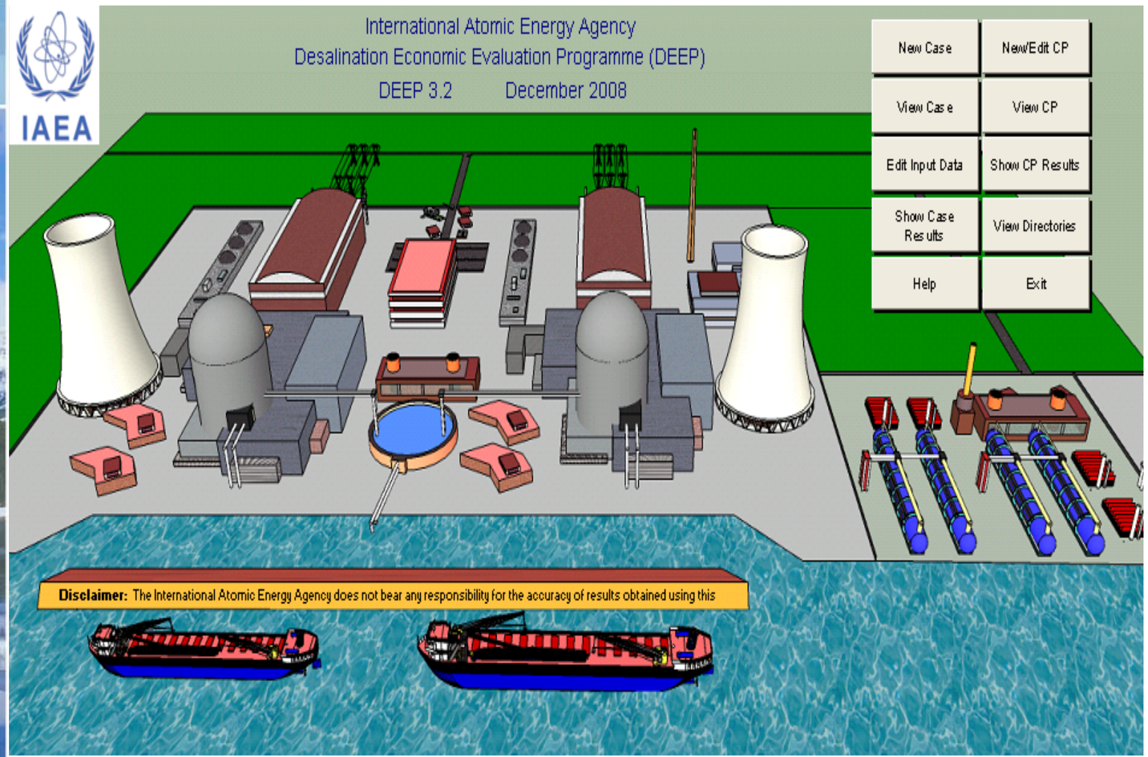
- The CRP will help support R&D in nuclear desalination technologies with the aim of producing large amounts of desalted water at the lowest possible cost and in a sustainable manner, and assist developing countries interested in nuclear programmes to master applications of nuclear energy for seawater desalination and cogeneration option.

- The objective of the CRP is;
  - To introduce innovative technologies which may help making nuclear desalination more safe and economical.
- The first meeting CRP will be 27-28 Oct 2009

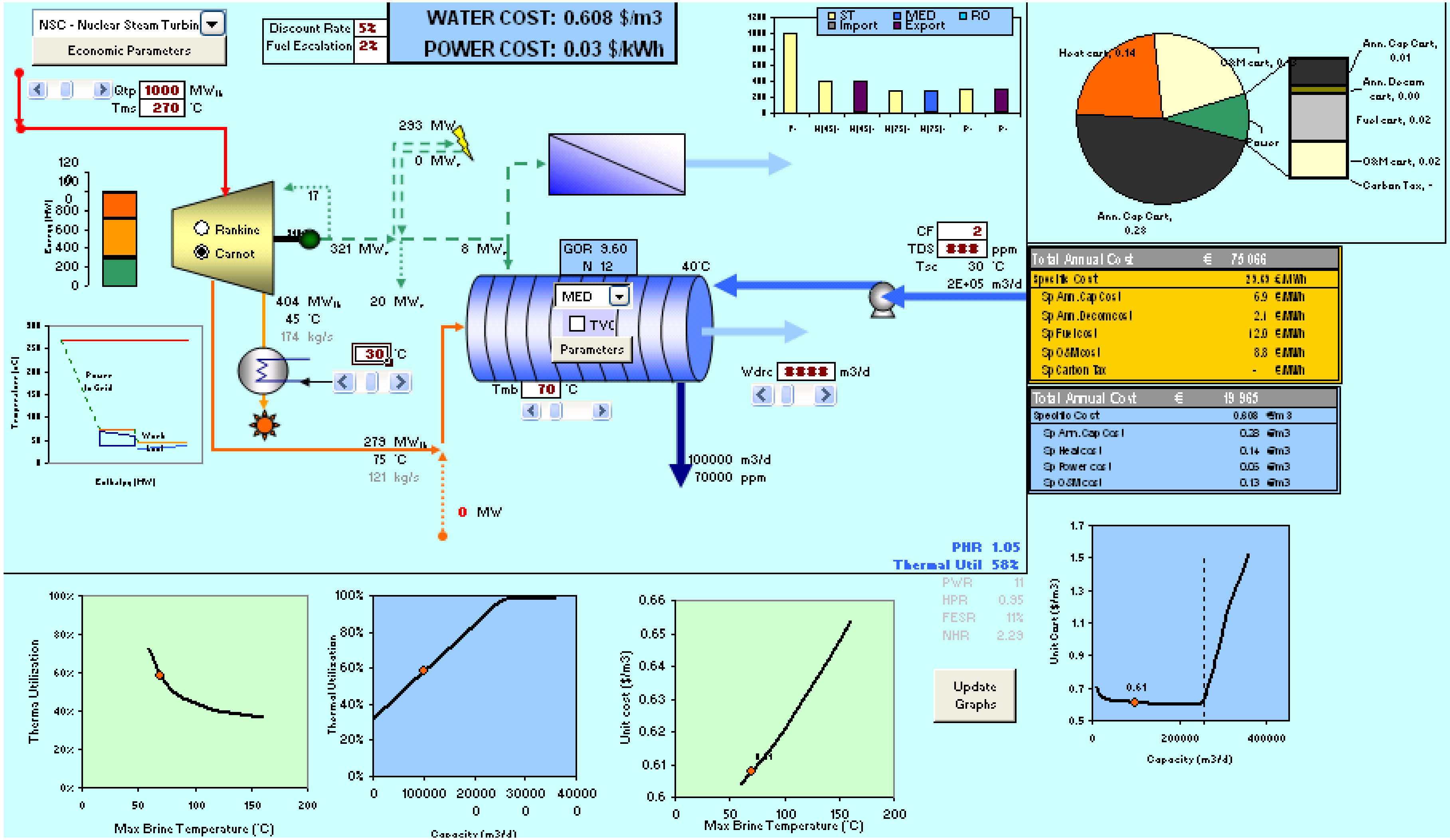
Algeria, Egypt, France (2), India, Indonesia, Kuwait, Libya, Morocco, Pakistan, Rep. of Korea, Syria, UK, USA,

IAEA Tools for Nuclear Desalination

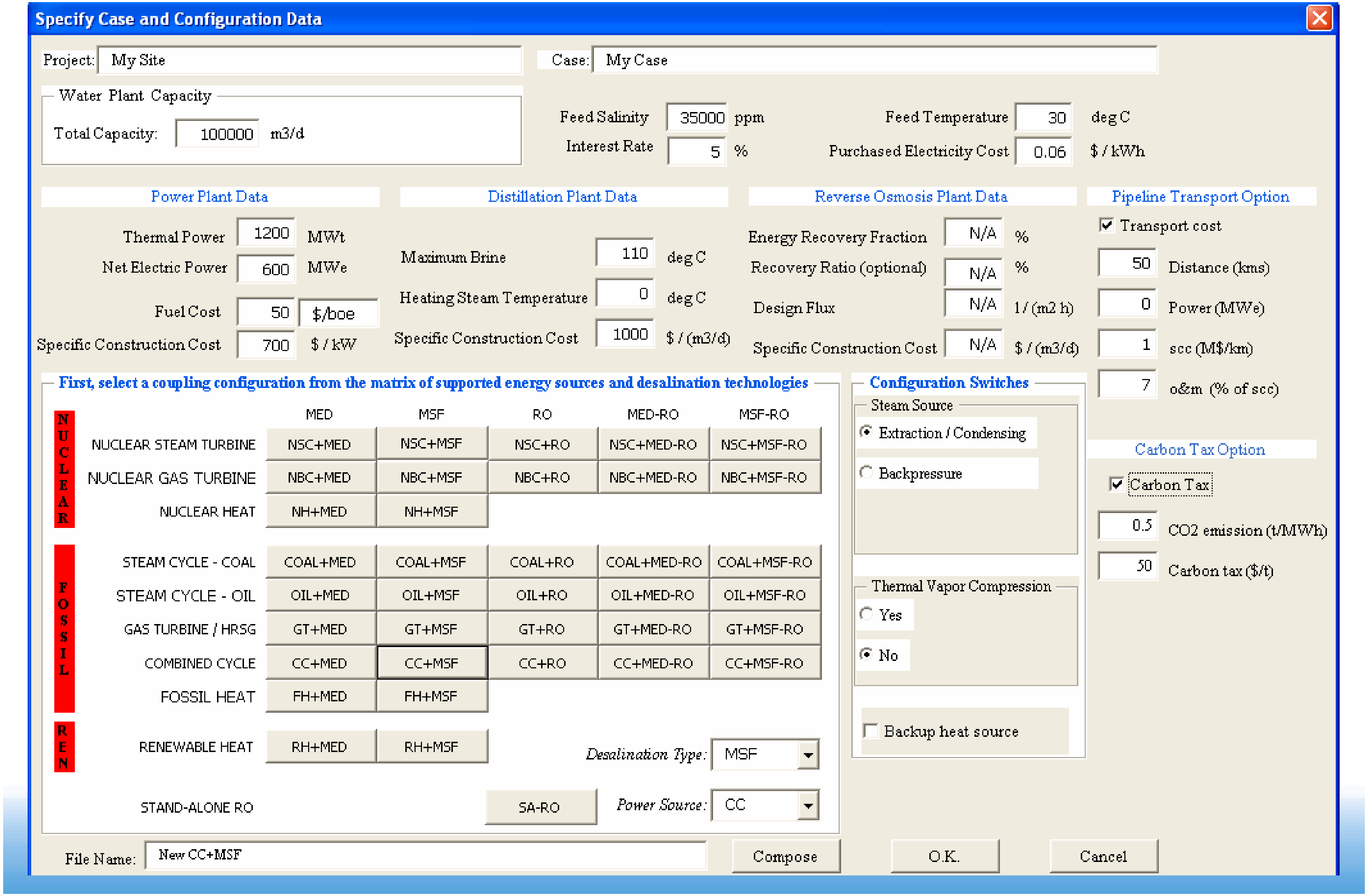




New Version of DEEP



Economics of Nuclear Desalination-DEEP



The Various energy options considered in DEEP

RC	Energy source	Abbreviation	Description	Plant type
1	Nuclear	PWR	Pressurised light water reactor	Co-generation plant
2	Nuclear	PHWR	Pressurised heavy water reactor	Co-generation plant
3	Fossil – coal	SSBC	Superheated steam boiler	Co-generation plant
4	Fossil oil - gas	SSBOG	Superheated steam boiler	Co-generation plant
5	Fossil	GT	Open cycle gas turbine	Co-generation plant
6	Fossil	CC	Combined cycle	Co-generation plant
7	Nuclear	HR	Heat reactor (steam or hot water)	Heat-only plant
8	Fossil	B	Boiler (steam or hot water)	Heat-only plant
9	Nuclear	GTMHR	Gas turbine modular helium reactor	Power plant
10	Fossil	D	Diesel	Power plant
11	Nuclear	SPWR	Small PWR	Co-generation plant

The desalination processes considered in DEEP

Process	Abbreviation	Description
Distillation	MED	Multi-Effect Distillation
	MSF	Multi-Stage Flash
Membrane	SA-RO	Stand-Alone Reverse Osmosis
	C-RO	Contiguous Reverse Osmosis
Hybrid	MED/RO	Multi-Effect Distillation with Reverse Osmosis
	MSF/RO	Multi-Stage Flash with Reverse Osmosis

Technical Working Group on nuclear desalination

Algeria	*Mr. BELKAID Abderrahmane*	Centre de recherche nucleaire de Birine Email: abbelkaid@yahoo.fr
Argentina	*Ms. JAPAS Maria Laura*	Comision Nacional de Energia Atomica Email: mljapas@cnea.gov.ar
China	*Ms. WEIHUA Li*	Institute of Nuclear and New Energy Technology Email: liweihua@mail.tsinghua.edu.cn
Cuba	*Mr. ZUNIGA Santana Juan Francisco*	Information Management and Energy Development Center Email: jfz@cubaenergia.cu
Egypt	*Mr. YASSIN M. Ibrahim*	Nuclear Power Plants Authority Email: yassin_brhm@yahoo.co.uk
France	*Mr. DARDOUR Saied*	CEA/Cadarache Email: saied.dardour@cea.fr
Germany	*Mr. TUSEL Guenther*	GFT Desalination GmbH Email: g.tusel@gft-gmbh.com
India	*Mr. TEWARI Pradip K.*	Atomic Research Centre (BARC) Email: pktewari@barc.gov.in
Indonesia	*Mr. SUDI Ariyanto*	National Nuclear Energy Agency (BATAN) Email: asudi@batan.go.id
Kuwait	*Mr. AL-AWADI Nader Mohammed*	Kuwait Institute for Scientific Research Email: nawadi@safat.kisr.edu.kw
Libyan Arab Jamahiriya	*Mr. GHURBAL S.M.*	Atomic Energy Establishment Email: ghurbal55@yahoo.com
Morocco	*Mr. BOUABDELLAOUI Yahya*	Institut Agronomique et Vétérinarire Hassan II Email: y.bouabdellaoui@iav.ac.ma
Russian Federation	*Mr. BARANAEV Yuri D.*	Institute of Physics and Power Engineering Email: baranaev@ippe.ru
Pakistan	*Mr. BUTT Waqar M.*	Pakistan Atomic Energy Commission E mail: buttwmb@yahoo.com
Saudi Arabia	*Mr. AL-ARIFI A. Suliman*	Saline Water Conversion Corp.. Email: ahmed_swcc@hotmail.com
South Africa	*Mr. VAN RAVENSWAAY Jan*	M-Tech Industrial Email: jvr@mtechindustrial.com
Spain	*Mr. ALONSO Felix*	Empresarios Agrupados S.A. Email: faz@empre.es
United States of America	*Mr. FAIBISH Ron*	Argonne National Laboratory Email: rfaibish@anl.gov
IAEA	*Mr. KHAMIS Ibrahim*	Scientific Secretary Email: I.Khamis@iaea.org

18 Member States

+

New Member State (expected): Kazakhstan

International Symposium on Nuclear Desalination

- An international Symposium on "Desalination of Seawater with Nuclear Energy" was held in May 1997 in Taejon, Republic of Korea. It was hosted by Korea Atomic Energy Research Institute.
- The Agency cooperated in organising the International Conference on Nuclear Desalination- Challenges and Options at Marrakech in October 2002. It was held jointly by World Council of Nuclear workers and Moroccan Association of Nuclear Engineers.
- An International Conference on Non-electrical Application of Nuclear Power was held in April 2007 in Japan. It was hosted by Japan Atomic Energy Agency.

Recent publications

- A Status Report on Nuclear Desalination Activities in the Member States was published as IAEA-TECDOC-1524 (2007)
- The results of the CRP on Economic Research on, and Assessment of, Selected Nuclear Desalination Projects and Case Studies were published as IAEA-TECDOC-1561 (2007)
- Nuclear Desalination Newsletter
- Proceedings of the **International Conference on Non Electric Applications of Nuclear Energy:** Nuclear Desalination, Hydrogen Production, and other industrial Applications. Oarai, Japan 16-19 April 2007, 2009.
- ***New:*** TECDOC-1642 on Environmental Impact Assessment, 2010.

Recent Publications in Int. Journals and Conferences

- Vladimir Anastasov and Ibrahim Khamis, " Nuclear desalination: environmental impacts and implications for planning and monitoring activities", Journal of Environmental Monitoring, DOI 10: 1039, 2010.
- Hussam Jouhara, Vladimir Anastasov, Ibrahim Khamis, "POTENTIAL OF HEAT PIPE TECHNOLOGY IN NUCLEAR SEAWATER DESALINATION", , Int. J. of Desalination, 249, 1055-1061, 2009.
- Ibrahim Khamis, "A GLOBAL OVERVIEW ON NUCLEAR DESALINATION", Int. J. of Nuclear Desalination, Vol. 3, No. 4, 311-328, 2009.
- Ibrahim Khamis and Vladimir Anastasov, "Environmental Aspects of Nuclear Desalination", CAIRO INTERNATIONAL CONFERENCE ON ENERGY & ENVIRONMENT, 2009.
- Ibrahim Khamis, Hussam Jouhara, Vladimir Anastasov, "HEAT PIPES AS AN EXTRA MEASURE TO ELIMINATE RADIOACTIVE CONTAMINATION IN NUCLEAR SEAWATER DESALINATION", J. of Desalination & Water Treatment, 13, 82-87, 2010.
- K. C. Kavvadias and I. Khamis, "The IAEA DEEP desalination economic model: A critical review", Int. J. of Desalination, 2010.

Future publication

- ***Guideline for environmental impact assessment of nuclear desalination***
- ***Cogeneration Options for New Nuclear Installation***

IAEA web page

- http://www.iaea.org/NuclearPower/Desalination/
- http://www.iaea.org/NuclearPower/Downloads/HEEP/HEEP-SW/HEEP-beta.zip

For contact:

I.khamis@iaea.org

…Thank you for your attention

International Atomic Energy Agency