IAEA-TECDOC-1642

Environmental Impact Assessment of Nuclear Desalination

IAEA
International Atomic Energy Agency

ENVIRONMENTAL IMPACT ASSESSMENT OF NUCLEAR DESALINATION

IAEA-TECDOC-1642

The following States are Members of the International Atomic Energy Agency:

AFGHANISTAN
ALBANIA
ALGERIA
ANGOLA
ARGENTINA
ARMENIA
AUSTRALIA
AUSTRIA
AZERBAIJAN
BAHRAIN
BANGLADESH
BELARUS
BELGIUM
BELIZE
BENIN
BOLIVIA
BOSNIA AND HERZEGOVINA
BOTSWANA
BRAZIL
BULGARIA
BURKINA FASO
BURUNDI
CAMBODIA
CAMEROON
CANADA
CENTRAL AFRICAN REPUBLIC
CHAD
CHILE
CHINA
COLOMBIA
CONGO
COSTA RICA
CÔTE D'IVOIRE
CROATIA
CUBA
CYPRUS
CZECH REPUBLIC
DEMOCRATIC REPUBLIC OF THE CONGO
DENMARK
DOMINICAN REPUBLIC
ECUADOR
EGYPT
EL SALVADOR
ERITREA
ESTONIA
ETHIOPIA
FINLAND
FRANCE
GABON
GEORGIA
GERMANY
GHANA
GREECE
GUATEMALA
HAITI
HOLY SEE
HONDURAS
HUNGARY
ICELAND
INDIA
INDONESIA
IRAN, ISLAMIC REPUBLIC OF
IRAQ
IRELAND
ISRAEL
ITALY
JAMAICA
JAPAN
JORDAN
KAZAKHSTAN
KENYA
KOREA, REPUBLIC OF
KUWAIT
KYRGYZSTAN
LATVIA
LEBANON
LESOTHO
LIBERIA
LIBYAN ARAB JAMAHIRIYA
LIECHTENSTEIN
LITHUANIA
LUXEMBOURG
MADAGASCAR
MALAWI
MALAYSIA
MALI
MALTA
MARSHALL ISLANDS
MAURITANIA
MAURITIUS
MEXICO
MONACO
MONGOLIA
MONTENEGRO
MOROCCO
MOZAMBIQUE
MYANMAR
NAMIBIA
NEPAL
NETHERLANDS
NEW ZEALAND
NICARAGUA
NIGER
NIGERIA
NORWAY
OMAN
PAKISTAN
PALAU
PANAMA
PARAGUAY
PERU
PHILIPPINES
POLAND
PORTUGAL
QATAR
REPUBLIC OF MOLDOVA
ROMANIA
RUSSIAN FEDERATION
SAUDI ARABIA
SENEGAL
SERBIA
SEYCHELLES
SIERRA LEONE
SINGAPORE
SLOVAKIA
SLOVENIA
SOUTH AFRICA
SPAIN
SRI LANKA
SUDAN
SWEDEN
SWITZERLAND
SYRIAN ARAB REPUBLIC
TAJIKISTAN
THAILAND
THE FORMER YUGOSLAV REPUBLIC OF MACEDONIA
TUNISIA
TURKEY
UGANDA
UKRAINE
UNITED ARAB EMIRATES
UNITED KINGDOM OF GREAT BRITAIN AND NORTHERN IRELAND
UNITED REPUBLIC OF TANZANIA
UNITED STATES OF AMERICA
URUGUAY
UZBEKISTAN
VENEZUELA
VIETNAM
YEMEN
ZAMBIA
ZIMBABWE

The Agency's Statute was approved on 23 October 1956 by the Conference on the Statute of the IAEA held at United Nations Headquarters, New York; it entered into force on 29 July 1957. The Headquarters of the Agency are situated in Vienna. Its principal objective is "to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world".

ENVIRONMENTAL IMPACT ASSESSMENT OF NUCLEAR DESALINATION

INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA, 2010

Sales and Promotion, Publishing Section
International Atomic Energy Agency
Vienna International Centre
PO Box 100
1400 Vienna, Austria
fax: +43 1 2600 29302
tel.: +43 1 2600 22417
email: sales.publications@iaea.org
http://www.iaea.org/books

For further information on this publication, please contact:

Nuclear Power Technology Development Section
International Atomic Energy Agency
Vienna International Centre
PO Box 100
1400 Vienna, Austria
email: Official.Mail@iaea.org

ENVIRONMENTAL IMPACT ASSESSMENT OF NUCLEAR DESALINATION
IAEA, VIENNA, 2010
IAEA-TECDOC-1642
ISBN 978-92-0-100810-7
ISSN 1011-4289

Printed by the IAEA in Austria
March 2010

FOREWORD

Nuclear desalination is gaining interest among the IAEA Member States, as indicated by the planned projects, and it is expected that the number of nuclear desalination plants will increase in the near future.

The IAEA has already provided its Member States with reports and documents that disseminate information regarding the technical and economic feasibility of nuclear desalination. With the rising environmental awareness, in the scope of IAEA's activities on seawater desalination using nuclear power, a need was identified for a report that would provide a generic assessment of the environmental issues in nuclear desalination.

In order to offer an overview of specific environmental impacts which are to be expected, their probable magnitude, and recommended mitigation measures, this publication encompasses information provided by the IAEA Member States as well as other specialized sources. It is intended for decision makers and experts dealing with environmental, desalination and water management issues, offering insight into the environmental aspects that are essential in planning and developing nuclear desalination.

The IAEA wishes to acknowledge the assistance provided by the contributors and reviewers listed at the end of the report, especially the exceptional contribution made by V. Anastasov, Former Yugoslav Republic of Macedonia. The IAEA officer responsible for this publication was I. Khamis of the Division of Nuclear Power.

CONTENTS

SUMMARY 1

1. INTRODUCTION 2
   1.1. Objectives and scope of the report 3
   1.2. Outline of the report 4

2. FUNDAMENTAL ASPECTS OF NUCLEAR DESALINATION 5
   2.1. Coupling of nuclear reactors to desalination processes 5
   2.2. Safety considerations related to thermal coupling of a nuclear power plant to a desalination plant 7
      2.2.1. Transient behavior of a nuclear power plant coupled to a desalination plant 7
      2.2.2. Experiences with nuclear desalination product water quality 7

3. ENVIRONMENTAL IMPACTS OF NUCLEAR DESALINATION 9
   3.1. Marine impacts 10
      3.1.1. Impacts from seawater intake 11
      3.1.2. Effluent disposal 24
   3.2. Coastal impacts of nuclear desalination 43
      3.2.1. Construction impacts 43
      3.2.2. Land use 44
      3.2.3. Noise and visual impacts 46
   3.3. Atmospheric impacts 47
   3.4. Siting and co-location environmental issues 51
   3.5. Conclusion on environmental impacts of nuclear desalination 56

4. SOCIO-ECONOMIC IMPACTS OF NUCLEAR DESALINATION 57
   4.1. Social impacts 58
   4.2. Economic impacts 61
   4.3. Public acceptance 64
   4.4. Conclusion on socio-economic impacts of nuclear desalination 68

5. CHALLENGES TO NUCLEAR DESALINATION 68
   5.1. Issues and preconditions related to nuclear power 69
   5.2. Addressing the challenge 71

6. CONCLUSIONS AND FURTHER RESEARCH 73

APPENDIX I. METHODOLOGY FOR ASSESSMENT OF ENVIRONMENTAL IMPACTS ON MARINE HABITATS 75

APPENDIX II. ALTERNATIVE COOLING OPTIONS FOR NUCLEAR POWER PLANTS 79

APPENDIX III. QUALITY ISSUES OF NUCLEAR DESALINATED WATER 82

APPENDIX IV. SMALL AND MEDIUM SIZED REACTORS SUITABLE FOR NUCLEAR DESALINATION 95

APPENDIX V. EXPERIENCE WITH NUCLEAR DESALINATION 98

REFERENCES 113

CONTRIBUTORS TO DRAFTING AND REVIEW 127

SUMMARY

Nuclear desalination as a concept has been around for almost 50 years as an economically reasonable option, though it has never achieved wider application. Still, sufficient experience was accumulated (~ 200 reactor years) in the use of nuclear power as the energy source for seawater desalination plants in various countries: Japan, USA, India and Kazakhstan.

Desalination raises concerns about the highly saline brine left after the process and usually disposed of in the ocean. In addition, its energy intensity is rather high. Many different methods are currently used to provide the energy (electricity and/or heat) needed to run a desalination plant, but mainly fossil fuel is used, thus continually affecting the environment. Today's conditions induced by climate change are shifting the attention back to nuclear desalination possibilities. The reasons for it are mainly environmental, as they were economic in the 1960s.

Nuclear power applied for desalination offers significant improvements in the area of environmental impacts, removing some of the impediments for the use of fossil fuel or renewable energy sources. Investigating the potential for environmental impacts from several perspectives, the report concludes that the possibilities offered by nuclear desalination are large and insufficiently used. The issues of safety of the product water, as well as operation of nuclear desalination plants have been found to apply sufficient solutions that guarantee problem-free operation.

While the marine impacts of a nuclear desalination plant have to be assessed on a site specific basis in order to recognize the best possible option for avoiding adverse impacts, they are not inherent for nuclear power. In addition, suitable mitigation measures can be applied. On the other hand, large benefits are identified in the area of atmospheric pollution as well as coastal impacts with land use, noise and visual disturbances, which are almost impossible to achieve with alternative options.

Regarding the socio-economic impacts originating from nuclear desalination, the report finds that the subsequent impacts are largely beneficial. As for the public acceptance of such a project at the moment, there are no certain indicators that could be used in advance to assess it. However, the rise of support for nuclear power, as well as the relatively undisputed role of desalination, may suggest that a positive attitude can be expected for such projects. Providing energy as well as water, nuclear desalination could be even more accepted than just nuclear power.

In addition to public acceptance, nuclear desalination faces several challenges, mainly regarding costs, infrastructure, proliferation, waste etc. Thus, right from the beginning of a nuclear project the public has to be informed and involved accordingly; the financing of a nuclear project needs special financial instruments; the construction and safe operation of a nuclear power plant needs a special infrastructure to be maintained during the life time of the plant; for nuclear waste long term measures have to be taken.

The report concludes that nuclear power is a well suited source of energy for all types of desalination plants, and economically and environmentally superior to alternative power sources. The optimal concept of nuclear desalination seems to be cogeneration, i.e. sizing the nuclear plant in such a way that – in addition supplying energy in form of heat and/or electricity to a co-located desalination plant – it also is supplying electricity to a local grid. Small and medium sized nuclear reactors currently under development will further increase the attractiveness of nuclear power to be used as energy source for desalination plants.

1. INTRODUCTION

From a technical and economical standpoint seawater desalination, as an alternative source of potable water, has become particularly attractive due to continuous innovations in the relevant technologies leading to a very significant reduction of desalination costs.

Yet, desalination has remained an energy intensive process. Over the long term, desalination with fossil energy sources would not be compatible with sustainable development: fossil fuels reserves are finite and must be conserved for other essential uses whereas demands for desalted water would continue to increase. Furthermore, the combustion of fossil fuels would produce large amounts of greenhouse gases and toxic emissions, underlining the need for options involving alternative energy sources.

It is for this reason that since the 1980s the IAEA has continuously promoted the use of nuclear power for desalination and provided its Member States with guidebooks [1], [2], technical documents [3], [4], [5], [6],[7] and computer programs [8], [9] on this subject as well as the provision of technical assistance through the framework of technical cooperation programs [10].

The International Nuclear Desalination Advisory Group (INDAG) was launched by the IAEA in 1997, with well known experts from participating Member States to advise the agency in nuclear desalination related studies and actions.

Several technical cooperation projects and international collaboration activities under the IAEA inter-regional technical cooperation (TC) framework have already been successfully completed.

Some nuclear power plants in Japan, India and the United States have been coupled with small capacity desalination plants. Their purpose is mainly to satisfy the needs of the power plants' cooling systems and, in some cases, to provide drinking water for the plant personnel or the local population.

The MAEC nuclear desalination plant though, on the Caspian coast in Kazakhstan, was built for the special purpose of supplying energy and water for the local industry, as well as main drinking water supply to the residents of the city of Aktau. Thus, over 200 reactor-years of combined experience have been gathered.

Since the last few years, interest in nuclear desalination has received additional impetus in view of the need for a low-carbon desalination, among other benefits of nuclear power. Many countries have expressed interest in related R&D studies or have already started them. Some have undertaken to launch demonstration projects. The demonstration plant at Kalpakkam, India is in the final stages of completion. More recently Libya, in collaboration with France, has decided to use its experimental reactor at Tajoura as a nuclear desalination demonstration plant.

Table 1 summarizes the past and present situation regarding the nuclear desalination plants in the world.

Table 1. GLOBAL NUCLEAR DESALINATION CAPACITIES

Plant name	Location	Gross power [MW(e)]	Capacity [m^3/d]	Energy/Desalination
Shevchenko*	Aktau, Kazakhstan	150	80 000 – 145 000	LMFBR/MSF&MED
Ikata-1,2	Ehime, Japan	566	2000	PWR/MSF
Ikata-3	Ehime, Japan	890	2000	PWR/RO
Ohi-1,2	Fukui, Japan	2 x 1175	3900	PWR/MSF
Ohi-3,4	Fukui, Japan	1 x 1180	2600	PWR/RO
Genkai-4	Fukuoka, Japan	1180	1000	PWR/RO
Genkai-3,4	Fukuoka, Japan	2 x 1180	1000	PWR/MED
Takahama-3,4	Fukui, Japan	2 x 870	1000	PWR/RO
NDDP	Kalpakkam, India	170	6300	PHWR/Hyb. MSF-RO
LTE	Trombay, India	40 [MW(t)]	30	PHWR/LTE
Diablo Canyon	San Luis Obispo, USA	2 x 1100	2180	PWR/RO

* Shevchenko was shut down in 1999, after 26 years of operation.

1.1. OBJECTIVES AND SCOPE OF THE REPORT

Complementary to the two Coordinated Research Projects (CRPs) that the Nuclear Power Technology Development section of the Agency (NPTDS) has launched to explore the economic and technical feasibility of nuclear desalination, the main objective of this report is to examine the issue of possible environmental impacts resulting from the deployment of nuclear desalination plants. The report aims at improving the understanding of, and the opportunities and challenges associated with, nuclear desalination in a variety of seawater desalination layouts.

Nuclear desalination facilities operating today are relatively small, offering information which is difficult to apply for environmental impact assessment of larger facilities. In some of the cases, the required information is not even available. Furthermore, every nuclear desalination plant is a site specific case.

The environmental assessment presented in this report is a generalized approach designed to review the environmental impacts of future large and medium capacity nuclear desalination systems. Therefore, the report's basic aim is to offer preliminary overview of the impacts which may be expected and their magnitude when nuclear desalination is deployed, as well as measures for mitigation of those impacts. It is primarily intended for the nuclear community, decision-makers, water management experts and project engineers, offering knowledge of potential impacts that is essential in planning and developing nuclear desalination. The report could also serve as a background and introductory material for environmental and desalination experts.

The scope of the report is limited mainly to operation related issues related to nuclear desalination and some commissioning issues. Decommissioning of a nuclear desalination plant is considered as an issue concerning more the nuclear power and covered in other relevant publications. Life cycle analyses (LCA) have been limited to LCA values and externalities in order to provide a suitable perspective for the assessment of a nuclear desalination project.

Thus, the objectives set for this environmental impact assessment are to:

- Review the available feedback of experiences on the environmental impact of nuclear desalination systems.
- Identify the possible impacts on the air, marine, coastal and socio-economic environment.
- Present some of the impact mitigation measures available today.
- Identify the future challenges for nuclear desalination.

In order to achieve these objectives, the research was conducted in the following manner:

- Review of IAEA material on the topic: proceedings, technical documents, safety guides and studies etc.
- Use of structured Questionnaires addressed to nuclear desalination facilities in Japan, India and Kazakhstan.
- Review of the available data on desalination impacts, especially environmental impacts of co-located desalination and power plants.
- Review of the environmental experiences with nuclear power
- Synthesis of possible combined impacts of desalination and nuclear power and comparison against existing cases, where possible.

1.2. OUTLINE OF THE REPORT

Chapter 2 of the report lays out the fundamental issues of nuclear desalination such as coupling of a nuclear with a desalination plant, as well as the experiences and concerns with product water quality.

Chapter 3 provides an overview of possible environmental impacts through the marine, coastal and atmospheric perspective. In addition, environmental considerations with co-location and siting are presented.

Chapter 4 reflects on the socio-economic dimension of the possible environmental impacts from nuclear desalination including development issues and economic costs. The chapter also tries to assess the issue of public acceptance.

Chapter 5 discusses the challenges and issues of nuclear desalination, as well as the steps that need to be taken to overcome those challenges.

Chapter 6 summarizes the findings in this document and lists issues of nuclear desalination which require further research.

The Annexes include related information on environmental impacts of nuclear desalination such as methodologies for assessing marine impacts, radiation safety of the product water and technical details and experiences.

2. FUNDAMENTAL ASPECTS OF NUCLEAR DESALINATION

2.1. COUPLING OF NUCLEAR REACTORS TO DESALINATION PROCESSES

The thermal coupling of a fossil power plant to a desalination plant (DP) is discussed in more detail in Ref. [10]. The main difference in the thermal coupling scheme of nuclear and fossil plants to a distillation DP is the necessary additional installation of an intermediate loop in case of a nuclear plant. This intermediate loop normally consists of a loop with heat exchanger and a re-circulation pump. An essential requirement for the intermediate circuit design is that it should operate at a higher pressure than the secondary loop of the nuclear power plant, in order to ensure that even in a hypothetical and highly improbable double rupture in the Steam Generator tube and the intermediate heat exchanger tube no contamination can migrate into the desalination system. In case of a MED system the intermediate loop contains a flash tank to produce the steam needed for the first effect of the desalination plant and in case of a MSF plant hot water from the exchanger can be used directly in the brine heater of the plant.

Typical coupling schemes of the PWR+MED and PWR+ROph processes (RO with preheating of the feedwater) are shown in Figure 1.

In the PWR+MED coupling scheme, the vapor 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 vapor then serves as the heating fluid in the first effect of the MED plant.

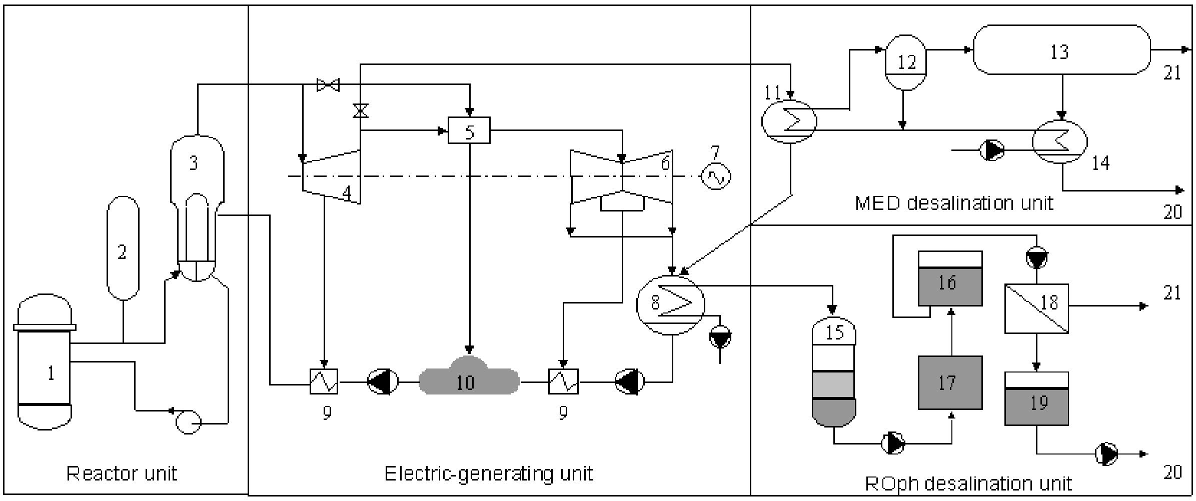

Figure 1. Conventional coupling of a PWR type of reactor to a MED plant [11].

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: Seawater heater;12: Flash tank, 13: MED plant, 14: MED output condenser, 15: Prefilter, 16: Chlorified water tank, 17: Ultra-filtration membrane, 18: RO membrane, 19: desalted water tank, 20: Fresh water out, 21: Brine out-fall

In new generation high temperature reactors, it is judicious and highly economical to make use of the waste heat produced in the intercooler and the pre-cooler circuits. Thus, for example, in the two such reactors currently being developed (the GT-MHR and the PBMR), circulating helium, which has to be compressed in two successive stages, cools the reactor core. For thermodynamic reasons, these compression stages require pre-cooling of the helium to about 26 °C through the use of the pre-cooler and intercooler helium-water heat exchangers.

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

Depending upon the specific designs, the temperature ranges of the water in these exchangers could be between 80 and 130°C. This is an ideal range for desalination with the MED plant, which can be coupled (Figure 2) between a mixer (of the flows from the pre-cooler and the intercooler) and the switch- cooling unit, evacuating the heat to the heat sink (sea or river). Waste heat from the experimental PHWRs can similarly be put to use.

A scheme was thus developed at BARC (India) to integrate a desalination unit such that the technology of utilizing reactor waste heat for desalination of sea water by a LT-MED process can be demonstrated [11]. This process is schematically shown in Figure 3.

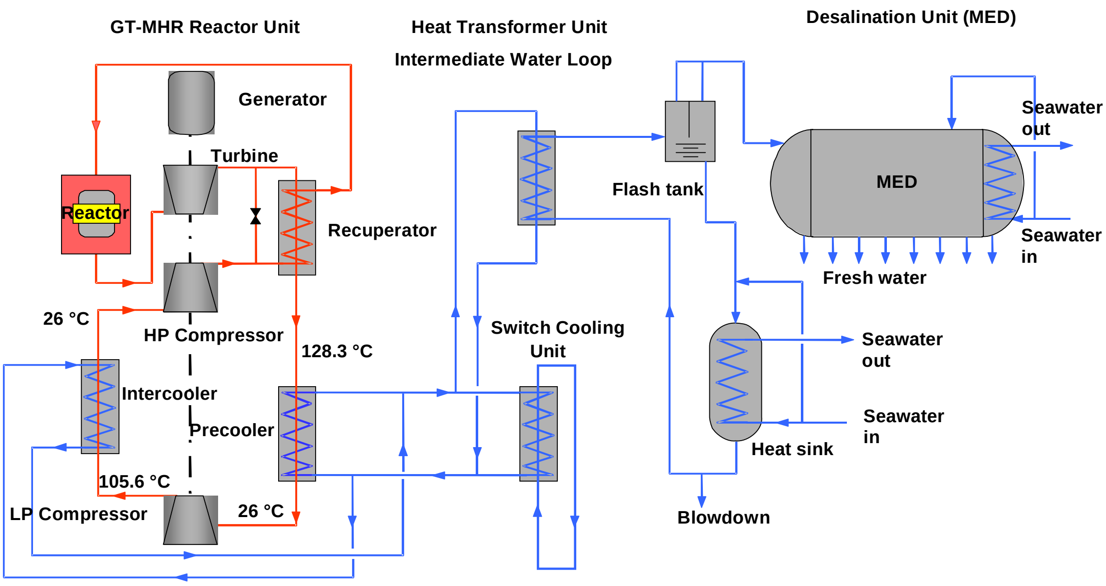

Figure 2. Principle of waste heat utilization from a GT-MHR (or PBMR) [11].

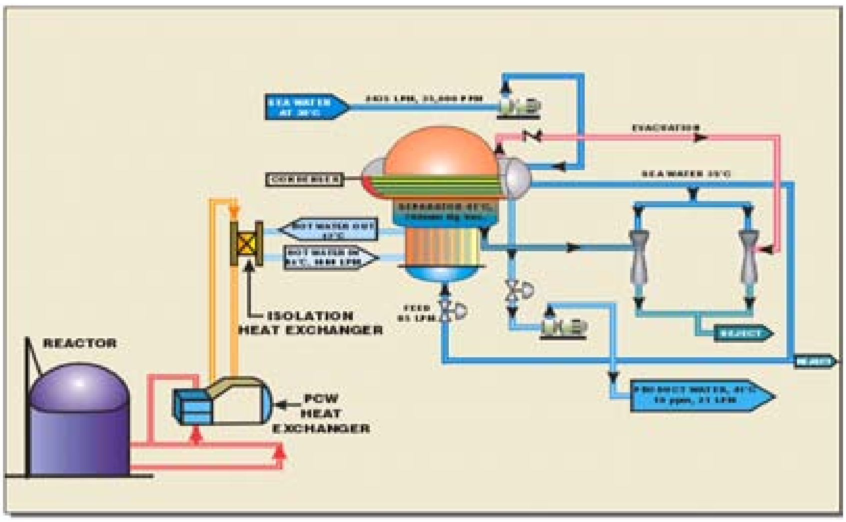

Figure 3. LTE-MED system coupled to nuclear research reactor in Trombay, India.

The LTE unit was then coupled to the CIRUS reactor. The nuclear research reactor (CIRUS) has a capacity of 40 MW(t) using metallic natural uranium fuel, heavy water (D_2O) moderator, demineralized light water coolant and seawater as the secondary coolant. An intermediate heat exchanger (IHE) has been incorporated between the nuclear reactor (CIRUS) and the desalination plant to ensure no radioactive contamination and high protection of desalted water.

The integrated system has since then been successfully operated and has clearly demonstrated the technical fesibility of the coupling to nuclear research reactor. The product water from the plant meets the make up water requirement of CIRUS.

2.2. SAFETY CONSIDERATIONS RELATED TO THERMAL COUPLING OF A NUCLEAR POWER PLANT TO A DESALINATION PLANT

Safety aspects of nuclear plants coupled to desalination plants are discussed in detail in Ref. [12]. The main aspects are the influence of the coupled desalination plant on the transient behavior of the nuclear plant and the risk of migration of radioactive substances into the product water of the desalination plant.

2.2.1. Transient behavior of a nuclear power plant coupled to a desalination plant

In principal, a thermally coupled desalination plant (e.g. MSF or MED) becomes (usually part of) the ultimate heat sink of the nuclear power plant. Thus, in case of a sudden shutdown of the desalination plant a (partial) loss of heat sink transient is to be considered. However, this transient is already covered in the design and safety analysis of the nuclear power plant itself.

In case of a sudden shutdown of a RO plant coupled via electricity supply to the nuclear power plant the heat removal via the condenser is not impaired but it leads to a (partial) loss of electrical load transient. Again, this transient is covered in the safety case of the nuclear power plant already.

The rupture of piping designed to transfer steam from the secondary side of a nuclear power plant to a distillation desalination plant leads to a (partial) steam line break. This transient is already taken care of in the design and safety analysis of the nuclear power plant.

2.2.2. Experiences with nuclear desalination product water quality

A basic issue of nuclear desalination is the potential of transfer of radioactive contaminant from a nuclear power plant to the desalination system. Radiation safety of the product water must be guaranteed constantly, with a system design avoiding any such risks. Regarding the product water quality, the primary concern from the radiation safety aspect is on tritium - a radioactive hydrogen isotope produced in the core of a thermal nuclear reactor mainly by fission of uranium (U), but also by interaction of neutrons (n, α) with, primarily, boron (B), lithium (Li), helium (He) and deuterium (^2H) [13]. It is highly permeable, able to get into the desalination loop where it forms tritiated water by oxidizing, and is not removable by RO membranes [14], [15]. It is important to note that tritiated water (HTO) is 25 000 times more radiotoxic to humans compared to gaseous tritium (HT) [16].

Most of the tritium in the nuclear loop, more than 90%, is in the form of tritiated water [17], and presents a contamination possibility which can be more severe in case of leakage from the nuclear to the desalination loop compared to gaseous tritium diffusion. The established solution to prevent radioactivity cross-contamination includes an intermediate (or isolation) loop between the nuclear and the desalination plants:

- This intermediate loop must have a higher pressure than the nuclear one in order to assure that a possible leak will happen from the intermediate to the nuclear side, not the other way around. Discovering small ruptures though, is very difficult, so it is important always to maintain the higher intermediate loop pressure. The intermediate loop includes an additional heat exchanger towards the desalination loop, allowing for another physical barrier that should prevent radionuclide contamination of the desalination loop. Ideally, the desalination loop would have a higher pressure than the intermediate loop for the same reasons. Nuclear power plants' district heating schemes also use the same radiation safety principle [14].

- To avoid the migration of tritium gas from the primary coolant to the desalination system several engineering provisions exist that remove non condensable gases like tritium from coolants. Firstly, already in the primary loop of the reactor coolant system a great deal of tritium produced in a reactor is removed together with other non condensable gases by the so-called off-gas system. Also in the steam cycle of a nuclear power plant degassing is performed. At MAEC, which uses a sodium cooled reactor, both coolant loops had cold traps removing tritium from the coolant. Not to be neglected is the fact that incoming feed water to the desalination plant is generally degassed thereby further reducing the possibility for tritium oxidization into tritiated water.

- Installation of sufficiently sized storage capacity of product water to ensure an adequate time delay before distribution of desalinated water to customers enabling measurements of operational parameters and follow up actions as discussed in the following.

To exclude the risk of radioactive contamination of the product water completely, appropriate instrumentation and control (I&C) are installed to detect non tolerable changes of operating conditions and if needed to shut down the desalination plant (DP):

- Monitoring of the pressure in the intermediate heat transfer loop and first loop of DP to detect depressurization (or pressure increase) indicating leakage in the heat exchangers between these loops; and

- Monitoring of the radioactivity level to detect intrusion of contamination into the turbine loop, the intermediate heat transfer loop and first loop of the DP.

Additionally, the final treatment of the desalinated water to convert it to drinking water standards includes several chemical and mechanical (e.g. filtration) processes which are also carefully monitored to assure the quality of the potable water before it is distributed to customers. Thus, this final step provides assurance that the drinking water delivered is safe for use.

In regard to desalination plants producing potable water the limits of tritium in drinking water are of interest. A list of international limits is provided in the following Table 2 [18].

These limitations can be compared to the existing nuclear desalination experiences with product water quality. The largest such facility, MAEC, was reported never to have had more than 6 Bq/L in the desalination plant streams. The mineralized water that was mixed with the desalinated water in order to achieve drinking quality, increased the tritium content in the drinking water, but never over the regulatory health limit [15, 19].

Table 2. LIMITS FOR TRITIUM IN DRINKING WATER

Country	Tritium limit (Bq/L)	Country	Tritium limit (Bq/L)
Australia	76 103	USA	740
Finland	30 000	WHO	10 000
Canada	7000	Kazakhstan	7700
EU*	100	Switzerland	10 000

* This is an alarm level rather than a regulatory limit.

The experience from Kalpakkam, India is similar. No specific value for the tritium activity in the drinking water was reported since it was below the measurable limit [20].

Additionally, nuclear desalination experimental results (China, Russia) as well as other nuclear heat applications such as district heating (Slovakia) have reported measured tritium activity of less than 50 Bq/L, with one experimental case reporting a measured value of 0.1 Bq/L [14].

The Swiss NPP Beznau does not actually measure the tritium content on the side of the district heating loop because its pressure is at 13 bar (compared to 1.5 bar at the turbine-steam side), preventing contaminated fluid leaks [21]. This experience is applicable to nuclear desalination with RO, since this desalination process involves even higher pressures.

Concerning fossil fuel conversion with heat from a HTR, the findings of Kirch and Scheidler (reported in 1985), provide a value of 500 Bq per kg of secondary energy carrier[1] during steady operation and around 1000 Bq/kg during plant start up. This value was achieved after continuous improvement from a tritium level in the secondary energy carrier of 8000 Bq/kg in 1980 [22].

As can be seen, nuclear power plants coupled with heat driven systems, such as desalination, are well capable of controlling the tritium activity level in the product water through system design and operation practices. More details about the issue are provided in the Appendices.

3. ENVIRONMENTAL IMPACTS OF NUCLEAR DESALINATION

Up to date, the environmental impacts of desalination are not known well enough to dismiss concerns regarding its environmental impacts [23]. Site specific studies present different impact results. It seams reasonable that this is due to the numerous influencing factors such as desalination capacity, technology, operation and maintenance practices, hydrology, bathymetry, geographical and meteorological conditions etc. Therefore, for specific desalination projects environmental impact assessments must be performed in order to investigate the options and mitigate possible impacts with optimal solutions.

As for nuclear desalination facilities so far, the available environmental monitoring data is rather scarce. Yet, the data which is available or applicable can offer an overview of various environmental impacts whose adverse potential will require them to be addressed in any specific nuclear desalination plant EIA. Since nuclear power plants are rigorously assessed, this report will concentrate more on the desalination aspect of nuclear desalination, although

[1] Converted fossil fuel such as coal into liquid or gaseous fuel, for purposes of easier transport and storage.

through the perspective of cumulative impacts some aspects will be examined for the nuclear plant as well.

The key concerns that should be covered by the scope of a nuclear desalination EIA, and hence this report, will be based on:

- Marine impacts: based on the intake of seawater and brine discharge from the facility, different options for these operations and characteristics that would influence the magnitude of environmental impact,

- Coastal impacts: defined by the construction, noise and visual impacts as well as land requirements for the operation,

- Atmospheric impacts: originating from the use of energy for a certain desalination capacity regarding greenhouse gas emissions including radioactive emissions,

- Siting and co-location issues: their contribution to the overall impact, including the water transport issue, and environmental concerns that arise with these issues,

- Socio-economic impacts: relocation of people and capital, development issues due to energy and water availability, economic competitiveness of nuclear desalination, impacts on sustainability, as well as

- Public health and public acceptance: quality, reliability of supply and radiation safety of the product water, concerns on plant safety and public perception of these issues.

As a generic assessment, this report does not have the possibility to discuss the alternatives to nuclear desalination in detail. To supplement, some general comparisons and principles are offered.

3.1. MARINE IMPACTS

Significant proportion of the scientific literature on seawater desalination is dedicated to the specific environmental impacts it has on the marine environment. Many organizations and authors (UNEP, WHO, MEDRC, CCC, Pacific Institute, Lattemann, Hoepner, Younos, Einav, Mickley, Meerganz, etc.) address this aspect of the desalination's environmental impacts at length. This high interest can be explained with two basic facts: first, the coastal ecosystems are increasingly depleted [24], and there are concerns that desalination could add to the cumulative adverse impacts, especially by its liquid multi-component waste discharge [25], contributing to the decline of coastal and marine ecosystems and their biological resources. The other fact is that the seawater represents a basic resource for the desalination process and degrading its quality will reduce the efficiency and quality of the desalination processes.

Desalination can impact the marine environment through two major operation phases: seawater intake and effluent discharge. Both processes are known in the power generating industry, including nuclear, and present similar concerns. Co-location of desalinating with a power plant though, involves additional issues that need to be addressed by the power generating community, such as the high salinity and the chemical composition of the brine discharge. As it has been found by the literature review on the subject, for minimizing or even eliminating these potential impacts feasible and applicable solutions do exist.

3.1.1. Impacts from seawater intake

This section will concentrate on the aspects and issues of intake systems that have to be addressed when considering seawater desalination co-located with a nuclear power plant. It will present the emerging new environmental regulatory situation, describe the intake systems as they are the main impact sources, explain entrainment and impingement as main factors of impact, asses their impact on the ecosystem, and offer recommendations and mitigation measures for the environmental impacts of the intake systems.

3.1.1.1. Environmental regulations applicable for nuclear desalination intakes

Regardless of whether the seawater intake systems are shared by a desalination and nuclear power plant or not, they are required to deliver sufficient quantities of water for their uninterrupted operation. The need for constant and good quality seawater should have great influence on the siting of the power and desalination plants. Until recently though, this was regarded more as a technical rather than a major environmental issue, aiming at lower and more predictable plant operation and maintenance costs.

New studies have suggested greater environmental impacts on the marine environment due to the intakes rather than brine discharges [26, 27]. The California Coastal Commission states: "The most significant direct adverse environmental impacts of a desalination facility are likely to be caused by its intake. These impacts also can be completely eliminated by using alternative designs and mitigation measures." [28]. Therefore, aiming for more environmentally conscious solutions, the existing power plant intake regulations are being adopted for desalination. Since nuclear desalination intakes are not specifically covered anywhere, the regulations that should be applied in the case, are the power plant intake regulations.

There is a growing pressure for desalination facilities to comply with these standards in the USA [29], where they are most detailed and stringent. In fact, California Coastal Commission has recently denied the permit for a desalination plant that wanted to use the existing intake system of a co-located power plant near Carlsbad, insisting that environmentally and operationally better solutions can be implemented instead [30]. The permit was eventually issued, but a tendency has emerged for desalination facility's licensing to include studies which are required by the Water Act Section 316(b) for power plant intakes. The California Coastal Commission has already recommended that coastal desalination plants conduct impingement and entrainment studies similar to the power plants', and achieve similar reduction targets: for impingement of 80-95% and an entrainment reduction of 60-90% from uncontrolled levels of conventional intake systems [31].

The environmental impact of the power plant intake systems addressed in the US Clean Water Act Section 316(b) requires that "the location, design, construction and capacity of cooling water intake structures reflect the best technology available for minimizing adverse environmental impact". Consequently, the US EPA issued in 2004 standards for existing facilities that use large quantities of seawater but suspended them in 2007 [32]. However, for newly built facilities, EPA established in 2001 standards for location, design and capacity [33].

IAEA's Safety Guide on Design of the Reactor Coolant System and associated Systems in Nuclear Power Plants asks for evaluation of locations and sizes of intake structures when assessing safety. This should be done "in terms of patterns and effects of biofouling […] on the effectiveness and performance of the proposed design".

3.1.1.2. Types of intake systems as sources of environmental impact

A substantial part of the total desalination plant cost can be attributed to intake infrastructure [26, 34]. Although this is not the only reason for co-location, it has a significant contribution to the tendency to co-locate desalination facilities with power plants using cooling water intake systems. In general, intake systems can be divided as direct and indirect.

Direct intakes are known as open or surface intakes (Figure 4). Any desalination plant can apply them, typically though for capacities higher than 20 000 m^3/d of feedwater [34]. Distillation processes (MED, MSF), whose performance is not very sensitive to water quality, can use open channels for intake of sea water. Membrane processes such as reverse osmosis are much more demanding in regard to their feedwater. Since for both types of desalination processes the quality of the feedwater has to be as constant as possible, in terms of temperature and composition, it is usual to place the feedwater entry point either in naturally protected areas (i.e. bays) or deeper waters further away from the coast.

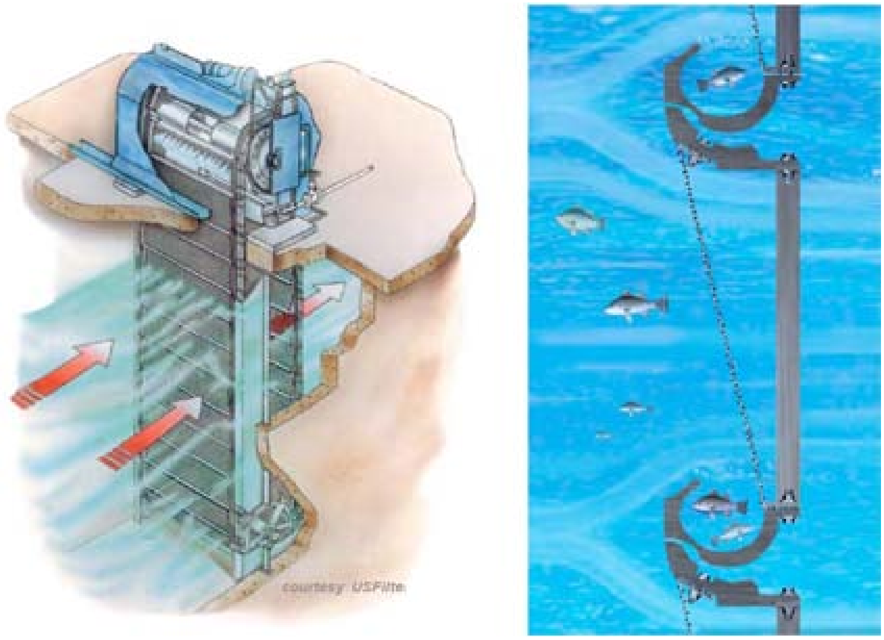

Figure 4. Traveling screen (left) and Ristroph traveling screen modification (right).

Thus, intakes are complex structures that can reach more than 3000 meters in length [35]. Regardless of the screens and filters that are used, open intakes are primarily located far from pollution sources such as brine discharge, ports, sewage, hydrocarbon spills and navigation routes in order to avoid negative influence on the pre-treatment procedure and the associated costs.

Large desalination and power plants traditionally use direct seawater intake systems since, unlike indirect intakes, they can guarantee delivery of large quantities of water. However, pumping out from the sea can cause great suction force and increased water velocity near the intake openings, which have a direct correlation with mortality rate for marine organisms [36]. Having in mind that, depending on the location, the seawater can contain considerable biomass, higher suction force from the intake will result in higher level of biofouling to the power and desalination systems. Aiming to achieve lesser systems biofouling, different types of screens and filters have been employed, and their brief description is presented below.

Travelling water screens are the oldest and most conventional type of intake screening equipment. (Figure 4, left) Their main features are the revolving mesh wire panels with 6 to 10 mm openings. The screens can be located either onshore or offshore, along the water intake line [26]. Once in a few hours, mechanical cleaning is applied, usually with a strong jet of water, disposing of debris gathered on the panel surface.

Lately, as one of the least marine protective technologies, this simple solution has encountered substantial regulatory difficulties. The US EPA requirements for reducing water organisms' mortality due to intakes means that in most cases, travelling screens can no longer be the only technology applied. Further modifications to this type of screen introduced the Ristroph travelling screen (Figure 4, right), with buckets that would contain marine organisms, from where they are removed and returned into their environment, and fine mesh travelling screens, preventing organisms to go through the screen.

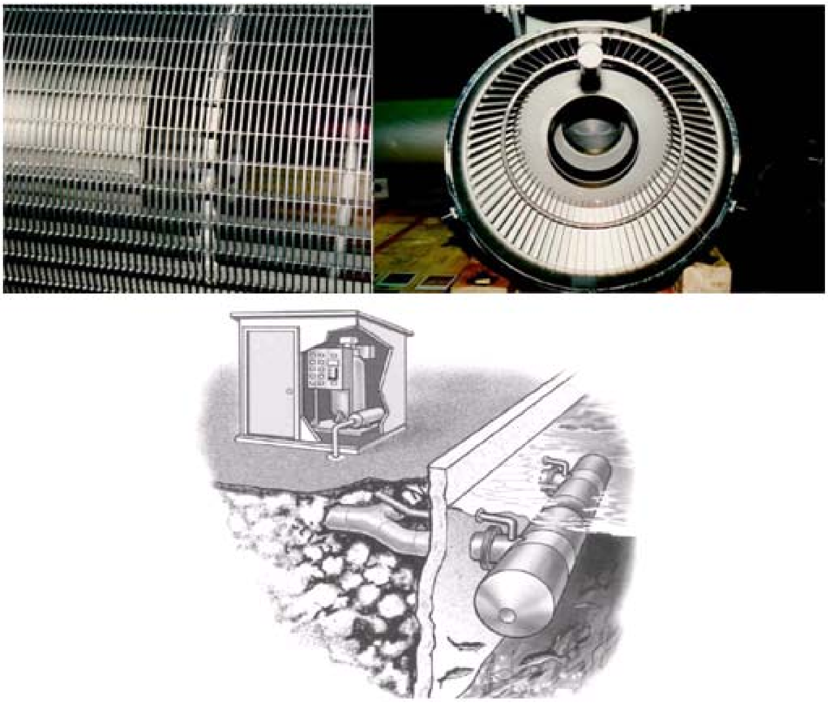

Figure 5. Wedgewire intake screens: outside surface (top left), inside look (top right), deployment scheme (below).

Passive wedgewire screens (Figure 5) are another newly developed type of screens that can be found in different shapes: flat, curved, cylindrical etc. They have a mesh size of 0.5 to 10 mm and will prevent organisms larger than the nominal screen opening to enter the intake system [37]. The corresponding low seawater intake velocity of 0.15 m/s results in lesser debris and marine organisms build-up on the screen, but adequate counter current flow is needed to transport organisms away from the screen [26]. One of the main problems with this type of screens is that the air backwash system is not always able to clean the screen surface covered with debris [38].

Behavioral barriers such as strobe lights, air-bubbles, sound and velocity caps have been tested with positive results. It must be noted that these results were obtained only when behavioral barriers were used in combination with other intake technologies [36].

Other parts of direct intake systems can have influence on marine organisms' mortality, notably the intake pumps [36]. Variable speed pumps are used to reduce the intake flow of feedwater when the demand for it is smaller. By reducing the intake volume, which is also reflected in a lower intake velocity, the quantity of undesirable material in the feedwater is also reduced. Clogging of the intake screens and pipes either with debris or marine organisms can cause an increase of intake velocity and suction force, further enhancing debris and biomaterial accumulation in the intake infrastructure.

Direct intake systems can provide substantial quantities of seawater supply if needed. Yet, overall experiences show that they are not as reliable solution as it may seem. Massive biofouling are known to cause power plant shutdowns for safety reasons [39], but it appears that appropriate design changes can reduce the occurrence of such events - albeit at the expense of reduced power plant efficiency [40].

On the other hand, their construction is technically feasible regardless of the site conditions. So far, environmental regulations have mainly targeted direct intake applications with rigorous standards, but these systems have demonstrated that conforming, though sometimes complicated, is achievable when some of the more advanced technologies, combined or alone, are applied. Concerning nuclear desalination, they appear to be the natural choice, if the plant should require considerable quantities of seawater – for desalination as well as for once-through cooling of the plant. All nuclear desalination facilities so far, have used a direct seawater intake to provide cooling and desalination feedwater.

As for indirect seawater intakes, several designs can be found in use (Figure 6). Their capacity for supplying water can vary per type, but is generally considered to be lower than the capacities of direct intakes. Small capacity facilities, which mostly use reverse osmosis technology, are known to apply indirect intake systems for feedwater supply. Their design includes geological structures such as porous rocks, sea mud, sand and other seabed material between the intake infrastructure and the sea, limiting the intake with its water permeability.

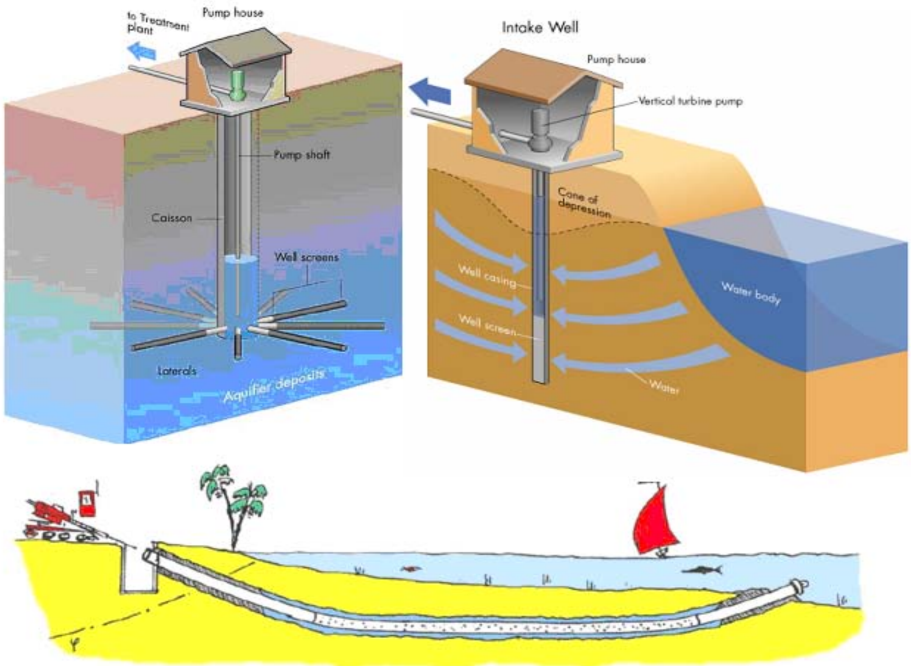

Figure 6. Indirect intake systems: horizontal well (left), beach well (right) and HDD (below).

On the other hand, that design allows all indirect systems to provide higher quality of feedwater when compared with the direct intakes. Acting as a pre-filter for the seawater by eliminating solids, the seabed material allows initial pre-treatment and a more constant temperature of supplied water. Furthermore, indirect intakes have two factors on their side which make them preferable over direct intakes when avoiding harm to marine life is considered. First of all, the layer over the porous intake pipes ensures that a minimal number of marine organisms will enter the intake system, providing an effective physical barrier as well as a filter for plankton, larvae, fish eggs and different forms of pollution. Secondly, the low water velocities resulting from the large intake surface and the limited permeability of the seabed do not generate a suction force large enough to constrain free movement to organisms. Additional advantage is the fact that they do not interfere with navigation in coastal waters.

The first indirect intake systems applied were beach wells as they are the simplest solution from a design point of view, similar to artesian wells. A typical beach well would consist of perforated inner and outer casings with a large number of slots from 0.3 to 0.7 mm. Usually the wells are positioned close to the seashore, where the largest quantity of seawater can be harvested, but currently, the individual capacity for such a well is only up to 4000 m^3 per day, depending on the hydrogeology of the site [26, 41]. The water properties from these intakes, such as seawater turbidity and Silt Density Index, can be respectively 1 NTU[2] and 2 SDI (compared to 20 NTU and more than 6.7 SDI for direct intakes), but would in general depend on the permeability of the geological structure where the beach well is located [41]. Nevertheless, it is obvious that the seawater pre-treatment, especially needed for SWRO plants, would be substantially reduced, using such an intake.

Horizontal collector wells are a further development of the beach well design, with pipes stretching in a radial pattern from the bottom of the well buried under the seabed in areas of brackish water. Such construction provides significantly higher intake capacities. It involves several layers of crushed stone, gravel and sand acting as a seawater filter on top of the 200 to 300 mm diameter pipes [26, 42]. Infiltration galleries function essentially in the same way as horizontal collector wells, with a more compact construction (Figure 7).

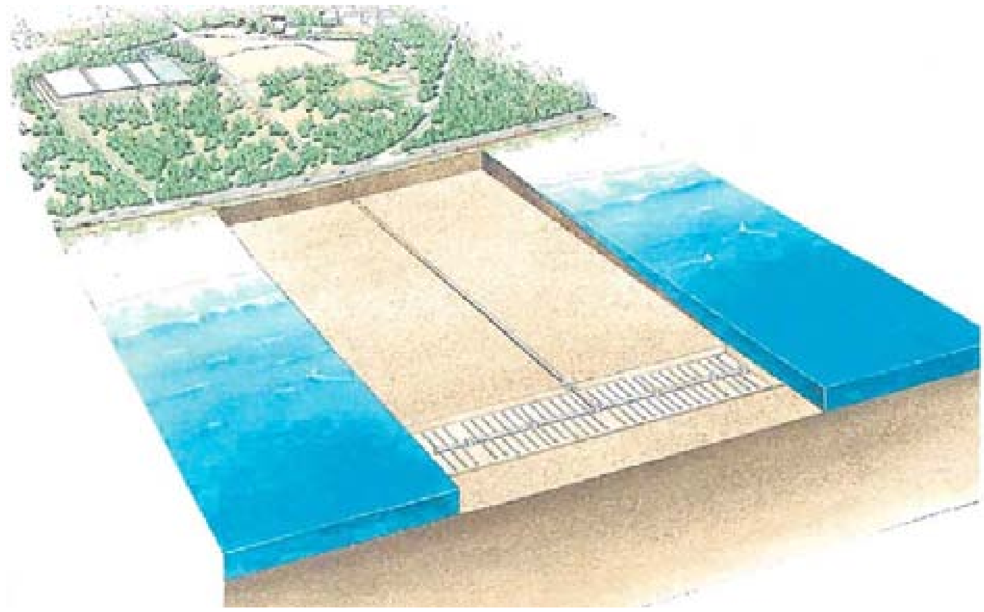

Figure 7. Infiltration gallery.

[2] NTU stands for Nephelometric Turbidity Units, used as an indicator of particulate matter quantity in the water.

Horizontal directionally drilled collectors consist of porous pipes that are inserted in bore holes drilled 5 to 10 meters in the geological structures under the seabed [34]. With the current possibility to drill approximately 2500 meters in length [43], their capacity exceeds the other indirect seawater intakes, needing less space. HDD collectors have been used for desalination processes with approximate output capacities of 100 000 m^3/d, proving to be a reasonable option even when compared to direct intakes. Another advantage for this system is that the pipes' endpoints emerge from the seabed and if the capacity proves to be insufficient, the sealed endings can be opened transforming the intake into a direct seawater intake.

Recently, a new concept was proposed for use of indirect intakes, involving geotextiles fabrics and microtunneling technologies for a synthetic infiltration gallery, which will allow intake placement in a variety of sites regardless of their geology and biological activity [43]. Further development regarding this proposal remains to be seen.

In general, it can be concluded that indirect seawater intake systems still lack the possibility of the direct intakes for guaranteeing delivery of larger quantities of water and are not likely to be applied for nuclear desalination. Furthermore, indirect intakes are dependant on the geological structures in the desalination site's vicinity, which might not allow for this technology in the first place. Despite this, indirect intakes have remained a serious option even for larger desalination facilities, although still not widely used by them today. This is mainly due to their operational advantages such as lower fouling rates and lesser usage of chemicals as well as more constant and higher seawater quality parameters such as temperature and pH values. The environmental impact of indirect intakes is also much smaller (see 3.1.1.4.), complying with the ever more restrictive environmental regulations. The new developments with their increasing capacity and placement variability might easily propel their use in power and desalination industry.

3.1.1.3. Receptors and pathways of environmental impact

Owing to the economic and logistic reasons which tend to dictate intake location as close as possible to the coastline, the predominant concern on affected areas is on coastal water habitats. These habitats are full of nutrients, brightly illuminated and warm, sited in the areas where most of the primary production[3] is to be found, provided by phytoplankton. Corals, seagrass, seaweed, and other marine plants also provide food, in addition to oxygen and much needed habitat for other organisms. Such suitable conditions are the basis for the intricate marine life ecosystems consisting of myriad different benthic, nektic and planktonic communities (as spores, eggs, larvae, juvenile or adult individuals) in quantities dependant on the local eco-balance.

Having in mind that seawater is a habitat rich in biodiversity, intake systems, especially the direct ones, become a matter of concern regarding their environmental impact. This impact is harder to identify and quantify compared to the discharge impact [28, 34]. There are two main pathways of environmental damage to marine organisms: entrainment and impingement. Both introduce an additional source of mortality in seawater habitats alongside natural mortality due to age, disease and predation [44].

Entrainment refers to organisms that have passed through the openings of the seawater intake screens and were drawn into the water manufacturing process. Due to the extreme pressures to which organisms will be subjected, collision with parts of the pump, high temperatures, as

[3] Primary production refers to living organisms' mass created in a certain area over a period of time.

well as the biocides that are used to prevent biofouling (e.g. chlorine), entrainment is considered to be deadly for all organisms.

Impingement occurs when marine life forms are trapped against the intake screens by the suction force and velocity of water. Experiencing starvation, exhaustion and asphyxiation, they do not necessarily succumb to either latent or immediate death. However, very often impingement does lethally affect marine organisms. If they do not die by injuries from the collision with the screen or suffocation while being trapped, there is a possibility that some life support function of these returned organisms will be damaged. If the organisms suffer from internal or external injuries that reduce their ability to move through the environment, and thus become an easier target for predation, their chances for survival can be significantly lower. More robust species of marine organisms can have higher impingement survival rates, but some species have a survival rate below 10% [45].

Impingement usually affects larger organisms. Fish, invertebrates, mammals, birds etc. can get trapped and killed on the intake screens, which is the real concern with impingement. For smaller organisms like phytoplankton and zooplankton, fish eggs and larvae, spores of kelp, seaweed and seagrass, entrainment is of higher concern (Figure 8). Depending on the size of the screen mesh, one or the other will have higher influence on the marine life. Of course there are technologies that have been applied with some success or currently are being tested as promising in reducing the impingement and entrainment effects.

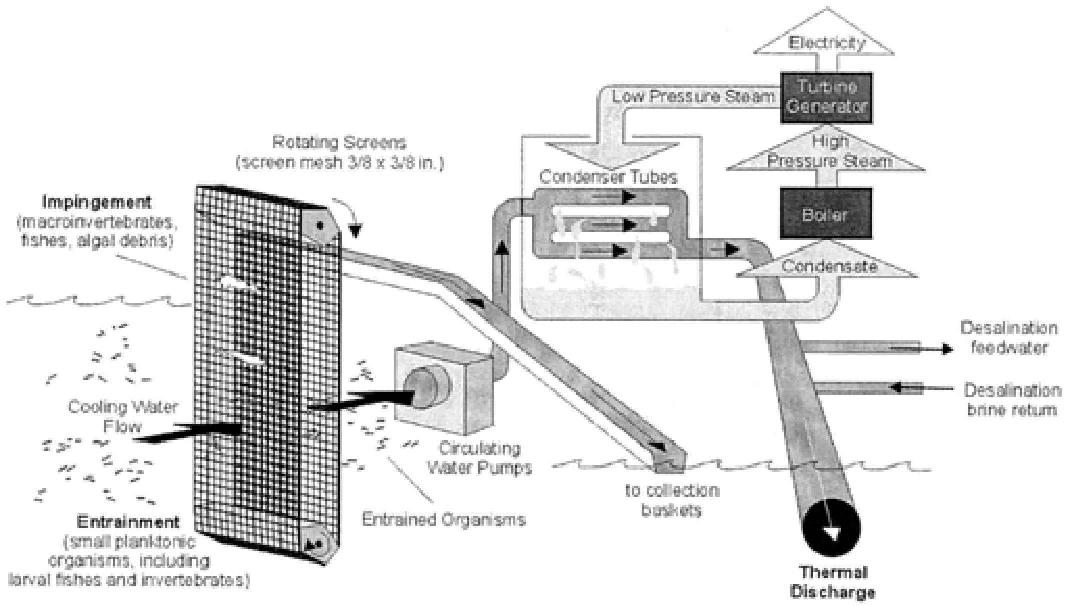

Figure 8. Entrainment and impingement.

Nevertheless, water withdrawal as a marine impact factor cannot be ignored and intakes of nuclear desalination plants should be of great concern, especially when direct intakes for once-through cooling are involved. The main reason for this is that nuclear power plants require greater specific quantities of cooling water compared with other thermal plants (Table 3) [46] and hence higher specific entrainment and impingement rates should be expected.

Table 3. COOLING WATER WITHDRAWAL RATES (m^3/MWh)

	Once-Through Cooling	Pond Cooling	Cooling Towers
Nuclear	95 - 230	2 - 4	3 - 4
Fossil	76 - 190	1 - 2	2
Natural gas/oil CC	29 - 76	/	1

Seawater temperature is important with respect to water withdrawal. Cooling systems are usually licensed for a certain temperature difference, but also for a maximal discharge temperature[4] [47]. When the seawater temperature at the intake point is closer to the licensed discharge temperature, the necessary quantity of cooling water is higher, therefore increasing the entrainment and especially impingement[5] rates.

Apart from the water quantity and velocity, as well as screening technology of the direct intake, additional factors influencing entrainment and impingement can be identified in the seawater properties such as temperature and dissolved oxygen levels. Low oxygen levels incapacitate the fish, reducing their ability to swim away and subsequently may cause major impingement incidents leading to possible plant shutdowns.[6] The frequency of the travelling screen's rotation and washing, the strength of the washing spray and the location where impinged fish may be returned, also influences the organisms' mortality rate [48].

Altogether, these seasonal variations, local disturbances, intake operational parameters, organisms' age and species strongly influence their swimming abilities, contributing to their vulnerability to entrainment and impingement. In return, all these factors also started influencing the intake system design, for desalination plants as well as for nuclear power plants. Subsequently, nuclear desalination will certainly inherit the consideration and experience in handling of entrainment and impingement factors with intake systems. Still, the next section will offer an overview of reasons why the concerns remain and should be carefully addressed prior to project implementation.

3.1.1.4. Environmental impacts of intake systems

The environmental impacts of the intake systems may be severe. A properly chosen and designed system though, can mitigate the potential for adverse impacts. Depending on the environmental conditions at the site, one or the other intake system will have an advantage in avoiding harm to the environment. Some environmental problems, especially during their construction phase, are common for all intake systems.

If existing seawater intakes cannot be used for the desalination facility, depending on the type of intake to be applied, such systems may require under-water works that can include: excavation, dredging, embedment, pipe lying, gravel and sand covering, and anchoring. Normally the impact from constructing the intake system is temporary and limited to the construction area [49]. Its intensity will depend not only on the chosen intake system and

[4] In the USA most of the thermal power plants using once-through cooling are allowed to discharge effluents with temperatures between 39 and 41 ^{o}C [47].

[5] The higher intake quantities of seawater through the same direct intake will inevitably cause greater intake velocities and increase the force with which the organisms and material will be impinged on the screens.

[6] This case was reported happening at the Calvert Cliffs NPP [48]. Fish were incapacitated by the cooler water withdrawn from deeper zones, which were oxygen deficient. The reason for low oxygen events was not described in detail, but it is likely that it was not connected with the discharge of the plant.

method of construction, but also on the site location and bathymetry, biological activity and ecosystem richness, currents, tides and wave activity, and the site's geological properties. This impact is mainly due to the increased turbidity that affects the photosynthetic process and sedimentation from the settling material. In that case, the benthic communities may suffer high mortality rates and inability to recover during the construction time in the affected area, the phytoplankton's photosynthesis can be affected negatively and the nektonic species are likely to migrate out of it. This ecosystem deterioration can cause local fisheries to decline or even collapse.

Studies of biological communities have shown that typically biological communities might need between one and three years to recover from the disturbances such as boat anchors [50]. Construction activities can affect much larger marine area, and depending on the measures taken to prevent such adverse impacts, the necessary time for ecosystem restoration can be even longer than three years.

The consequences of entrainment and impingement impacts on aquatic communities are difficult to define. According to Brining *et al* (1981), entrainment and impingement caused by the seawater intake systems "may adversely affect recruitment of juvenile fish and invertebrates to parent or resident populations or may reduce breeding stocks of economically valuable fishes bellow their compensation point resulting in reduced production and yield" [51]. Effects of impingement and entrainment depend on the species and intake site [23]. If the intake is positioned in highly biologically active areas, which are usually close to the coast, it could well cause significant environmental damage through entrainment and impingement of marine organisms.

Yet, locating water intakes often is done in zones of relatively high biological activity. Apart from economic reasons that favor short intake piping, the sensitivity of the intake systems to meteorological conditions is also a factor that dictates the intake location in naturally protected areas. Indeed, the quality of the seawater supplied by direct intakes depends on the magnitude of wave activity, strong winds, storms and other harsh weather conditions which can adversely affect its quality as well as damage the intake structure [26]. In the same time, many marine organisms very often use the same protected environment for spawning and larvae hatching. For instance: more than half of the California's 21 coastal, mainly fossil fuel power plants, have intakes located in bays, harbours, coves, or estuaries [40].

Out of those, Diablo Canyon NPP (Figure 9) is the only one that qualifies to be a nuclear desalination facility according to the IAEA definition [52], despite its small desalinating capacity ranging around 2180 m^3/d mainly used for cooling water make up. Built in the times when the adverse impacts of any power plant on the environment were largely unknown and overlooked, its seawater intake system with a seawater withdrawal of up to 9.5 million m^3/d [53] is situated in a coastal cove.

Subsequently, researchers have estimated its attributed entrainment/impingement rate for five selected near-shore fish larvae to be from 10-30% with "potential dramatic effects on the local coastal environment" [44, 53]. The California Energy Commission analysis of the Diablo Canyon intake impact suggests that the larvae loss due to entrainment equals 120-240 hectares of rock reef habitat [40]. The methodology used to calculate these impacts is presented further (see Appendix I) and is considered as a proper tool although it is difficult to firmly ascribe changes in the marine organisms' populations to a specific impact due to lack of knowledge on impact interactions.

Figure 9. Diablo Canyon NPP.

The experience with direct intake entrainment and impingement impacts from the largest nuclear desalination plant near Aktau, Kazakhstan, shows that no significant impact was noticed, probably because the direct intake equipped with rotating mesh drum was located far away, at 3800 meters from the coastline and at 10 meters depth [54].Unfortunately, it was not assessed with systematic studies.

Following the experience with the intake for the Cypriot Dhekelia desalination plant located some 150 meters from the coastline (and 200 meters from the discharge point), the Larnaca desalination plant implemented a 1100 meters long intake pipe (2 km away from the discharge point) [49]. The reported results refer only to the discharge impact which was lower, but it is certain that part of it was due to the intake location.

Studies of different locations can provide, with the help of specific calculation models, best suitable location for intakes in terms of entrainment and impingement reduction. It should be noted though that the calculations do not explain the meaning of the loss for the environment. In some cases, no matter what the calculated loss quantity is, the entrainment and impingement might not add to the species' mortality rate in the intake affected area given the fact that egg and larval mortality can be naturally high [23].

Moreover, no method takes the spatial factor of distribution of impacts into account [55]. In general, even small, hardly detectable local impacts may have great impacts across a larger area. Also, commercially non-usable species are rarely taken into account although they do have equally important role in supporting the commercial species and the whole ecosystem. Since such extensive studies would be extraordinarily expensive and therefore are not conducted [55], the application of the precautionary principle is recommended.

As mentioned, many factors contribute to the marine species' demographics, and their interactions are difficult to assess with the current knowledge on the subject. Yet, some of the fish species that have experienced population decline in Southern California were also noticed to be the ones with most entrained larvae; the impingement impact, which is considered to be lower, adds to the magnitude of entrainment impact [56]. These observations have contributed to the arguments that intake systems may have a substantial environmental impact.

Installing direct intake structures may also affect water exchange and sediment transport and obstruct shipping routes. On the other hand, they may also act as artificial reefs for marine organisms providing a new habitat [57].

Although never applied in a nuclear desalination facility, indirect (subsurface) seawater intakes remain an option. From an environmental impact perspective, their greatest problem lies in possible fresh groundwater aquifer deterioration from seawater intrusion, if not well designed and constructed. Most commonly this happens by disturbing the flow balance that exists between waters with different salinity. When water is pumped out of a beach well, higher salinity water moves in the upper layers thus, for instance, enlarging the coastal brackish water zone where the fresh water is mixed with seawater. (Figure 10)

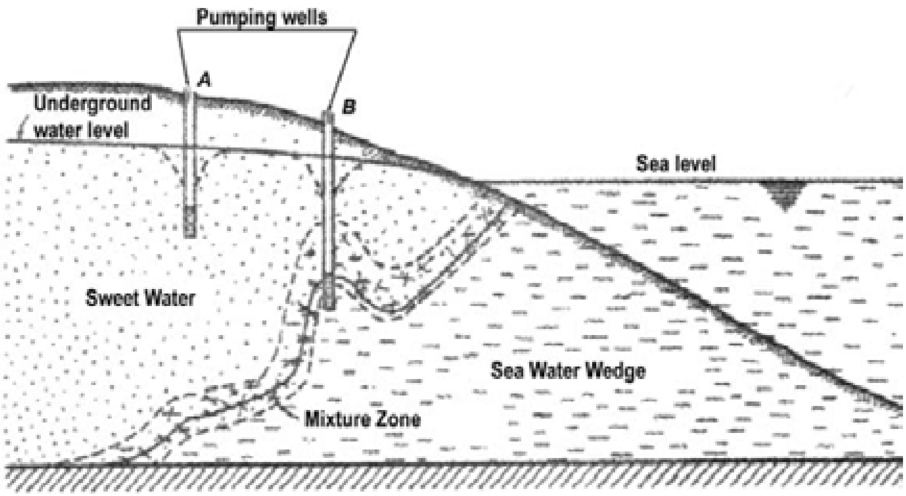

Figure 10. Aquifer deterioration due to beach well pumping.

Intake pipes positioned through aquifers present another potential danger due to possible leaks of seawater, which is why, for instance, this option was ruled out in advance for the desalination plant in Ashkelon, Israel [49]. Over time, increased salinity of the fresh aquifer water can lead to soil salinization and subsequently to floral deterioration including agricultural decline. Changes in the salinity stratification of the aquifer waters may also lead to lower quality of the desalination feedwater, affecting the performance of the desalination process. Finally, the initial disturbance due to construction may be higher when indirect intakes are applied, as seabed sediments are replaced or resuspended [25]. Their entrainment and impingement potential though, is negligible.

3.1.1.5. Environmental impact mitigating recommendations

Mitigation measures have lately become a necessity through the environmental regulations, especially in the USA, although such specific regulations are expected to be introduced in other countries as well. The current US EPA standard requires that the best available technology should be used in order to achieve impingement reduction of 85-95% and entrainment reduction of 60-90% [31]. On the other hand, experience has shown that, on a broader basis, no uniform solution exists for minimized entrainment/impingement impact by intake systems [48]. The design and location of the intake should be site specific, adjusted to the particularity of the local marine ecosystems. This is especially so given the possible combinations of desalination processes and capacities with nuclear power plant's energy output and cooling applied, since they all allow for different intake solutions.

The first recommendation for reducing the entrainment and impingement impacts would be to avoid systems that will inevitably deliver such impacts. Therefore, indirect, subsurface intakes are recommended whenever feasible. Even additional installation of indirect intakes to the existing intake structures is recommendable if suitable conditions exist.

The second one is to change from once-through cooling systems of power plants to closed cooling systems that need much less water. For instance, nuclear desalination plants with smaller desalination capacities[7] using cooling towers would require only make-up water for the cooling system and feedwater for the desalination process. These relatively small intake needs may be met with indirect intake systems thus allowing for shorter environmental licensing periods and lower operation and maintenance costs. Retrofitting direct intakes with entrainment and impingement reduction technologies is costly and reduces the efficiency of the plant, leading the California Energy Commission to conclude in a report from 2005, that dry cooling and recirculating cooling are the only feasible and effective solution for reduction of environmental impacts [40]. EPA has even concluded that recirculating cooling for the power plants is a highly cost-effective solution [58].

It is essential that proper hydrological studies are conducted prior to the decision for using subsurface intakes in order to insure that in addition to the availability of sufficient quantities of seawater, the coastal aquifers will not be affected. Proper sealing to eliminate the risk of seawater leaks in the aquifers is necessary along with monitoring for leakages [59].

As for nuclear desalination plants that are large producers of fresh water, the use of subsurface intakes might not be possible even with closed cooling systems, either due to the terrain or because of the capacity required. In that case direct intake systems can be the only solution capable to provide the needed quantity of feedwater. Subsequently, the recommendation would be that direct intakes should be located in the zones of lower biological activity, far from organisms' migration pathways as well as seasonal shelter and spawning zones for certain species. Usually these suitable locations include the deeper zones, sometimes kilometers away from the cost, with slightly higher salinity but cooler temperatures of the withdrawned seawater by few degrees. Of course, with respect to the alternative cooling recommendation for the nuclear power plant, in such a case these intakes would preferably be supplying the desalination facility and additional make up water for the cooling system.

The literature overview shows that measures have been implemented in different situations with diverse results, sometimes making the process of finding a suitable solution long and difficult since adequate intake systems are very site specific and their environmental impact can vary upon many factors such as intake structure, operation, location, capacity etc. Nevertheless, appropriate mitigation measures can be found and implemented for any direct intake system. Some of them are presented below and should be implemented if once-through cooling is applied.

Factors like the frequency of the travelling screen rotation, frequency and jet force of the applied washing process as well as the location to which the impinged fish are returned, depending on the species, could be very important influences on marine organisms' mortality due to impingement [48] and should therefore be carefully considered.

---

[7] Refers to capacities smaller than 100 000 m^3/d potable water.

Different screen technologies can be applied to reduce the entrainment and impingement effects. Fish collecting systems such as the Ristroph travelling screens have been reported to lower the impingement mortality rate by 70-80%. Physical barriers like fine mesh screens may reduce entrainment rates by more than 80% from the baseline (Figure 11) [48].

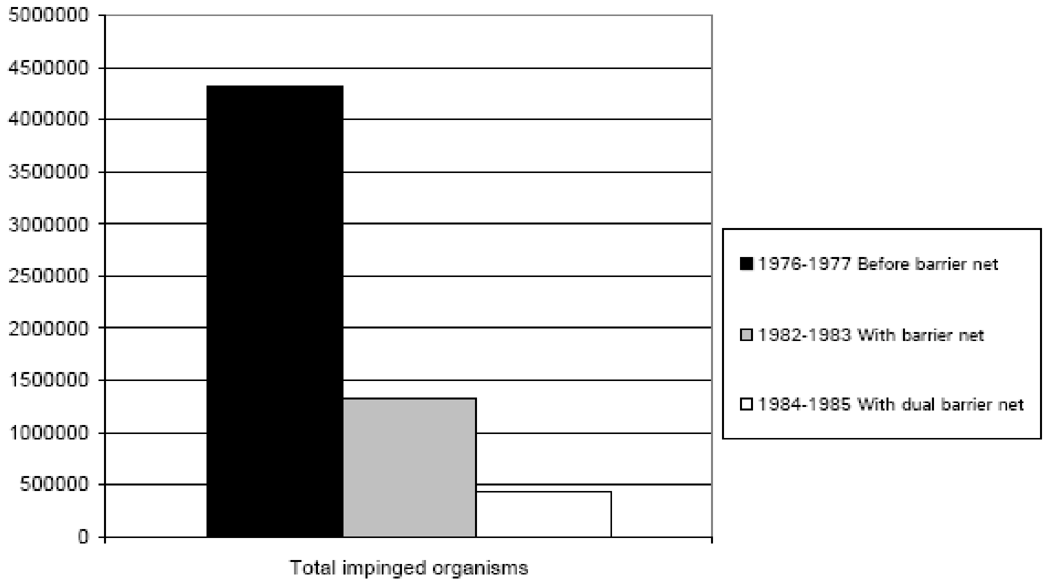

Figure 11. Average annual total number of fish and crabs impinged at Chalk Point power plant. (First barrier net with 3.2 cm mesh, second added with 1.9 cm mesh).

Seawater velocity at the intake is considered as a huge influential factor, which is one of the reasons why the EPA has accredited flow velocities of 0.15 m/s as Best Available Technology [28]. UNEP recommends flow velocities of 0.05 m/s thus limiting the effect to the one of slow sea currents [25]. Based on these velocity recommendations, filter net barriers or aquatic filter barriers were developed. They are essentially passive type of screens, consisting of porous filter fabric with a large surface. That effectively decreases the speed of the water going through the barrier in comparison with the seawater speed at the intake entry up to 98%, allowing even smaller organisms to swim away while the narrow filter openings prevent entrainment. Although as a general rule this should decrease entrainment and impingement rates, there are reported cases when in fact the opposite happened, demonstrating how site specific approach is needed when mitigation is considered [23, 26, 48, 60].

Other mitigation measures involve fish diversion pathways. Angled screens, modular inclined screens and louvers can allow fish diversion rates of more than 75% under various conditions for a wide range of species, with minimal latent mortality [60]. Low dissolved oxygen might incapacitate fish and hence cause large impingement problems. Removing some curtain wall panels in times when oxygen levels are below the necessary minimum to allow an oxygenated path for the fish to swim out, together with installation of aerators, had significant effect on reducing entrainment and impingement for the Calvert Cliffs NPP in the USA [48].

Another mitigation measure would be to reduce or stop the intake of water when plankton, larvae and eggs are particularly abundant, setting windows of operation in times when marine organisms are less abundant in the seawater [61]. This solution though, requires alternative sources of water to cover for the desalination facility’s inactivity as well as power plant cooling.

Particularly interesting are measures such as habitat restoration and creation of marine reserves which compensate for, rather than mitigate, the impact. The size of a new area that needs to be restored, whether an artificial reef, soft bottom open coast habitat or wetland in order to compensate for the entrainment impacts can be determined using the HPF[8] calculations. Unless the benefits for the impacted species are proven regardless of the habitat restored, the environmental action taken should always refer to the original endangered habitat. Establishing marine reserves can be less direct in compensating for the entrainment and impingement impacts. This is due to the fact that the most beneficial from this type of mitigation measures will be the harvested species, and they might not be the ones most impacted by the intake system [62].

3.1.1.6. Conclusions on intake issues for nuclear desalination

What is important to note in cases of compensatory mitigation efforts, is that a recent court decision in the USA prohibited the use of habitat restoration as a Section 316(b) compliance alternative [29]. Thus, the decision calls for avoiding environmental harm through technical solutions, rather than compensating for it. Furthermore, the proposed desalination plant in Carlsbad, California, has been repeatedly denied the building permit by the California Coastal Commission, due to refusal to apply the Best Available Technology for intake systems. The rejected plan calls on using the intake from the power plant where desalination plant should be co-located [30]. These two events will certainly influence nuclear desalination development in the USA, and as previously said, it is expected that similar approaches will be adopted in the near future in other countries, with similar effect on nuclear desalination.

In conclusion, it can be said that environmental considerations and regulations are a major influencing factor for the location and design features of nuclear desalination plant intakes, as demonstrated with the intake systems' regulations in the USA. From this standpoint, the important aspect for the nuclear desalination is that there are some doubts on co-located power-desalination plants. This issue emerged mainly because of the use of environmentally unsound intake systems by the older power plants. Designed before the consequences of the intake design and location were conceived as a threat to the environment, some of them have still not implemented mitigation measures. This is partially the reason for the doubts expressed in the latest US National Academy of Sciences analysis on desalination [23], as well as the increasing refusal to co-location plans by the US regulatory bodies.

Therefore, we may expect nuclear desalination to be affected only if existing nuclear power plants, that are neither retrofitted with closed cooling systems nor have applied suitable technology for reducing the impacts, are considered for nuclear desalination. New nuclear desalination facilities, most probable intended primarily for the production of electricity, will simply have to comply with the applicable regulations incorporating the desalination facility's need for water in their design.

3.1.2. Effluent disposal

This section will present the discharge perspectives and issues that are not common to nuclear power plants but will need to be addressed when considering nuclear desalination. It will display some of the environmental regulatory approaches to discharge into the sea, describe the pre-treatment as the main impact source, explain the importance of effluent discharge as an impact pathway, asses the impact on the ecosystem in a generic manner, and offer

[8] Habitat Production Forgone. Further explanation in the Appendix I.

recommendations and mitigation measures for the environmental impacts of the discharge systems.

3.1.2.1. Environmental regulations applicable for nuclear desalination discharges

Production of potable water from seawater requires exclusion of suspended and dissolved solids. These solids are rejected with the unprocessed water, increasing its density and solids concentration, so that together with the chemicals added in the pre-treatment stage, they form the reject brine (concentrate). The quantity of solids and chemicals in the reject brine and its temperature will depend on the desalination process as well as quality of intake water.

The higher concentration of chemicals and solids may deteriorate the seawater quality causing severe environmental impacts despite the fact that most of the brine constituents are naturally occurring in the seawater, so consequently the brine disposal is of great concern. For instance, due to TDS increase of the intake seawater, the AdDur seawater desalination plant in Bahrain operates with a daily capacity of 11 500 m^3/d in spite the fact that it was originally designed to produce 38 000 m^3/d [63]. There are other factors that might have contributed to AdDur's higher salinity at intake apart from recirculating discharge, but it enhances the growing awareness of the importance of preserving the feedwater quality. This has propelled possible environmental impacts from desalination as key issues for project permits, often considerably influencing plant commissioning and design [64].

Though desalination discharges are rarely explicitly mentioned, in many countries they are regulated as point-sources or land-based sources of marine pollution. For instance, the 1995 Barcelona Convention focusing on the protection of the Mediterranean Sea is demanding that the signatories take all appropriate measures against polluting the Mediterranean with discharges from outfalls or any other land-based sources within their territories. The Convention introduced the so-called LBS protocol whose Article 6 states that any discharge that may affect the Mediterranean Sea will be "strictly subject to authorization or regulation by the competent authorities of the Parties" [65].

Similarly, desalination discharges in the USA are regulated by, what are considered to be, well-developed environmental standards. Just as the Section 316(b) regulates the intake structures, the US Clean Water Act Section 403(c) regulates discharges. It requires that NPDES permits for ocean discharges are issued in compliance with EPA's Ocean Discharge Criteria for preventing "unreasonable degradation of marine environment". To clarify what must be prevented, in short, this phrase is defined as significant adverse changes in ecosystem, and/or direct or indirect threat to human health, and/or loss of value which is unreasonable in relation to the benefit derived from the discharge. In accordance with this definition, ten criteria were introduced to help establish whether discharging represents unreasonable degradation of marine environment [66].

The common way of controlling marine environment degradation involves two basic approaches [23, 64]. The first one places limitations on pollutants' emissions, preventing dangerously high concentrations in the discharge. In order to comply with such regulations, a desalination facility has to improve its design, water intake process, and recycling techniques using the Best Available Technology or Best Available Technology Not Entailing Excessive Costs principle [67]. The other approach introduces ambient standards or environmental quality standards (EQS), setting overall pollutant concentrations that can not be exceeded in the water body [67, 68]. That way, the cumulative impact from other dischargers is also taken into account. EQS require establishing of mixing zones (allocated impact zone) in which numerical water quality standards can be exceeded and where initial dilution occurs. What is more interesting now is that legislation, such as the EU Water Framework Directive and US Water Quality Standards, restrict polluting elements from the brine both at the outfall point and in the receiving water body, hence requiring not only treatment efficiency but in the same time consideration for the response of the receiving water body. [64, 68, 69].

On the other hand, specific standards for nuclear desalination discharges are so far not covered by IAEA since they are subjected to national regulations. However, environmentally sound practices are required - according to IAEA's Technical Reports Series No. 400 - Introduction of Nuclear Desalination: a Guidebook [1], the maximum concentrations of some of the chemicals in the discharge system, such as chlorine, zinc and phosphate compounds, sulphuric acid and demineralizers, "should not exceed levels that are toxic to aquatic life". Furthermore, IAEA Safety Guide No. NS-G-3.2 requires measuring of the radioactive, chemical and physical properties[9] of the discharged effluents for examining the suitability of the site and establishing an environmental monitoring program [70].

The environmental issues of nuclear desalination discharge are therefore fundamentally covered by the abovementioned legislation on effluent discharges and nuclear power plant safety guidance. The later indicates that it is generally not probable that nuclear desalination plants will have to deal with additional regulations and especially regulating parameters. Complying with them though, will require careful system design which will take into consideration the specific discharge characteristics from a nuclear desalination plant.

3.1.2.2. Sources of environmental impact

Desalination processes, with their respective pre-treatment procedures, can be identified as the main sources of environmental impact. In general, we can identify several types of desalination processes, such as: ion exchange, membrane and distillation processes. Out of these, mainly one membrane process (reverse osmosis - RO), and two distillation processes (multiple effect distillation – MED and multistage flash distillation – MSF) are used for desalination of seawater [71], due to the ability to work with feedwater that has a high content of dissolved solids. Both processes' impacts on the environment are strongly influenced by the seawater intake in their magnitude and character.

Nuclear desalination has been also applied with these three desalination techniques. The largest operating capacity so far, designed for 80 000 to 145 000 m^3/d of desalinated water, was based in Aktau, Kazakhstan, using MED desalination [19]. Reverse osmosis on the other hand has so far been used only on small scale, with the largest capacity of 2600 m^3/d co-located with the NPP Ohi in Fukui, Japan [72]. Its overall lower energy requirements per 1 m^3 of product water have recently propelled the use of RO systems even when co-located with power plants (Table 4).

It is important to note that, regardless the energy source or desalination technique applied, the quality of the feedwater is a crucial parameter for the efficiency of the process. Therefore, all three of the desalination techniques mentioned above require pre-treatment of the seawater which will not only improve, but also ensure consistent quality necessary for achieving the planned freshwater output [34]. The necessary pre-treatment must be decided on the basis of the intake water quality, the desalination process applied and freshwater (product water)

[9] Chemical properties are monitored through the presence of certain elements and substances (Ca, Mg, Cl, etc) and physical properties through parameters such as temperature and density. Since they are the same ones which are of concern for desalination processes, it can be concluded that the Safety Guide requirements are adequate for nuclear desalination as well.

quality [25]. Common pre-treatment procedures for the mentioned desalination processes include use of chemicals that should prevent biofouling and scaling as well as pre-heating of the feedwater [59, 71]. Specifics of the desalination processes and their respective pre-treatment procedures are presented in the following paragraphs.

Reverse osmosis is a process that applies pressure which is higher than the osmotic pressure on the side of the saline solution, thus forcing the water molecules through the membrane where low concentration water is collected. The product water of RO desalination is of drinking quality and varies between 200 and 500 mg/L [23]. The desalination process is displayed in Figure 12.

Table 4. ENERGY NEEDED FOR SEAWATER DESALINATION PROCESSES [23, 73]

	RO	MSF	MED
Electrical energy use (kWh/m^3)	2.5 - 7	3 - 5	1.5 – 2.5
Heat consumption (MJ/m^3)	/	250 - 330	145 - 390
total energy with +10% for auxiliary systems (MJ/m^3)	10 - 30	290 - 385	165 - 440

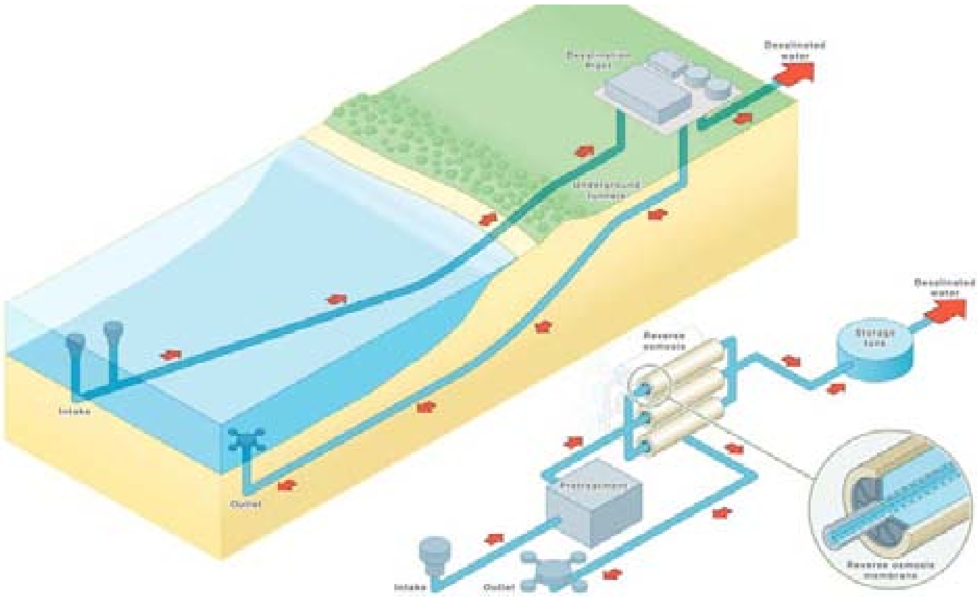

Figure 12. Reverse osmosis diagram.

Although seawater reverse osmosis (RO) requires high pressures of 70 to 80 bar applied on the feedwater, this desalination technique is less energy intensive in comparison to the distillation processes: for seawater RO with energy recovery devices, the specific energy consumption is in the range[10] of 2.5 to 7 kWh/m^3 [23, 52]. The RO energy needs vary depending on the salinity of the intake water. According to the principles of osmosis, lower salinity of the feedwater will mean lower energy consumption for producing fresh water. Due to overall lower energy consumption, RO is predominantly used in countries that are lacking energy resources, such as Spain, Cyprus, Malta etc. For instance, Ashkelon, the largest RO desalination plant with a capacity of 330 000 m^3/d, is in Israel [74].

[10] The usual energy requirement for modern seawater RO with energy recovery is 3 to 4 kWh.

Another efficiency factor for the RO desalination process is the temperature of the feedwater. Membrane producers usually recommend 45°C [23]. Lower temperatures, such as the seawater's ambient temperature, contribute to lower efficiency rates.

On the other hand, RO seawater desalination, in spite of its great technical progress, is still not considered as reliable as the distillation processes, mainly due to the sensitivity of RO membranes' to fouling. The use of different materials has helped in reducing the fouling impact on the production of desalinated water, but fouling-resistant membranes are yet to be introduced [23]. In order to have a stable performance, RO desalination needs feedwater quality of SDI 5 or less, with SDI 2 to 3 being desirable values. Owing to the fragility of the membranes, the necessary degree of feedwater pre-treatment is higher than the one for distillation processes.

The removal of suspended solids to avoid membrane fouling is achieved with the use of coagulants such as ferric chloride, ferric chloride sulfate or aluminium chloride. Thoroughly mixed in the feedwater, they start the process of particle coagulation, thus improving the removal rate of the pre-treatment filters, since larger particles are easier to remove [75].

Furthermore, the process of pre-treatment usually includes the use of biocides. Chlorine, in various forms, is the most commonly used additive in desalination facilities for prevention of intake structure biofouling [57, 75]. Typical chlorine addition is 2 mg/L, but shock chlorination used for eliminating any organisms that might have survived in the intake systems can contain up to 6 mg/L chlorine. However, since most of the membranes are sensitive to chlorine due to enhanced oxidization, it must be eliminated from the feedwater. Hence sodium bisulfite is added in concentrations 2 to 4 times higher than chlorine, or the chlorinated feedwater is filtered through granular activated carbon [25, 34].

Antiscalants are common additives for both, distillation and membrane processes, preventing scale formation. For such purpose, usually policarbonic acids and phosphonates are being used. They disperse and complex calcium and magnesium ions, reducing scale formation [57]. Reverse osmosis may utilize sulfuric acid as well to prevent scaling [71].

Membrane cleaning chemicals are applied to clean the material which was not removed in the pre-treatment and accumulated on the membranes. Alkaline solution with pH 11-12 are used to dispose of fouling organisms and silt deposits, while acidic solutions are used to dissolve scales and metal oxides [57, 75].

Typically though, RO plants do not use less chemicals per unit of seawater intake, but their higher recovery ratio means less chemicals per unit of desalinated water [76].

Multiple Effect Distillation (MED) is a technique which uses evaporation for desalinating seawater (Figure 13). The basic concept is very simple and requires heat that can be brought to the seawater effect (chamber). The vapor from that effect is then condensed in the next effect, providing water with very low solids content, TDS < 50mg/L [34]. The released condensation heat is then used for the next effect.

MED is characterized with reduced pumping requirements and ability to use low quality waste heat, resulting in lower power needs compared to MSF. Top brine temperature is around 70 to 75°C [23, 34]. This is an important factor which contributes to the enhanced application of this technique. Currently, the largest MED facility is Jubail II, Saudi Arabia, with 800 000 m^3/d of capacity [77].

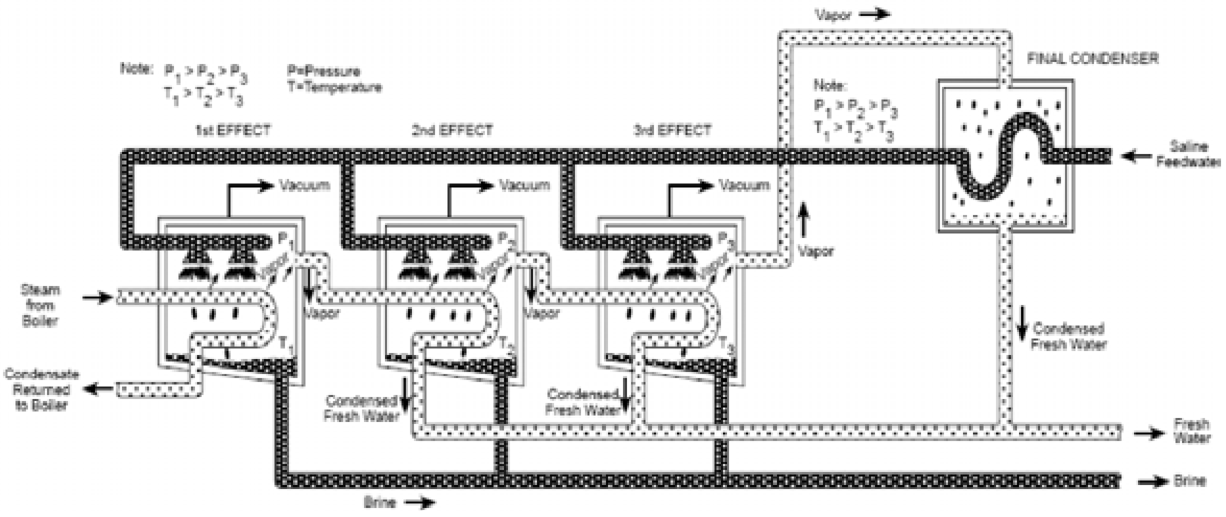

Figure 13. Multiple effect desalination.

Multistage flash (MSF) desalination process, involves heating of seawater with steam condensing on the tubes that carry it. (Figure 14) Flowing into the next stage, where typically for MSF the pressure is lower and allows for lower boiling temperatures, the heated seawater then boils rapidly flashing into steam. This steam condenses to fresh water and the heat released in the process is used for the next stage. MSF typically operates with a top brine temperature of 90 to 120^{o}C [23, 34] and providing product water of TDS < 10 mg/L [44]. In general, 25-50% of the seawater evaporates and is converted to potable water, depending on the pressure [25, 34].

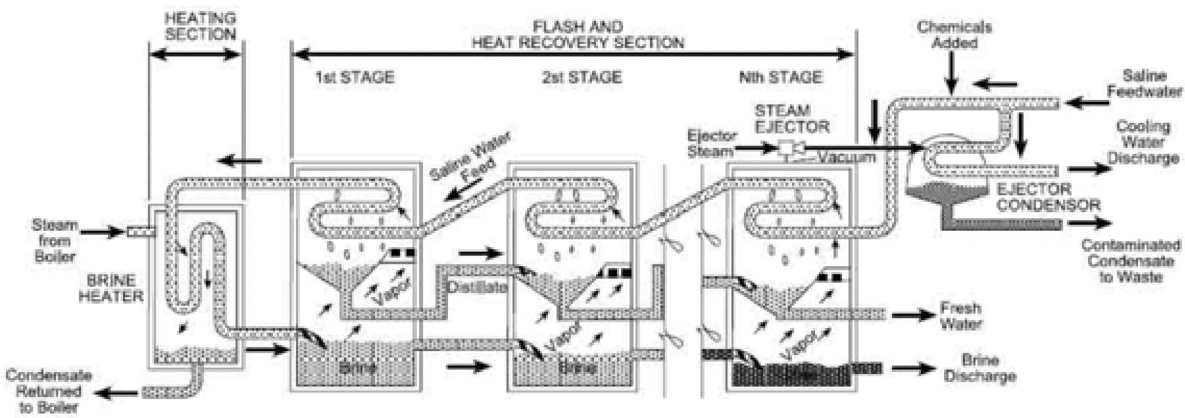

Figure 14. Multistage Flash diagram.

The world's largest MSF plant is the Shoaiba 3 desalination plant in Saudi Arabia with a capacity of 880 000 m^3/d of desalinated water [77].

As mentioned earlier, the pre-treatment of intake seawater for all seawater desalination processes involves chlorination. A continuous dose of 0.5 to 2 mg/L active Cl_2 is usually added for RO, with a shock dose of around 4 mg/L every one to five days lasting for 30 to 120 minutes [34]. Chlorine ensures that the efficiency of the process will not be negatively affected due to biofouling of the structure (e.g. evaporation surfaces), but since it can damage the membranes it is neutralized prior to reaching them. The chlorination levels in the pre-treatment are similar for RO and distillation. However, the robust distillation processes, usually applying the same level of chlorination do not require treatment of the used chlorine and it is therefore rejected together with the brine [71].

The antiscalants used in both distillation processes include organic polymers (mainly policarbonic acids) or, phosphonates[11] to disperse and complex calcium and magnesium ions, reducing scale formation [57].

Antifoaming agents, such as polyglycol, are specific primarily for MSF [34]. They are added in concentrations lower than 0.1 mg/L to disperse foam-causing organics originating from the biomaterial in the feedwater. They must be soluble in water over a wide temperature range [71].

Corrosion is a vulnerable spot for distillation processes which occurs due to their higher operating temperatures. The most important heavy metal discharged with the brine is copper, with natural levels ranging between less than 1 µg/L in the open ocean to a 100 µg/L level in estuaries. Usual copper levels in the discharge range around 15 to 100 µg/L [71]. Therefore, depending on the location and the corrosion rate of the desalination plant systems, the discharge copper level can be normal, or even lower, than the natural level. Yet, some cases have been reported discharging more than 200 times higher concentrations of copper compared to the local marine environment [76].

As corrosion is of particular importance for the discharge impacts, the heat exchangers should especially be protected from it. Thus physical deaeration is applied to lower the content of dissolved oxygen down to a level of 100 µg/L, and further addition of sodium bisulfite may result in 20 µg/L dissolved oxygen [71].

As a summary, it can be said that these processes with their discharges can affect the salinity, pH and, much as the nuclear power plants, the temperature of the receiving waters.

Every desalination process rejects brine with increased salinity which depends on the applied desalination technique and technology. It is undisputed that reverse osmosis provides highest recovery ratios that may be as high as 65% [34]. Sadhwani et al. reported 60% recovery from the Maspalomas II plant with a high pressure second stage [78]. Younos [59] reports recovery of 30-50%. As for the distillation processes, recovery rates are reported to be between 10-50% [23, 25, 59]. Therefore, it can be expected that the salinity of the reject brine may reach more than twice the value of intake seawater and up to 90 000 mg/L [78]. Although it is common to blend this rejected brine with cooling water, or other less saline effluents, the discharge released into the marine environment may still have much higher salinity than the receiving waters.

Intake seawater will require pre-heating to achieve process efficiency. Reverse osmosis desalination, unlike distillation processes, does not result in highly elevated brine temperatures [71, 79]. Typically though, an MSF plant will produce brine with temperatures prior to blowdown of 3 to 5^{o}C higher than seawater [34]. For MED, these values would be even higher, in the excess of 10 to 15^{o}C – similar to power plants, and able to reach as much as 25^{o}C above seawater temperature if no regulatory limits are imposed [34, 76].

[11] Lately, the use of phosphonates is less common, due to potential impacts from increased nutrient levels at the discharge area.

Furthermore, in reverse osmosis processes, sulphuric (H_2SO_4) or hydrochloric acid (HCl) are used to facilitate antiscalants' action, keeping the pH value below the saturation point of scale ($CaCO_3$), and thus significantly lowering the pH value of the brine [25, 71]. During normal RO operation, due to pH adjustment for protection of the membranes, pH is lowered only to 6 or 7 [71], and the use of acid may range in quantities of 30 to 100 mg/L. It should be noted that this lowest pH value is intermittently achieved, during the acid cleaning of membranes, which for most plants occurs once every three months [23]. Acid cleaning is also used in distillation processes, together with corrosion inhibitors, and it can result in effluents with pH as low as 2 [34, 76, 79].

3.1.2.3. Receptors and pathways of environmental impacts

The ocean, as the most common discharge location, is typically attributed with average seawater salinity of approximately 35 to 38 g/L. This salinity levels vary between the maximal value for the Arabian Gulf of 45 g/L and the minimal value of 7 g/L for the Baltic Sea [73]. Meanwhile, seawater surface temperatures range from around -2^{o}C up to more than 30^{o}C in landlocked seas like the Arabian Gulf [80]. The coastal waters, which are of highest interest in discharge assessments, are characterized with average alkalinity of 8.3 ± 0.3 [71].

The marine organisms that inhabit these waters are well adapted to those conditions, including the naturally occurring variations. However, the marine species' tolerance with desalination induced change in habitat surroundings is often low. The reason for this is that the speed of change and its magnitude are often more than what the ecosystem can sustain, having in mind the difference between the natural levels of environmental parameters and the previously mentioned characteristics of the discharge brine.

Disposing of the remaining brine after the desalination process can be performed with several management approaches. The choice of the disposal technique though, will depend on the regulations, finances, technology and other such factors.

As the cheapest and simplest way for disposal, surface discharge is the most common method [23, 59] (Figure 15). It releases a high salinity plume immediately at the coastline. This plume, with certain density which depends on the salinity and the temperature, can be negatively, positively or neutrally buoyant in the receiving water [71]. However, since even brine from thermal desalination processes with higher temperatures and smaller concentrations can be significantly denser than the receiving water [64], very often brine buoyancy is negative. Due to the slow mixing while spreading on the bottom, significant increases of salinity at the bottom have been reported several kilometers from the discharge point [64, 81].

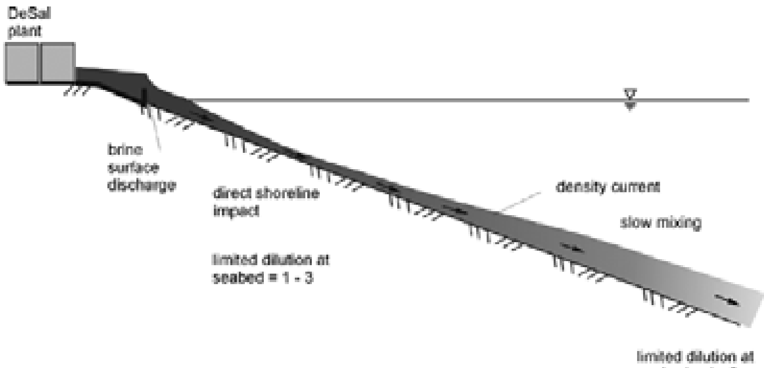

Figure 15. Surface brine discharge.

On the other hand, if favorable conditions exist, regarding the coast bathymetry, depth, wave activity and currents, fast dilution may be possible even with surface discharge. Indeed, Lattemann and Hoepner have reported that a considerable degree of dilution can occur even in coastal waters [71] as have Perez Talavera and Quesada Ruiz in their study on brine discharges from Maspalomas II desalination plant [82]. Furthermore, surface discharge in the tidal zone can be practiced without environmentally adverse effects using the significant amount of turbulent energy brought by the tides if their capacity for mixing and transport of the brine is not exceeded [34]. The brine can also be diluted prior to discharge by mixing it in a stream of sewer or waste water. Power plant discharges are particularly interesting for brine dilution prior to sea surface disposal. In all cases, the receiving water's capacity to self-purify has to be taken into account [75].

For co-located plants which use once-through cooling, including nuclear desalination plants, the combined effluent from desalination brine and warm power plant cooling waters would typically be positively buoyant.

Nuclear desalination experiences with surface water discharge involve the nuclear desalination plant in Aktau, Kazakhstan, where after evaporative concentrating, the brine with up to 50 g/L was blended with the nuclear plant cooling waters in the nearby 2,5 to 5 meters deep artificial lake, Karakol. There the waters were aerated and cleared of solids remaining at the bottom before released back into the Caspian Sea [54]. A different solution is applied at Diablo Canyon power plant, featuring a common intake as well as discharge pipeline for the desalination facility and the once-through cooling system, thus providing dilution of small brine quantities with large volumes of seawater used for cooling [83].

Submerged water discharge (Figure 16) involves long pipelines stretching into the ocean, beyond the coastal habitats, in areas of low biological activity. Environmental regulations concerning mixing zones have contributed to additional development of design approaches for faster mixing of the brine in the receiving water. Multiport discharge diffusers with high velocity jets positioned at a certain angle above horizontal (30^o to 45^o, even 60^o) are employed to achieve faster and more efficient dilution [23, 64]

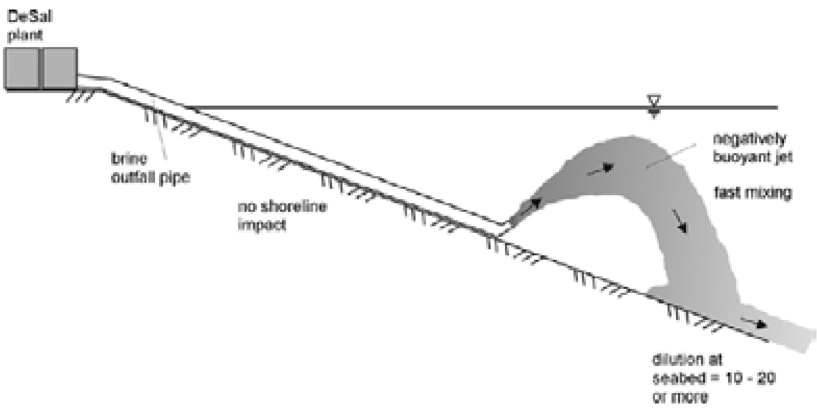

Figure 16. Submerged brine discharge.

Deep well brine injection can be done either in geological structures that will contain the concentrate or under the seabed for slow diffusion.

The first approach is suitable in locations where aquifers which are not used for drinking water can be found, imbedded in fractured rock, isolated with impermeable dolomite or limestone from the surrounding aquifers [59, 75]. They can be between 300 and 2500 meters deep and provide 1 m^3 of storage for 10 000 m^3 of aquifer material [23, 84]. This ratio can be lower, about 1 m^3 of storage for 10 m^3 of aquifer material, if depleted oil fields are used for discharge injection [23].

The second deep well injection possibility is the disposal of brine under the seabed or in coastal wells. It requires specific hydrogeological conditions, but it can be an environmentally effective way of disposing brine because the mixing occurs beneath the seabed and the brine slowly dissipates into the receiving water [23].

Zero Liquid Discharge is required when the desalination facility's approach for brine disposal is to prevent any possibly adverse environmental impacts on the marine habitats.

The first ZLD approach is an ancient method for extracting salt from the sea - evaporation ponds. They can be used to reduce and solidify the brine but would require large land area for a shallow basin where the evaporation will occur. Also, suitable meteorological conditions are necessary for faster evaporation rate. Of course, such a pond is designed so that no brine can penetrate the soil below. After a certain period, the solids start filling out the pond and it can be either cleaned regularly, with disposal of the salts somewhere else or closed and sealed [23]. It is therefore common only for small brine flows to be treated in this way.

Einav et al., based on experiences gathered at Israel's Eilat desalination plant, have proposed directing the brines to a salt production plant [49]. In that sense, adopting the ZLD approach, the Nuclear Desalination Demonstration Plant (NDDP) in Kalpakkam, India, is feeding its 1500 m^3/d of brine to the local salt production facility, enhancing their production. The planned expansion of the desalination capacity is partially based on this successful experience [20].

Zero liquid discharge convert concentrate liquid into dry solid via thermal evaporators (concentrators) and crystallizers [25, 59]. Given the fact that brine with a concentration of 150 to 200 g/L is a valuable resource for extraction of materials and fertilizers, increasing the desalination brine's density through partial evaporation seems a viable option. For instance, using a reference desalination plant with 425 000 m^3/d intake capacity, Nisan et al. [85] have proposed a series of treatment steps for this highly concentrated brine which would yield approximately 2 billion US dollars per year from material extraction. This solution for the brine discharge has not been applied yet on a large scale, but it should be expected that this will change. Recently, ZLD desalination projects were announced for Bahrain and Taiwan [86], with results that remain to be seen.

3.1.2.4. Environmental impacts of brine disposal

Marine habitat conditions greatly differ depending on the geographical location and sea depth. As mentioned earlier, main factors (out of many defining those conditions) are temperature, salinity and pH value of the seawater. These factors are interrelated and variable throughout the year. Therefore, in order to survive, each marine species has developed tolerances depending on the magnitude of the variations in its habitat conditions. The pace of these variations however, is much slower when compared to the sudden changes in habitat conditions originating from desalination effluent releases.

As with every other stand-alone or co-located power and desalination plant, nuclear desalination plant's discharge properties may put additional strain by amplifying the variations of habitat conditions. Along with intake issues, possible impacts of the desalination discharge, whether co-located or not, are of major environmental concern.

In addition to the construction impact that the discharge structures share as an issue with the intakes, as well as the discharge salinity, temperature and pH, the discharge impact may be a result of toxicity due to presence of chemicals and heavy metals, low oxygen content, large nutrient concentration, turbidity etc. Depending on the desalination process and practice prior to discharge, all of these factors may cause adverse effects on the environment individually or in reaction with one another. It is also important to take into account the impact magnitude which may not be instantaneously noticeable on the marine organisms, but can cause sublethal effects that take time to be manifested, such as bioaccumulation [51].

The primary issue in sea discharge of the brine, whether surface or submerged, is the impact of increased salinity around the discharge point [29]. The importance of this impact is in correlation with marine organisms' dependence on salinity conditions. Marine organisms can be defined according to their ability to tolerate the variations in their environment's salinity, which affects the osmotic pressure of their body fluids, as euryhaline species (wide range of salinity tolerance) or as stenohaline species (narrow range of salinity tolerances). Furthermore, due to the higher salinity of the brine and hence the higher density, the discharge plume will in most cases spread on the bottom of the discharge area, thus primarily affecting the benthic vegetation which is usually very sensitive to changes in salinity [23] and basic to coastal marine habitats.

It must be noted that even euryhaline species may not survive changes of salinity concentrations if they are sudden and frequent. A study [87] on benthic vegetation in Northeastern Florida Bay, reported that variations in salinity levels resulted in changes of the species composition in the affected habitat, and that frequent changes of habitat salinity result in lower benthic vegetation biomass due to its inability to develop and survive long enough in changing conditions. The study concludes that not only can frequent salinity variations lead to disappearance of species altogether in affected habitats, but also that salinity variation had the greatest impact on plant biomass.

Many other studies have reported on the salinity impact on marine life with similar findings. A study [81] on the impacts from a desalination plant in Alicante, Spain, showed that stenohaline species such as echinoderms have either disappeared in the area of brine influence, or such as in the Mediterranean seagrass *Posidonia oceanica*[12], their vitality has been affected. In addition, life cycle stage and age may be in a correlation with species salinity sensitivity, where younger individuals are more sensitive than older ones adversely affecting the biogenesis [27, 28]. For instance, salinity tolerance of invertebrate larvae is lower than for the adult population [49]. Salinity increase impacts can also be manifested with delay of hatchability and high egg mortality rates that may occur after a certain species specific limit [88].

On the other hand, the experiment with salinity increase between 37 and 40 g/L (expected after brine discharging is initiated) for three endemic species near the proposed Carlsbad desalination plant, was ended after five and a half months, with no noticeable impact on the growth rate or fertility of the species [89].

[12] This endemic species is included in the European Council's high priority conservation catalogue for natural habitats (Directive 92/43/EEC) and is very sensitive to salinity changes with a tolerance margin of 1 to 2 mg/L around its habitat ambient salinity of 37 to 38 mg/L [82]

From these and other studies on salinity impacts, it can be concluded that they are very species specific. Nevertheless, despite natural variations of ± 10% of average annual ambient seawater salinity, most of the species can tolerate significantly higher levels than 10% salinity increase [34]. Del Bene [90] gives a conservative estimate of 3% increase from normal ambient salinity as a value that will not adversely affect benthic organisms. It must be kept in mind though, that even if salinity does not kill the organisms directly, it may have sublethal effects that stress the organisms and increases their susceptibility to other pollutants [28]. Elevated salinity levels of the brine discharge may also affect the marine organisms indirectly, by fostering stratification of the receiving waters, limiting the oxygen supply to benthic communities [27]. Increase of salinity levels reduces the oxygen solubility [75] and although this is not the largest, nor the primary reason for low oxygen levels in the brine, it can still adversely affect the marine environment.

Similar significance for the marine ecosystems can be attributed to seawater temperature as one of the most important environmental variables, which affects the survival, growth and reproduction of aquatic organisms [91]. Raising seawater temperatures may cause adverse effects such as increased metabolic rate of the organisms and enhanced uptake of toxic pollutants, decreased levels of oxygen and nitrogen solubility in the seawater and increased evaporation rates that may further elevate seawater salinity [27].

The impact of higher temperature was noticed on Mediterranean seagrass *Posidonia oceanica*. This study [92] has reported that for the same salinity levels, survival of the species decreased with higher temperatures. Primary production is likely to be affected due to decrease in abundance and diversity of plankton species resulting from oxygen and nitrogen decrease in the seawater [27]. Such an impact may lead to overall habitat deterioration. Furthermore, although nutrient enrichment is the main cause, higher temperatures may facilitate eutrophication [92]. It must be also remembered that temperature increases have the potential to kill marine organisms. While fish have the ability to abandon the impacted area, benthic communities, such as corals which are very sensitive to temperature changes will simply bleach and die.

Increased brine temperatures impacting the marine environment are an issue mainly for distillation processes which tend to dissipate a lot of thermal energy into the receiving water [34] (Figure 17). Nuclear power plants also have a large effect through high cooling water discharge temperatures (Figure 18).

For instance, Diablo Canyon Power Plant, with a limit of cooling water temperature increase by environmental regulations to $\Delta T = 11^oC$, has shown significant thermal impacts on the environment, mainly because of the once-through cooling system and not the RO desalination. A research on the environmental consequences of thermal discharges from DCPP reported that during a period of 10 years, a seawater temperature rise of 3.5°C has occurred, with significant changes to 150 species of marine algae and invertebrates [93]. The thermal impacts were noticeable 3 km farther from the discharge point and can be regarded as a proper illustration of the potential for adverse environmental impacts due to thermal discharges.

To put the allowed discharge temperature for nuclear power plants into perspective, the discharge temperature which is believed to be of no ecological importance is just 1^oC higher than the natural temperature [76]. Corals are among the most sensitive marine organisms when it comes to temperature increases in their environment: 2 to 3^oC higher than normal sea temperatures may kill them [94]. Of course, the temperature of a thermal discharge can be allowed higher, if the receiving ecosystem is capable of withstanding such ΔT values.

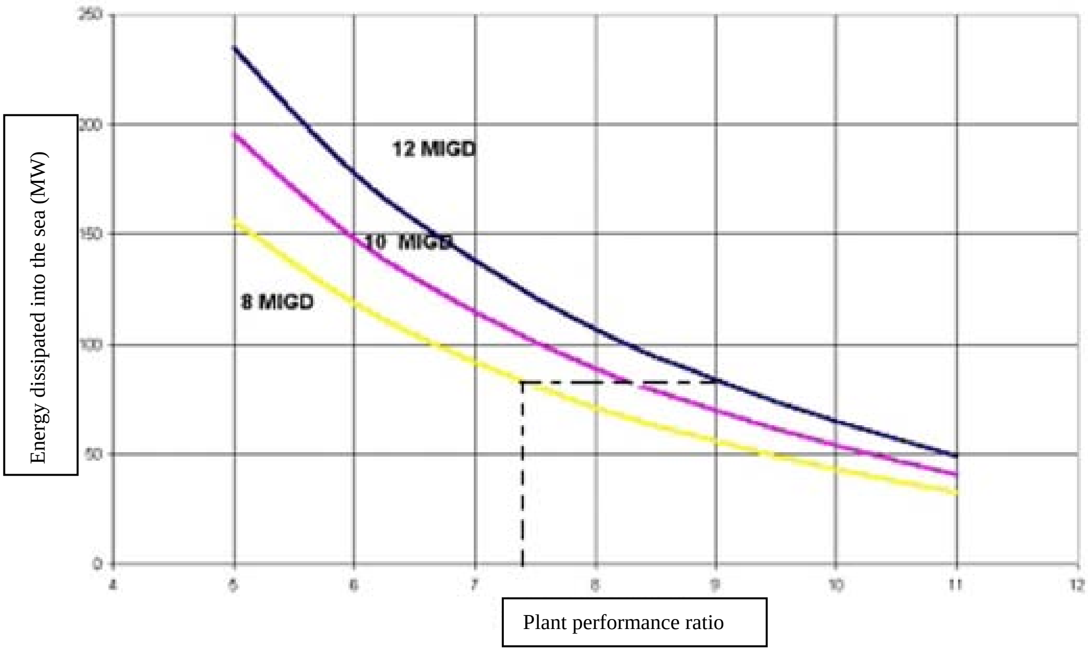

Figure 17. Thermal energy discharge load of MSF plants.

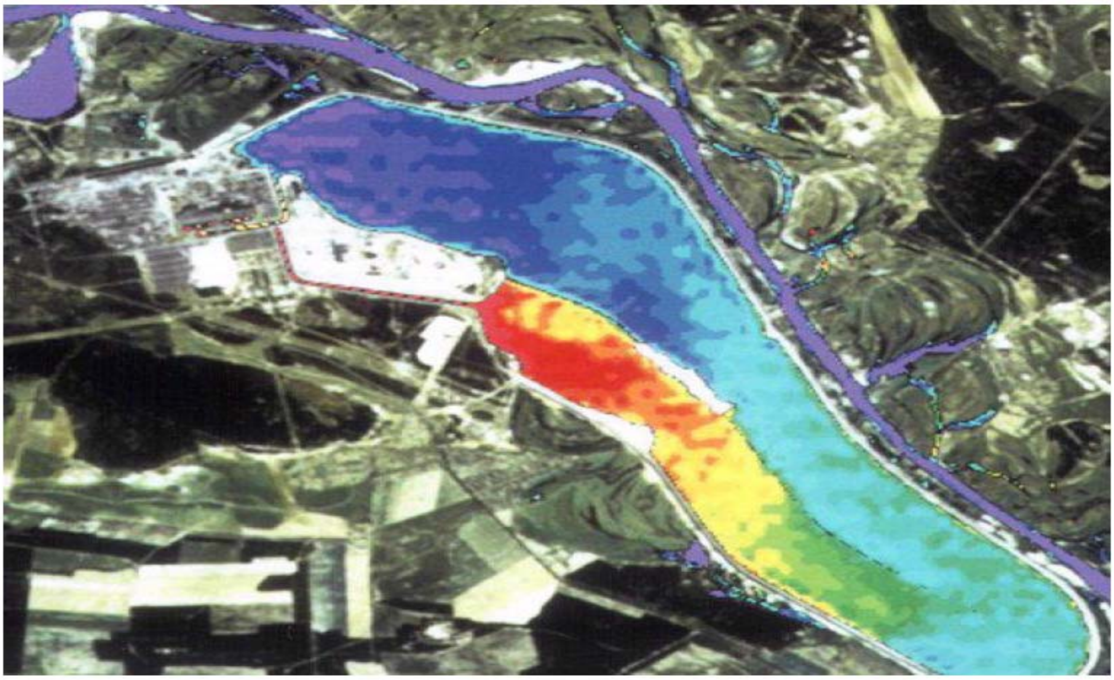

Figure 18. Thermal discharge from a nuclear power plant into a cooling lake (warm water is in the areas marked red, cold water areas are marked blue).

As for the MAEC nuclear desalination plant, the thermal impact was not noticeable, due to the artificial lake that cooled the water prior to discharge back in the Caspian Sea (Table 5). Furthermore, its artificial discharge lake is now the habitat for flamingos, swans, juvenile fish etc [54]. The radiological survey of the facility in Aktau, based on nearby soil and Karakol bottom sediments, has concluded that the facility also had a negligible contribution to the radiological situation within the investigated territories [95]. Thus, the brine is also excluded from posing as a possible radioactivity threat to public health.

On the other hand, the consequences and impacts on marine life of pH variations are not very well known [96]. Generally, acidic levels in the range of pH 6 to 7 are considered as insufficient to cause seawater quality impairment, but discharges resulting from cleaning processes may cause adverse environmental impacts if large quantities of pH 2-3 or pH 11-12 are released into the sea [25]. It is certain though that pH values influence the scale formation rates and consequently may have effect on benthic populations in the area: corals and some species of plankton (Coccolithophore and Foraminifera) use carbonate ions obtained from the surrounding water to build their skeleton and protective shells. As oceanic pH and carbonate ions decrease, the calcification mechanisms and abilities of marine organisms will be negatively impacted. Experiments already showed that pH decrease reduces calcification rates in tropical coral reefs by 7-40% [97, 98, 99, 100]. Coral reefs should not be subjected to effluents with value lower than pH 8 [101].

Recent experiments demonstrated that a pH decrease has also an important impact on shellfishes (oysters, mussels), by decreasing their calcification rates [102], this would have an impact on coastal biodiversity and ecosystem functioning as well as potentially lead to a significant economic loss. pH sensitivity has been noticed with the autotrophic nitrifying bacteria (important for the marine primary production), which were noticed to suffer adverse impacts if acidic conditions occur in their environment [23]. Lattemann and Hoepner cite the Hazardous Substances Data Bank (HSDB) results for mortality of several species exposed at pH values of 2 to 3.5 during 48 to 96 hours periods. The results were similar, with 50% mortality and impaired swimming ability at sublethal acid concentrations [71].

Enhancing all the adverse environmental impacts originating from the previously discussed factors, is the brine's toxicity, defined by the use of biocides, traces of heavy metals due to corrosion, organic material, different types of chemicals etc. Its effect's magnitude is depending on the combination with salinity, temperature and pH.

Chlorine is a biocide that is used not only in desalination but also in power plant's once-through cooling systems for control of biofouling. The highest concentration rates of chlorine may be found in distillation processes' discharges, due to the fact that, unlike RO membranes, their sensitivity is such that the need to neutralize chlorine is practically nonexistent.

Initial decrease in warm sunlit waters of 90% can be expected after discharging due to self-degradation and dilution [25]. Desalination discharges in the mixing zone can thus have chlorine concentrations of 0.02 to 0.05 mg/L which is still very harmful to marine life having in mind that the PNEC[13] by the EU environmental risk assessment is defined at 0.04×10^{-3} mg/L of free available chlorine (FAC) [71, 103]. Chlorination of seawater leads to the formation of bromine (hypobroumous acid and hypobromite) and organohalogens (typically trihalomethane species such as bromoform) - known carcinogens and mutagens, although not necessarily toxic [25, 79]. Furthermore, chlorine toxicity acts in a synergistic way with elevated temperatures [27].

Chlorine concentrations higher than 0.01 mg/L may cause photosynthesis decrease and lethal effects on zooplankton, larvae and post-larvae marine organism shapes as well as kill fish by oxidizing the hemoglobin in their gills. It has also been noticed that certain species have chlorine tolerances which are age dependant [27].

[13] Predicted no effect concentration.

Heavy metals may also be part of the discharge stream due to corrosion of pipe and condenser surfaces. Depending on the used alloys, traces of Cu, Ni, Mo, Fe, Cr, Zn and other metals can be noticed, but the highest concentrations found are for copper (Cu) and iron (Fe) [27, 76]. The data for MAEC nuclear desalination plant in Aktau, Kazakhstan, also confirms this (Table 5, column 2) [54].

Table 5. SALT WATER PROPERTIES AT MAEC NDP

	Brine from the desalination plant	**Flow into the Caspian Sea***	**Quality of withdrawned Sea water**
Volume [1000 m^3/a]	100 000	844 220	/
TDS (total amount of dissolved salts) (mg/L)	/	/	13 500
Temperature (°C)	/	2-24	2-24
pH	8.1-8.3	8.1-8.3	8.2-8.3
Iron	0.12-0.2 mg/L	0.04-0.07 mg/L	0.02-0.04 mg/L
Copper	0.012-0.02	0.004-0.006	0.003-0.005
Oil products	0.02-0.07 mg/L	0.03-0.05 mg/L	0.02-0.05 mg/L
Suspended substances	13-20 mg/L	11-16 mg/L	10-20 mg/L
Cesium-138	/	$< 4.96 \times 10^{-2}$ Bq/L	$< 4.96 \times 10^{-2}$ Bq/L

*The flow into the Caspian Sea includes the cooling waters from the MAEC nuclear desalination plant as well as the brine from the desalination process.

While metals are really important for the metabolic functioning of many marine organisms at trace concentrations, they can be also very toxic when in excess, forming dangerous free radicals [104]. For example, copper is highly toxic to critical life stages of corals. Copper and lead are particularly harmful to corals [105].

As said, at its ambient concentrations in seawater copper is very important for the primary production of phytoplankton for instance. At elevated concentrations, it is highly toxic to most of the marine species [25, 27]. Background copper concentrations vary greatly in the world ocean, from 0.01 to 100 µg/L [25, 57]. Nevertheless, Hoepner states that desalination discharges in the Gulf, may have 200 fold (or more) higher copper concentrations than the ambient concentrations in the receiving water [76]. To illustrate, copper concentrations that are 5 to 10 times higher than the ones in ambient seawater have been found to be toxic [106]. Significant effects were noticed even with concentrations as low as 10 µg/L [25]. The main problem with copper concentrations though, is the irrelevance of dilution prior to discharge. Copper tends to adsorb to suspended matter and is thereby transported into sediments, entering the food chain through the benthic organisms and bio-accumulating in the higher trophic levels [25, 76]. The impact on the marine organisms ranges from tissue inflammation to genetic derangement and death [27]. Recommended values for copper concentrations range from 3.1 µg/L (EPA for long-term exposure) to 8 µg/L (water quality objective for the Mediterranean) [57].

As for the ferric pollution, high concentrations and loads are discharged in the marine environment only if backwash waters from reverse osmosis plants are discharged into the sea, provided that iron-containing coagulants are used. In addition to the aesthetic effect from the brine with red shade, potential adverse impacts include: high turbidity and high suspended solids zone which would reduce penetration of light and affect photosynthesis, as well as sediment accumulation and possible creation of anoxic zone [107]. Corrosion effects from RO or distillation are not high enough to have an aesthetic effect on the environment.

Anoxic characteristics of the brine discharge though, can be attributed mainly due to corrosion protection measures such as use of oxygen scavengers and deaeration of feedwater [25]. In addition to that, higher temperatures and salinity reduce the solubility of oxygen in seawater. Finally, entrained organisms enrich the discharge with organic matter whose decomposition further depletes the receiving seawater of oxygen [28].

Concerning the distribution of such a concentrate and its environmental impacts, the systems' outfall location has a significant role. The determining criteria should be the amount of mixing and the receiving capacities of the seawater at the outfall location (transport by the prevailing currents) [64]. The receiving seawater's capacity has great influence on the discharge impacts and depends on the seawater's turbulence, wave and tidal activity, currents, wind, bathymetry and other naturally occurring parameters that improve mixing [25]. Together with the possibility to dilute the brine by mixing it with other effluents, several possibilities for discharge management can be engineered. Some have been commonly used and some are under consideration, but again it seams that site specific approach will determine what is the best discharge management option available.

One of the most practiced solutions has been blending of the brine with other effluents. Co-location shows its advantages here, with the large quantities of water that are available from the power plant's once-through cooling system. Cooling waters have the same TDS content as receiving seawater and provide initial mixing and dilution thus lowering the salinity of the desalination discharge to almost ambient level. However, the higher temperature of the discharged cooling water may amplify the impact of the pollutants in the blended desalination discharge. They may also help faster mixing of the brine with the whole water column, lifting the discharge plume from the bottom to the surface.

On the other hand, blending desalination discharge with treated sewer waters can dilute the salinity of the desalination discharge but may also cause formation of by-products such as chlorinated organics, possibly influence aggregation of contaminants into particles of different sizes and exhibit whole effluent toxicity on species such as echinoderms [25, 34, 44]. Nevertheless, cases of reduced toxicity of the sewer due to mixing with saline discharges have also been reported [108]. Regarding the spent cleaning solutions[14], some desalination plants have been using the method of separating chemicals and solids that would otherwise be discharged in the sea, and sending them to sewer treatment plants, thus lowering the desalination plant's direct discharge impact [23].

As for discharging with deep well injection, due to increase of fluid pressure in the area, impacts may include even large-magnitude earthquakes (Richter > 5) when located in areas with recent geological activity [23]. Furthermore, geologically unstable areas may provide a hydraulic connection between the discharge well and the water supply aquifer, which will result in contamination of the aquifer with salts and pollutants [34].

[14] Not the concentrated brine. For large desalination capacities the brine is usually not discharged in waste water treatment facilities due to potential for adverse impact on the treatment facility as well as the potential for enhanced toxic effect on the environment, or because of other practical reasons [30].

Evaporation ponds may impact underlying aquifers, degrading their water's quality if leaking occurs, might be problematic for migrating and breeding birds and may also impact the environment in cases of major precipitations or floods [23]. On the other hand, the solidified residue will have to be disposed of and the possible solutions include transport to salt producers or disposal sites that may for instance, include abandoned salt mines.

Nuclear desalination, with larger desalinated water capacities, is likely to use seawater discharge (whether surface or submerged) and/or ZLD with material extraction. For smaller product water capacities the other two options may also be suitable.

3.1.2.5. Environmental impact mitigating recommendations

Though the discharge impacts may affect ecosystems to a considerable degree, it is typically considered easier to mitigate those impacts than the ones from impingement and entrainment [29]. As in the case of intake, discharge practices will be site specific and dependant on the oceanographic conditions. The difference though, is that they will be also strongly influenced by additional two groups of factors. The first group of factors revolves around the quality of seawater that is used to feed the process, which is largely a result of the applied intake technology and its location, consequently defining specific pretreatment. Second group of factors stems from the desalination process that generates the discharges.

In any case, the first recommendation would be to use the brine commercially, for extraction of valuable materials or salt production, thus eliminating the necessity for sea or land disposal. Even if the quantity of the brine exceeds the requirements of those industries, this quantity reduction will ensure lower environmental impact of the discharge disposal. The infrastructure needed in this case will raise the initial cost of the project, but will avoid the risk of non-compliance with the environmental regulations and provide additional income to the power and water generating facility. After all, although the scale of the nuclear desalination in Kalpakkam is small and brine is used only for salt production, it does indicate that such discharge management practices can be implemented on a larger scale as well.

Should that possibility be unfeasible, or some portion of the brine remains for disposal, the impacts of the brine composition must be mitigated, regardless of the disposal approach. Not only is this to be done when sea disposal is practiced but also with land disposal, since it has demonstrated problems with adverse impacts such as polluting drinking water aquifers [109].

The first necessity when mitigating discharge impacts is to find a suitable location for discharge. When the seabed geology permits, subsurface discharge should be practiced. If not, the location of sea discharge should allow mixing of the discharge plume after it is disposed of in the area regardless whether previously mixed with other effluents or not. This would require selection of a discharge site with high energy waters. In that sense, as mentioned, even sea surface discharge near the coast may prove as an environmentally acceptable solution provided that sufficient transport capacity exists at the discharge site, the biological activity is minimal and that organisms in the area will be able to tolerate the change in toxicity and salinity.

Higher salinity of the discharge should be reduced as close as possible to the ambient seawater salinity in the discharge area. Blending the once-through cooling waters from a co-located power plant may substantially decrease the salinity of the discharge to within the level of 10% above ambient salinity, which should be non-toxic for most of the marine organisms. For faster and better mixing of the saline discharge, it is also recommendable to use multiple diffusers positioned under an angle of 30 to 45 degrees above the horizontal and approximately 2 meters above the seabed. The exit speed should be more than 3.5 m/s [101]. However, lowering the recovery rate of the process in order to decrease the discharge salinity is, generally speaking, not recommended due to the fact that the product water output will have to be maintained with higher seawater intake volumes, which increases the impingement and entrainment effects and makes commercial brine processing less profitable. Blending the discharge with seawater prior to discharge will exhibit the same problems, so these solutions should be carefully evaluated. Dilution with sewage effluents should be avoided for environmental reasons as well as the fact that waste water can be reused after appropriate treatment [25, 64]. Even if sewage water is available for mixing, due to the fact that it too can competitively be used for water production, a situation may arise where the desalination facility will have to seek other brine disposal solutions after using this method. Nevertheless, should this option be considered, the toxicity of the whole effluent on the marine life must not be higher than its constituents.

Concerning different chemicals that may be found in the discharge, it should be said that their use will be minimal in the first place if indirect intakes are used for the desalination facility. This will result in minimizing or even eliminating the use of biocide chemicals, and their substitute with UV treatment, since some degree of biofouling control might still be needed. It should be noted that UV may not be very useful in high turbidity seawater, but subsurface intakes should provide seawater that is clean enough for an effective use of this technique.

If direct intakes must be used, other techniques for eliminating the need for biocide chemicals involve combination of micro (MF) and ultra filtration (UF). MF removes suspended material from the seawater, including bacteria and algae, while UF removes smaller viruses from it [50]. These biocide alternatives also avoid the need for storage of handling of chemicals, possible formation of toxic by-products and their effect does not change the physical and chemical properties of the seawater [25, 50, 73]. Minimizing and eliminating the biocide impact also includes measures for neutralization of the chlorine using sodium bisulfite or sulphur dioxide [73].

As a source of heavy metals pollution, corrosion should be prevented with the use of materials that are corrosion resistant. Dilution is of no importance in mitigating corrosion impacts due to the fact that it is not the concentration, but rather the heavy metal load which is the main problem for the marine environment. This primarily means use of heat exchanger materials that will assure no heavy metal release into discharge and enhanced use of titanium for the plant sections that work under elevated temperature conditions [23, 110]. Thermoplastic heat exchangers coupling the nuclear loop with the desalination one is not recommendable due to poor tritium containment properties of plastic materials [15]. Non-corrosive materials for other sections, e.g. the intake and outfall piping, should also be applied whenever feasible. Corrosion inhibitors may also be used for that purpose [25].

Temperature pollution impact of a nuclear desalination plant is smaller compared to a stand-alone nuclear plant and can substantially reduce its adverse impact. Not all of the thermal energy though can be transported from the reactor to the desalination plant. Due to safety reasons, the intermediate loop is a standard feature in nuclear desalination facilities, but as a side effect it acts as heat barrier as well. The calculations show that for GT-MHR[15]

[15] Gas turbine modular helium reactor (GT-MHR) is a helium cooled, direct-cycle NPP with a relatively high electricity production efficiency of around 50%. It features enhanced safety, economic, non-proliferation and environmental characteristics. Currently is under development. [52].

(305.9 MW(t)), 23% of the waste heat can be used for desalination and for PBMR[16] (345 MW(e)), about 22% of the waste heat can be utilized for desalination, instead of being dissipated into the environment [52].

Still, the use of large heat pipes or thermoplastic heat exchangers that can maintain 1 to 2^{o}C temperature rise for the discharge water [110] is recommended. Large heat pipes may also be a suitable choice. If this solution is unfeasible, cooling ponds or artificial lakes, even cooling towers, are advisable. Additionally, mixing with seawater prior to discharge may be applied as well, although that may increase the impingement and entrainment impact.

It should be noted that under NPDES, for instance, it is allowed to discharge effluents with 10 to 11^{o}C increased temperature above ambient seawater temperature. This temperature increase is the limit at the discharge point, but temperature increase of somewhere around 1^{o}C must not be detected further than 300 meters away (increase also recommended by UNEP, but without specifying the size of the impact zone [25]) [23, 25, 76]. Regardless of these limitations, there are cases of discharging which manage to limit their thermal impacts much closer than the allowed zones such as the plant in Antigua or in Bahrain [23,71].

Eliminating cleaning chemicals toxicity from the discharge may be achieved by removal of cleaning solutions and not blending them with the brine discharge. Cleaning is intermittently applied and the volumes are not as high, so its impact can be prevented with directing effluents with high concentration of cleaning chemicals to waste water treatment facility [25].

The other components of the discharge are not of such high importance and their impacts can be easily mitigated since they are non-toxic or have very low toxicity. All of them include sufficient diluting as a mitigation measure. On the other hand, antiscalants may have an adverse environmental impact through influence on the magnesium and calcium in the seawater, which needs to be investigated further. Reduction of their use can be achieved with nanofiltration (NF), thus partially removing divalent cations like magnesium or calcium from the intake seawater [25]. As for antifoaming additives, their use can be avoided if the intake seawater is low in planktonic algae [76]. Coagulants are non-toxic, but their environmental impacts are indirect, derived from the removal of suspended matter in the intake seawater and its subsequent discharge into the sea. In this way, the turbidity of the discharge is increased. Substituting coagulants with ultrafiltration (UF) has shown certain advantages [111], but disposing of suspended matter remains an issue. This is usually solved with dilution, but depending on the quantities of suspended material, disposal at landfills is also an option [25]. Similarly, acid impacts should be avoided with sufficient dilution or neutralization [76].

Deep well injection is likely to be unsuitable for nuclear desalination because of the large quantities of discharge, though the possibility should be investigated on a site specific basis and it does have some positive experiences for smaller desalination discharges under the seabed [110]. Evaporation ponds require large areas and landfill disposal for the solidified brine might involve significant transportation and land use needs, which is likely to be expensive and unsuitable for large nuclear desalination facilities.

3.1.2.6. Conclusions on brine disposal issues for nuclear desalination

Much as with the intake structures' case, nuclear desalination will not exhibit problems that are not attributed to any other co-located desalination plant. Accordingly, a variety of applicable solutions for avoiding environmental damage are available. Concerns over the

[16] Pebble-bed modular reactor (PBMR) has the same working principle with GT-MHR [52].

adverse impacts from brine disposal are very real, but developments in seawater treatment and discharge techniques indicate that the problem with it can be solved in an economically and environmentally feasible manner even if the power plant does not use once-through cooling, which would help diluting the brine discharge.

It is important to remember that the advantage of co-location with power plants using once-through cooling from an environmental point of view is due to avoidance of additional construction impacts and, more importantly, the possibility to mix the desalination discharge with the power plant's cooling waters. This last advantage however, comes at the cost of increased, or better said – prolonged[17], intake impact, which would need to be weighted against discharge impacts. Still, sharing of discharge infrastructure between power and desalination plants is considered as preferable without any doubts - the environmental regulatory bodies do not pose any constraints regarding that issue.

However, should it be decided by those bodies that once-through cooling is not the best available technology, which is not unlikely, diluting brine in cooling waters will no longer be possible and other mitigation measures will have to be taken, placing the burden of regulation compliance on the facility. The use of multi-port diffusers has been successfully applied in diluting the discharged brine. Still, if the economics allows it, the use of ZLD with commercial use of the brine, for instance for material extraction, may not only prevent significant environmental impacts and ensure regulation compliance, but in the same time allow for greater economic gain from the nuclear desalination facility. All of that contributes to the attractiveness of the option and in the same time increases the chances for potential implementation. The energy intensity of ZLD though, is a factor to be considered.

3.2. COASTAL IMPACTS OF NUCLEAR DESALINATION

As any other coastal industrial project, nuclear desalination plants have impacts on the environment through construction, land use, noise and visual disturbances. However, as shown in the following sections, all of these impacts are minor compared to other comparable power and desalination co-located plants.

3.2.1. Construction impacts

Construction of a nuclear desalination plant, or simply adding a desalination facility to an existing nuclear power plant, requires a construction effort typical for any industrial development at the coast. This effort will entail use of heavy machinery for grading, removal of vegetation, excavation, de-watering, transport of materials, sand and gravel covering, pipe laying, power supply, building road infrastructure etc. The construction impacts will therefore be expected in the form of noise and visual disturbance, with consequences on local communities and habitats. Possible runoff into the sea should also be expected as an impact, introducing oil, grease, sediments, nutrients and other pollutants which will degrade seawater quality in the area. Construction of intake and outfall structures presents another issue whose impacts must be mitigated (see 3.1.1.4.) The site activities may result in clouds of particulate matter polluting the atmosphere and depositing locally on agricultural, tourist or residential areas. Additional contribution to the noise and air pollution should be expected from the

[17] It should be kept in mind that there is a regulatory tendency to reduce the entrainment and impingement effects of OTC systems by replacing them with a cooling system that has lower water withdrawal rate, as well as the tendency to reduce the use of water by nuclear power plants altogether. Therefore, the use of power plant's OTC system for desalination feedwater, although not increasing the adverse environmental impacts substantially, may delay or make unfeasible the retrofitting of the power plant with cooling systems which are less environmentally harmful.

higher traffic movement that will be created in the construction area. It can also be expected that previously contaminated soils may be exposed during excavation.

The mitigation of these impacts is achieved through a construction management plan that consists of site specific measures for avoidance and minimization of environmental damage due to building activities. Such measures involve use of existing infrastructure, seasonal restriction of certain activities[18], strict refueling procedures, vegetation restoration, sediment retention structures, use of biodegradable materials etc. [50].

When construction impacts are compared to other energy sources co-located with desalination plants, not only the smaller size of an adequate plant site, but also the specific use of materials for the power plant, gives nuclear desalination an advantage from the environmental impact aspect (see next page, Table 6) [112]. As an illustration, wind infrastructure takes five to ten times the steel and concrete per MW(e) generating capacity as that of nuclear [112, 113].

On the other hand, solar and wind power plants can be built in less than a year [114], while typical nuclear power plant requires 4 to 6 years to construct, about the same time as a coal power plant, and twice the average time for construction of a gas plant [115]. This comparatively long construction time indicates that the advantage of lower specific construction impacts for nuclear, may be offset by prolonged impacts if a sound construction management plan is not implemented.

Table 6. MATERIAL USE PER TYPE OF POWER PLANT

Method	Specific steel use (metric tons/MW capacity)	Specific concrete use (m^3/MW capacity)
Nuclear (1970's vintage PWR)	40	190
Wind (1990's vintage)	460	870
Coal	98	160
Natural gas combined cycle	3.3	27

3.2.2. Land use

In general, co-location of power with desalination plants has a positive land use aspect because of infrastructure sharing – such as laboratories, administration, maintenance shops, access roads, parking lots, storage and personnel facilities, security installations, intake and discharge structures, piping etc.

The land use issues are similar to other development projects [57]. The estimated area required for a seawater desalination plants is about 1 to 2 m^2 per m^3/d [11]. This means that typically, for desalination capacities of 100 000 m^3/d an area of 200 000 m^2 should be planned.

This figure can be considered to be on the downside when compared to the 730 000 m^2 that are occupied by the desalination plant and water treatment station at Aktau's MAEC.

However, the whole MAEC complex seams to be oversized: total area of the nuclear desalination facility (Figure 19) is 44.08 km^2 which means that desalination occupies only 1.65% of the total MAEC area [54].

[18] Such measures usually are referring to intake/discharge construction during biologically insensitive periods of the year, use of roads by heavy vehicles outside traffic rush-hour etc.

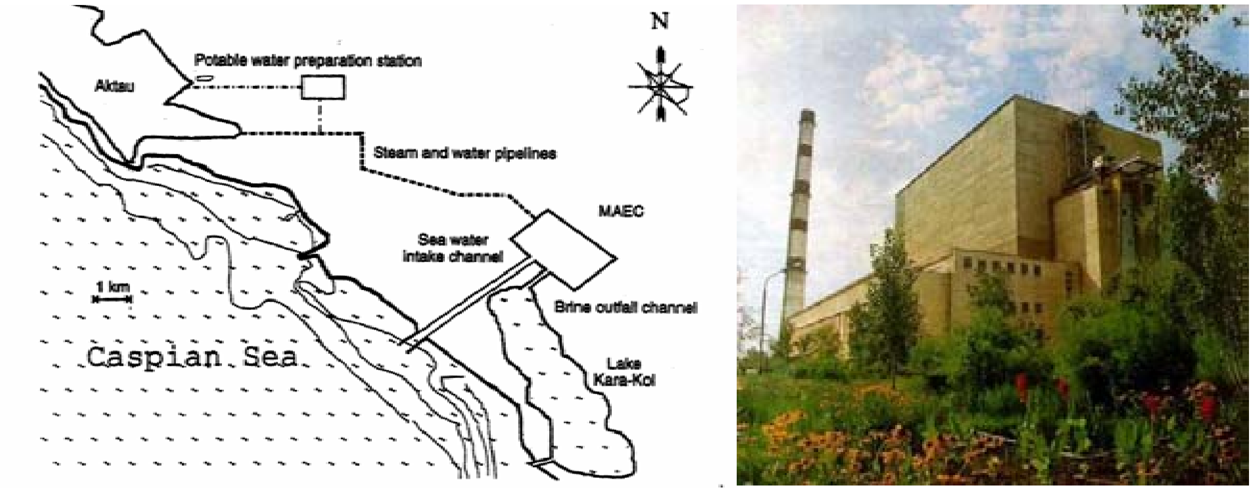

Figure 19. MAEC layout and NPP.

In addition to the facility itself, the land necessary for the piping and pumping stations must be considered. This is strongly influenced by the siting of the desalination facility in relation to the consumers. Land use for nuclear desalination purposes may change the surrounding land use. For instance, agricultural land may give way to the necessary land for plant infrastructure. As a development issue this is discussed in more detail in Section 4.

Overall, smaller land use for co-located desalination (at foreseeable level of technology) can not be achieved with any other energy source. Desalination is an energy intensive process and would therefore require large energy capacities. A 100 000 m^3/d desalination facility may require 1 to 44 TJ (see Table 4) which is equivalent to approximately 12 to 550 MW of installed capacity, depending on the used technology.

Supposing that 12 MW installed power are needed for a high efficiency RO operation, from Table 7 it can be seen that this installed capacity can be achieved using 0.25 km^2 covered with solar and 0.6 km^2 with wind power.[19] This would amount to a total land use of 0.35 and 0.7 km^2 for a desalination facility coupled with a renewable energy source. Comparatively[20], the best case for nuclear desalination would be 1.1 km^2 - a higher land use, but in this specific case providing roughly 80 times higher installed power capacity to serve other energy purposes as well. In case a desalination capacity of 500 000 m^3/d is considered, the size of a nuclear desalination plant would be 1.5 km^2, but it would amount to 1.7 and 3.5 km^2 for solar and wind coupled desalination respectively, and still with no energy available for other purposes.

Therefore, it can be concluded that not only the land use issue is not a constraint for nuclear desalination, but, depending on the desalination capacity, it is may be one of its largest advantages: when the needs for water and power should be addressed simultaneously or in case of spatial limitations requiring the plant to be fitted in an already developed zone.

---

[19] The Perth Seawater Desalination Plant (RO) requires 21 MW for average capacity of 123 000 m^3/d and peak capacity of 144 000 m^3/d [117]. The energy it uses is offset from a windmill plant.

[20] Having in mind that nuclear power plants are not able to supply only 12 MW(e), the best case for nuclear is estimated with 1 km^2 for 1 GW(e) capacity.

Table 7. LAND USE PER ENERGY SOURCE (Source: WEC, IAEA and CEC [116])

Method	Area needed for a 1 GW(e) electrical plant [km^2], according to:	
	WEC, IAEA	CEC
Solar PV	20 - 50	10 - 50
Wind	50 - 150	22
Biomass	4000 - 6000	/
Nuclear	1 - 4	3
Gas-fired	/	6.5
Geothermal	/	7

For smaller desalination capacities though, with no clear demand for extra power supplied to the grid and especially in areas with insufficient infrastructure, nuclear power is unlikely to be a good alternative to renewables from the perspective of land use impacts.

3.2.3. Noise and visual impacts

Noise from a RO desalination facility can reach over 90 dB(A), mainly as a result of the operating high pressure pumps [78]. In comparison, distillation plants have lower noise levels [25]. Thermal power plants, including nuclear, also can be a source of noise from the steam ejectors and turbines. In their case though, once-through cooling systems have an advantage over the cooling towers which add to the noise level of the facility. CEC [40] has even described noise as a “major disadvantage” of the air cooled condenser systems compared to once-through cooling. Compared with renewable energy sources, it should be said that windmills also have a disturbing noise effect [113]. Nevertheless, the nuclear desalination plant’s operation may result in noise which is disturbing to the surrounding habitats and residential areas. Mitigation of such impacts however, is relatively easy. Appropriate acoustical planning and use of acoustical barriers may result in sufficiently low levels of noise that allow greater choice of sites for the nuclear desalination plant.

The visual impact (Figure 20) on the other hand is appropriately small, which results from the lesser land use requirements for nuclear desalination. In case of retrofitting a nuclear power plant with a desalination facility, no significant addition of the visual impact should be expected. However, newly constructed nuclear desalination plants would be situated in coastal areas which are considered to be of great scenic value. Of course, they will have lower visual impact if their construction is planned in an already developed, industrial area. The previously recommended power plant cooling systems will no doubt increase the visual impact of the plant, compared to the once-through cooling systems. Yet, even so, nuclear desalination’s visual impact is lower compared with renewable energy coupled desalination. For instance, covering 1 or 2 km^2 with 80 meters tall wind turbines reaching 115 meters with their blades, or with PV laid over the same size area with dark solar panels [113], has a far greater visual impact.

3.3. ATMOSPHERIC IMPACTS

The direct air emissions of desalination plants consist only of oxygen and nitrogen discharges resulting from de-aeration processes [25], with a negligible environmental significance. The main adverse impacts on the atmosphere are indirect, originating from the energy source used to drive the desalination process.

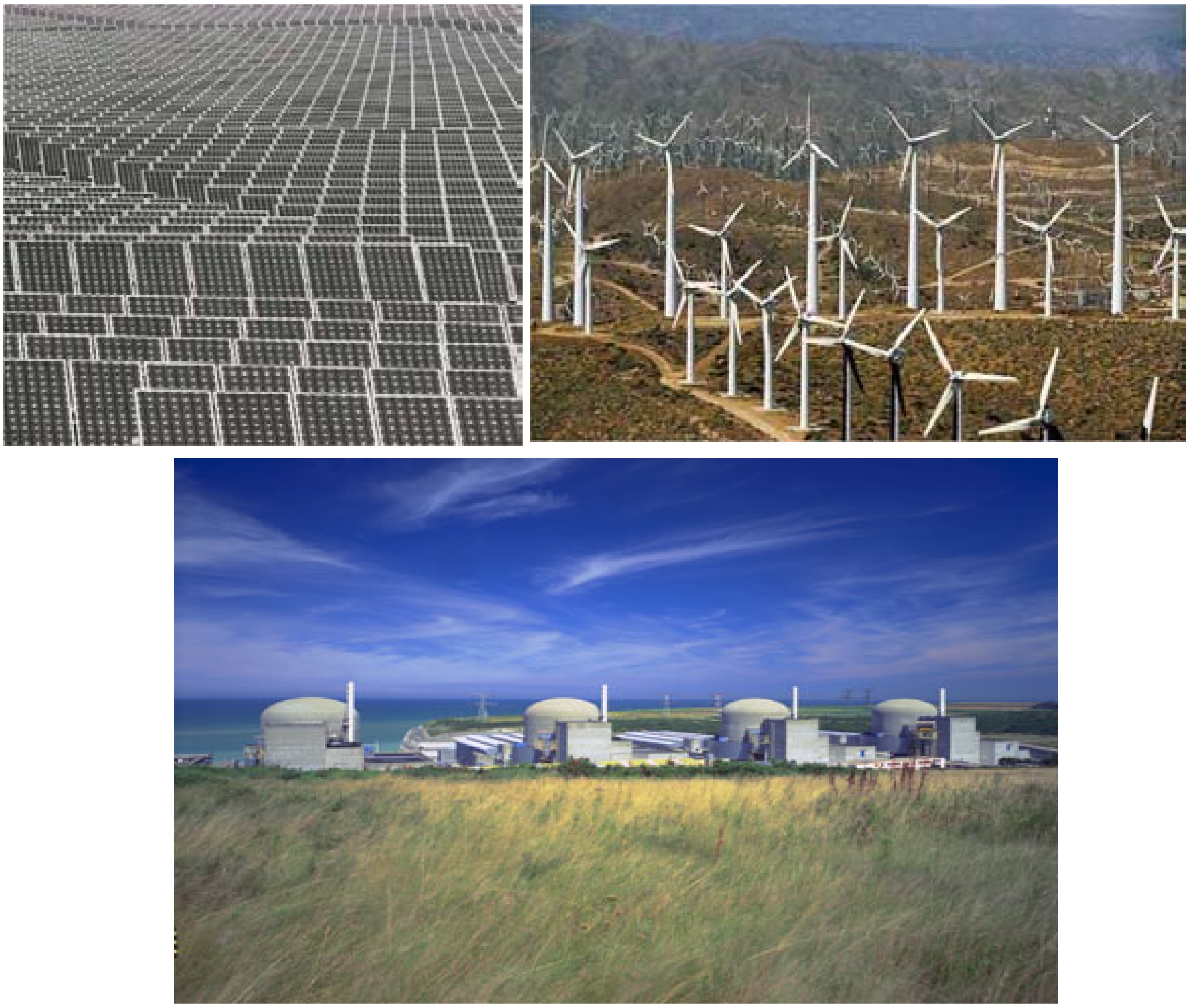

Figure 20. Solar plant, Serpa, Portugal (top left) Windmill plant, Palm Springs, USA (top right) Nuclear power plant, Paluel, France (bottom).

As previously mentioned, seawater desalination is a very energy intensive process. It can use ten times the energy needed for surface water treatment or water recycling [23]. In fact, it is considered that one of the biggest impediments for desalination is its energy intensity. Most of this energy, about 90%, is for the process itself - for distillation processes in the form of heat, and for reverse osmosis as mechanical energy. The additional electrical energy is needed for the auxiliary systems, such as pumping or dosing [73].

The climate change effect of desalination may be described as far from minor, having in mind that a large portion of the world's 20 million[21] cubic meters per day production [11] is based on fossil fuels as energy sources, emitting CO_2, NO_x and SO_x gasses. The equivalent GHG emissions from the energy use for seawater desalination in 2005 may be broadly estimated at 44.6 million tones of CO_{2eq} equivalent per day[22], amounting to around 0.6% of the global CO_2

[21] Data for 2005 [44], selected to correspond to the available energy data. Current water desalination estimates are significantly higher – 39 million cubic meters [77].

[22] This is an illustrative figure, with rounded up values and simplified calculation, thus probably on the high side, but the desalination's carbon footprint is obvious. For instance, waste heat as an energy source for desalination was not taken into account since no precise data was found, energy was calculated with 2005 global TPES value and not the value for the countries which desalinate most. Global and annual data was used from: IEA 2005 statistics [121] for Total Primary Energy Supply = 478 760 580 TJ, CO_2 emissions = 27 136 Mt, energy conversion efficiency from primary energy = 40%, presumed

equivalent emissions for the same year. On the other hand, out of the global 4.200 km^3 freshwater withdrawal (of which consumption accounted for 2.300 km^3 or 52%) in 2005[23] [118], seawater desalination contributed only around 13 km^3 in the corresponding year, which is 0.56% of the total consumption.

Somewhat similar result can be derived from the air pollution figures reported by Minton [119], who estimated the GHG emissions potential at 122 250 to 183 750 tons of CO_2 per year, for a 190 000 m^3/d RO desalination plant. Meerganz [120] suggests that the GHG emissions may be as follows (Table 8):

Table 8. GHG EMISSIONS PER CUBIC METER OF DESALINATED WATER WITH FOSSIL FUELS ENERGY

Emissions per m^3 desalinated water	RO	MSF/MED
CO_2 [kg/m^3]	2 - 4	20 – 40
NO_x [g/m^3]	4 - 8	25 – 50
SO_x [g/m^3]	12 - 24	27 – 54
Non-methane volatile organic compounds [g/m^3]	1.5 - 3	7 – 14

Using waste heat though, as an energy source for desalination processes can significantly lower the pollution resulting from the process. Naturally, since distillation processes use more heat to desalinate seawater, the reduction in GHG emissions will be more efficient. Typical values derived from the European energy mix for MSF/MED emissions per cubic meter of desalinated water are presented in Table 9 [122].

Table 9. GHG EMISSIONS OF DISTILLATION BY WASTE HEAT

Emissions per m^3 desalinated water when using waste heat	MSF	MED
CO_2 [kg/m^3]	1.98	1.11
NO_x [g/m^3]	4.14	2.38
SO_x [g/m^3]	14.79	16.12
Non-methane volatile organic compounds [g/m^3]	1.22	0.59

On the other hand, desalination capacities are growing exponentially (Figure 21), driven by a necessity for drought alleviating measures. Combined with the presented data on desalination’s significant contribution to emissions [120 and Table 8], it can be concluded that desalination’s climate change impact may potentially rise to a much larger proportion. As an example, Spain’s[24] plan for increasing desalination capacity by 600 million m^3/a (1.65 million m^3/d) is estimated to increase the state’s CO_2 emissions by as much as 9% [120]. For perspective, the additional desalination capacity would account for a national water supply increase of 15.3 or 0.03%, depending on whether the agricultural water is calculated in the total supply [123].

---

average for specific energy needs = 20 MJ/m^3 for RO and 300 MJ/m^3 for MSF/MED (Table 1), desalinated water production for 2005 at 20 million m^3/d and approximated production share of 50% between RO and MSF/MED.

[23] Precise data for 2005 is not available. The given figure is derived from estimates in [118].

[24] More than 80% of Spain’s desalinated water is produced with reverse osmosis. 51% of the electricity in Spain originates from fossil fuels and 35 from nuclear energy. Most of the new desalination capacities are planed to be supplied with electricity by fossil fuel power plants [25, 120].

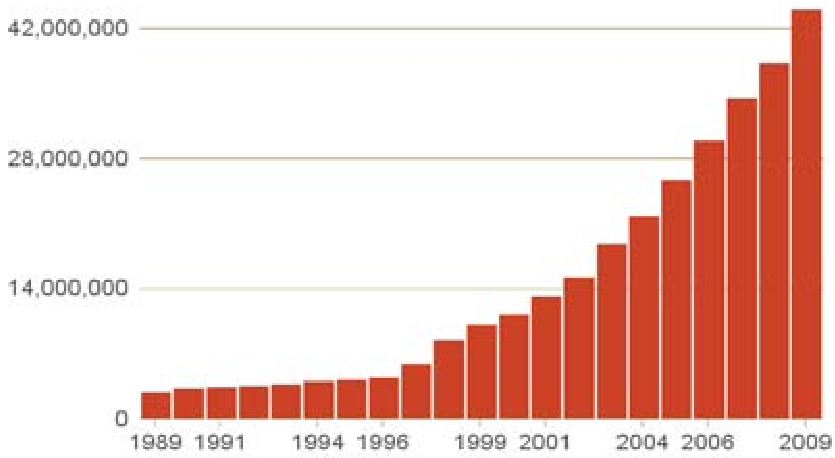

Figure 21. Cumulative seawater desalination capacity [m³/d] [77].

Desalination's energy intensity has been significantly lowered in the past decades. But this approaching to the thermodynamic minimum energy value, in the case of RO for instance, leaves no more than 15% energy reduction potential [23]. From the aspect of successful atmospheric pollution mitigation, further solutions for the energy intensity of desalination require low carbon energy, in addition to energy efficiency. Hence, the US National Academy of Sciences in its recent report on desalination suggests the use of nuclear and different types of renewable energies for desalination [23].

It is undisputed that renewable energy has gained massive support from the public, and therefore the decision makers and investors, as pollution-free energy. Many authors suggest coupling with renewable energy sources or at least purchasing such energy in order to offset the impact, as done in Perth, Australia. However, this is not without environmental impacts, as widely perceived [124, 125]. Actually, when average GHG emissions over the complete Life Cycle Analysis chain are calculated per kWh output, it can be seen that renewables rarely outperform nuclear power. (Figure 22) The well studied atmospheric impacts of nuclear power are considered minor in comparison with other energy sources.

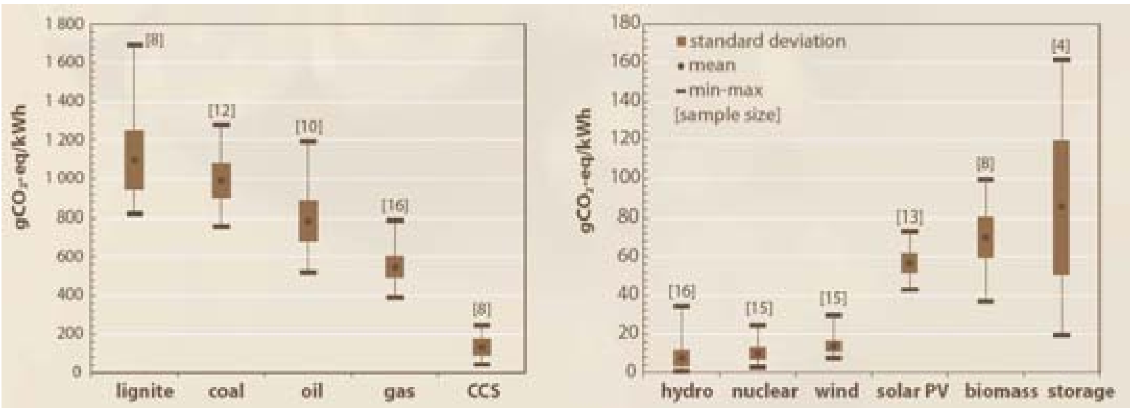

Figure 22. Carbon footprint of different energy sources. Source: Weiser, 2007 [125].

The following Table 10 [126] presents the direct (power generation) costs of various energy sources, as well as their external costs. In the energy sector, external costs are caused by emissions and waste which are the reason for health and environmental impacts. Impacts on public and occupational human health (mortality and morbidity), on natural ecosystems, fauna and flora, agriculture, building and cultural objects as well as global environmental impacts, such as climate change induced by greenhouse gases, are usually not accounted for in the energy supply price [126].

Therefore, nuclear desalination offers a solution for one of desalination's greatest impediments – its atmospheric impact. As can be seen, nuclear power greenhouse emissions per kWh are much lower than coal, oil and natural gas; lower than solar power's emissions; and at the same level or lower than wind power. For instance for an efficient SWRO process:[25]

- The GHG emissions per 1 m^3 of desalinated water with natural gas contribute 1000 to 2000 g of CO_2eq to the atmosphere.

- When coal is used as the energy source for SWRO desalination, one cubic meter of desalinated water contributes 1950 to 3250 g of CO_2eq to the atmosphere.

- The respective case for nuclear and wind may result in GHG emissions of 10 to 65 g of CO_2eq to the atmosphere for a cubic meter of desalinated water.

Table 10. COSTS OF ELECTRICITY GENERATING IN EU [in m€/kWh]

External costs	Coal & Lignite	Oil	Gas	Nuclear	Biomass	Solar PV	Wind
Austria			11-26		24-25		
Belgium	37-150		11-22	4-4.7			
Germany	30-55	51-78	12-23	4.4-7	28-29	1.4-3.3	0.5-0.6
Denmark	35-65		15-30		12-14		0.9-1.6
Spain	48-77		11-22		29-52		1.8-1.9
Finland	20-44				8-11		
France	69-99	84-109	24-35	2.5	6-7		
Greece	46-84	26-48	7-13		1-8		2.4-2.6
Ireland	59-84						
Italy		34-56	15-27				
Netherlands	28-42		5-19	7.4	4-5		
Norway			8-19		2.4		0.5-2.5
Portugal	42-67		8-21		14-18		
Sweden	18-42				2.7-3		
UK	42-67	29-47	11-22	2.4-2.7	5.3-5.7		1.3-1.5
Direct costs	**32-50**	**49-52**	**26-35**	**34-59**	**34-43**	**512-853**	**67-72**

Still, it must also be noted that renewable energy usually is not used directly as an energy source. Due to the temporal power output variations of those sources, they are usually used as offset - to the more constant in its availability - fossil fuel power. Such an example may be seen in the case of Perth, Australia desalination plant. The carbon footprint of Perth's desalinated water is actually higher than claimed due to the required use of fossil fuel energy in water production, although precise values are still not available [127].

Radioactive emissions to the atmosphere should also be kept in mind. Coal, among thorium, radon and other radioactive materials, contains uranium in the excess of 1 to 4 ppm [128]. Since large quantities of coal are used in power plants, the overall quantity of uranium in the plant's air emissions is rather high. Research so far indicates that nuclear power plants release 100 times less radioactive material in the atmosphere compared to a coal power plant of comparable size (1000 MW) [129].

---

[25] The subsequent figures are acquired by multiplying values from *Table 6* (2.5 kWh/m^3) with values from *Figure 22*.

Therefore, nuclear desalination may be considered as environmentally benign from the aspect of air pollution and a suitable energy source for large desalination capacities. Furthermore, the cost of externalities associated with nuclear are much lower than the respective fossil fuel costs (in large part due to atmospheric impacts). Compared with renewables though, nuclear externality costs are slightly higher, but the specific investment and production costs on a life-cycle basis may be significantly lower [124, 126].

3.4. SITING AND CO-LOCATION ENVIRONMENTAL ISSUES

First of all, it has to be emphasized that siting is largely, but not entirely, dependant on environmental issues. Socio-economic factors play a significant role in the process as well. Having in mind all the impacts that may adversely or beneficially affect the environment, as well as the socio-economic factors presented later on, selecting a site for a power-desalination facility becomes an important and complex matter which probably will include many tradeoffs. Proper siting though would be reflected in the lowest possible overall adverse environmental impact of the facility, with maximized environmental and socio-economic benefit outweighing it.

When considering nuclear desalination siting, the first criteria to be fulfilled are those regarding nuclear power plants. This mainly refers to a site that provides sufficient safety in terms of accident possibilities and subsequent effects. Safety guidelines and requirements for siting of nuclear power plants are already available [70, 130] and will not be dealt with in this report.

Provided that the regional water management plan includes the use of desalinated water in the produced quantities, a nuclear desalination facility would need to address three additional general issues of importance when choosing a site: distribution of product water, quality of intake water and disposal method for the discharge.

Siting the facility in the proximity of a water distribution network lowers the construction impact on the coastal habitats as well as transportation costs and energy. Of course, an already developed coastal site should be preferable to unspoiled coastal area because of existing infrastructure, and those sites are usually closer to water distribution systems. On the other hand, nuclear plants are required to be further away from settlements (water distribution systems) and a compromise is likely to be needed from that perspective.

Water transportation costs will depend on the distance, the diameter of the water pipe and the differences in elevation of the desalination plant and consumer. Some transport cost calculations were in the order of about 0.001 to 0.003 $/m^3/km [11]. For a water transport over a distance of 100 km the additional costs for transportation would be between 0.1 and 0.3 $/m^3. Compared to the production cost of fresh water by desalination in the range of about 0.70 to 1.20 $/m^3 these additional costs are significant. Since sometimes desalinated water will be needed in areas further from the coast, possible solutions to avoid large water transport costs could involve increased share of surface water use for the inland communities, offsetting the closer (or coastal) communities with desalinated water instead.

Similarly, losses in an electrical grid are direct proportional to the distance (km), to the second power of the power (Watt) and inverse proportional to the second power of the voltage (Volt). In a cable with a voltage of 110 kV losses of about 6% per 100 km of length will occur. Increasing the voltage to 800 kV will reduce the losses to 0.5% for the same length, but increase the costs for insulators.

In deciding the location of desalination plants and their corresponding energy source the above discussed losses and additional costs should be taken into account.

As for the second issue, availability of high quality seawater as source water is of great importance, able to influence the economics of the project, the process efficiency and subsequently, the levels of marine pollution. Proper siting insures that the seawater source will result in lowest possible use of chemicals and filters which need constant maintenance. An ideal site would have a geological structure of the seabed that allows the use of indirect seawater intakes.

Finally, the disposal process with the brine properties and quantity conclude the site choice. Discharge plumes may cause different environmental impacts depending on the receiving environment, and thus encourage siting of desalination facilities in areas which have low biological activity and strong fluid forces facilitating mixing and dilution. Water sources available for dilution should be taken into account as well as: water temperature, wave activity, winds and tidal regime. Since those parameters may strongly influence the effect of the discharge on the marine environment [25], they should not be neglected in the process of selecting a suitable site.

Every site involves specifics that need to be taken into account when making a selection. However, for a preliminary assessment of a proposed nuclear desalination site, a general shortlist of preferred ecosystems may be used. This shortlist of ecosystems' salinity tolerance, produced by Hoepner and Windelberg [131], is based on an adapted model where ecosystem sensitivity to oil spills was the main criteria. It describes 15 sub-ecosystems. Starting from the least to the most sensitive sub-ecosystems, they are:

1. High energy oceanic coast, rocky or sandy, with coast-parallel currents: the input of oxygen, energy and rapid water exchange, insure biodegradation, prevention of local accumulation and damages by elevated salinity and temperature.

2. Exposed rocky coasts: good water exchange even in small niches.

3. Mature shoreline: characterized by high sediment mobility, without any locations where water and sediment may have a long residence period.

4. Coastal upwelling: stagnant seawater may be expected and conditions change seasonally, containing suspended solids, plankton and nutrients.

5. High energy soft tidal coast: large intertidal areas and large sediment accumulation, with high sediment mobility and water exchange.

6. Estuaries and estuary-similar systems: similar with high energy soft tidal coasts, and with high nutrient content (and biodegradation), high turbidity and seasonal changes in the water quantity. Not suitable for desalination plants.

7. Low energy sand, mud and beach-rock flats: limited water exchange, high individual numbers from a low number of species, and large surfaces that may accumulate the discharge loads

8. Coastal sabkhas: large areas of shallow water and thus very warm due to solar stress.

9. Fiords: biologically active enclosed deep water bodies with limited water exchange and possible low oxygen content in the deeper zones.

10. Shallow low energy bays and semi-enclosed lagoons: similar to sand, mud and beach-rock flats, with lower water exchange, and high natural stress due to changing salinity, water levels and solar irradiation. Discharge loads add to those conditions.

11. Algal (cyanobacterial) mats: although relatively resistant to salinity and irradiation changes, other stress factors' impacts are not well known. Therefore, as a precautionary measure, algal mats are high on the sensitivity scale.

12. Seaweed bays and shallows: variations in salinity, irradiation and water levels. Rich in species and therefore, as a sub eco-system bearing their tolerance to the desalination induced seawater changes.

13. Coral reefs: basis for a coastal eco-system rich in species. The tolerance of each species to variations in the seawater quality parameters influences the higher or lower sub eco-system tolerance.

14. Saltmarsh: variations in salinity, irradiation and water levels exhibiting the sensitivity of macrophytes and other organisms inhabiting the saltmarshes. Nutrients carried by tides provide sufficient base for development of saltmarsh vegetation, which in turn provides protection from storm floods.

15. Mangrove flats: similarly sensitive as saltmarshes, but presumed to be slightly higher due to rapid decline of mangrove areas in the past.

As mentioned, this is an adapted list, and therefore it can likely be misleading in certain cases. For instance, mangroves are known as halophytic (salt loving) species [132] and the Californian rocky habitats with kelp beds are considered critical sensitive ecosystems [44], but the list above suggests that they are the most and least sensitive habitats, respectively.

Regardless of the type of ecosystem at the site, hydrological analysis are necessary to determine which nearby habitats will be affected by the discharge plume, and biodiversity calculations (such as the ones for the Shannon-Wiener Index) must be performed in order to indicate the habitats' biodiversity richness. Other criteria must also be applied, including the presence of species which are of specific interest, or species which are protected, endangered or endemic. Thus, the site selection process must insure that not only there is enough natural capacity for dilution but also that the direction in which the dilution should occur will be harmless for the impacted ecosystems [71]. Preferable sites should have ecosystems which can sustain the impacts of the plant's operation.

Finally, similar to all coastal-dependent projects, nuclear desalination review of environmental issues should take into account that siting might interfere during construction as well as operation, with other activities in the area. These may include navigation, tourism and recreation, aquaculture and fishing etc. Depending on the specific plant distance from the coast, assessment of the erosion risk and rate is necessary when selecting a proper site.

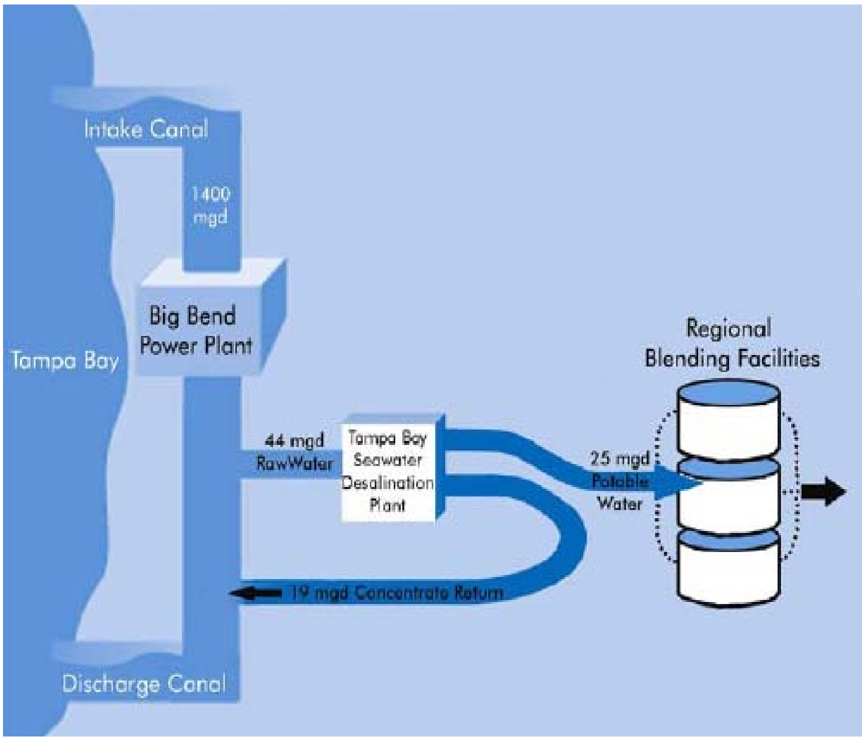

Figure 23. Co-location scheme of desalination and power plants [44].

As for co-location of power and desalination plants, the issues refer mainly to the combined intake and discharge practices. The core of the debate among experts, are the once-through cooling systems. Coupling desalination with power plants is usually done by connecting the desalination source water pipe to the once-through cooling discharge pipe, as presented in Figure 23.

The positive aspect is seen not only lower construction costs, but also lower product water price. For an RO facility, the pre-warmed feedwater coming out from the power plant's cooling system can lower the electricity consumption of the process by 10-15%. For a distillation facility using cogeneration, the additional energy requirements may be decreased by 20-25% [133].

Environmental benefits also found in co-location, are notably the lower construction impact on the marine environment, lower salinity of the desalination discharge due to the mixing with the power plant coolant and lower temperature impact of the coolant due to the mixing with the desalination discharge [23]. Heat from the cooling discharge is also removed for the purposes of desalination. For example, a 1 GW(e) nuclear power plant will have 173 TJ of waste heat per day to disperse in the environment, while a fairly efficient distillation process with capacity of 200 000 m^3/d would need 40 TJ per day. Although all of the waste heat is not entirely removed with a once-through cooling, this example illustrates the role of the desalination facility as a heat sink for the nuclear plant. Of course, not only the economic, but also the environmental benefits are proportional to the percentage of waste heat used.

According to the Pacific Institute, it can even be argued that desalination facilities do not have additional entrainment and impingement to the once-through cooling system impacts [44], which is a great environmental benefit. Therefore, it is only natural that most of the proposed desalination projects in the USA are in fact planned as co-located with power plants [26]. Co-location scheme of a nuclear desalination plant is presented in section 2.1. of this report, Figure 1, and below in Figure 24.

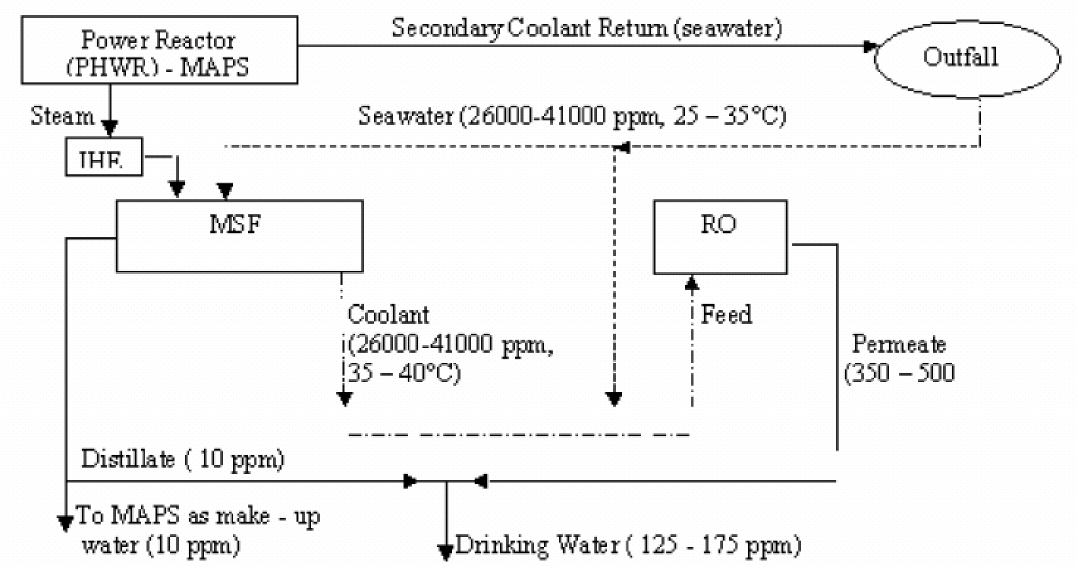

Figure 24. Coupling scheme of NDDP in Kalpakkam.

Newly built power plants have to perform adequate assessment of environmental impacts in order to be licensed. Co-locating desalination facilities in such cases is relatively easier. However, most of the coastal power plants which are operating today were built and licensed when, or before, environmental issues and regulation were emerging [28]. Hence, many of them presently use once-through cooling with direct intakes, as an inexpensive, technically simple solution, but with adverse environmental impact on the marine habitats.

Today, the main issue when co-location is considered, causing the public as well as the environmental regulators and experts to react to, is that environmentally harmful power plant intakes and discharge systems will have an excuse for continuation of use if coupled with desalination facilities [23, 44]. If such a power plant is shut down for maintenance, emergency or decommissioning reasons, the direct intake will be used for production of potable water, and thus continue causing all the environmental adverse impacts due to the operating desalination plant. The public reaction to desalination in some cases has been very negative, in cases when co-location was perceived as prolongation of causing environmental damage. One such case is the Tampa Bay desalination plant [23].

The US National Academy of Sciences in its latest analysis on desalination [23] concluded that the "source water impacts of co-located desalination facilities still need to be considered". Among the other concerns is the fact that additional energy[26] may need to be produced for the operation of the desalination plant, which would require more cooling water for the power plant, increasing entrainment and impingement as a direct result of the co-located desalination facility. With RO facilities, seawater intake increases may occur if the warmed cooling water is too hot for safe operation of the membranes (which have recommended working temperature 45^0C), thus additionally pulling in quantities of seawater to cool down the RO feedwater [28]. Furthermore, operating the two facilities would need to be coordinated tightly,

[26] Actually, although some smaller plants can do so, nuclear power plants usually can not follow the electricity demand and are mainly used for base supply. Therefore in most of the cases this argument would be of no importance. Renewable energy sources would also avoid this criticism.

since changes in the operating regime of one will affect the other. For instance, discharge salinity can increase, if the power plant reduces the intake of cooling water, thereby violating its discharge permit and in all probability cause environmental damage [44].

It is also important to note that the US Clean Water Act 316(b) has been declared as a technology-based regulation by a court decision in 2007 [29], which required direct mitigation of entrainment and impingement impacts instead of habitat restoration. Knowing that Clean Water Act 316(b), requires large reductions in these impacts, direct intakes must use additional technologies and alternative operating practices to comply, and consequently hindering plant efficiency [40].

Essentially, power plant intake regulations affect co-located desalination facilities by limiting their possibilities for sharing water supply with the power plants. Therefore, nuclear desalination, just as other co-located plants, might have to consider as of the near future separate water supply solutions for the desalination and the power plant. Although such stringent regulations exist currently only in the USA, it will not be surprising when other developed countries, where nuclear desalination is feasible, will follow in regulating environmental issues such as seawater intake. Needless to say, large environmentally adverse impacts on the marine organisms may be a reason for environmental regulators to withhold a permit based on other regulations, such as the ones that refer to endangered species protection, even if there is no specific national regulation for seawater intake systems. Thus, indirect intakes for desalination plants and closed cooling systems for power plants, whose design practically inherently avoids entrainment and impingement, are highly recommended.

3.5. CONCLUSION ON ENVIRONMENTAL IMPACTS OF NUCLEAR DESALINATION

Nuclear desalination presents an environmentally sound option for addressing water and energy shortages. It encompasses the benefits that co-location of power and desalination facilities offers, while avoiding some of the issues that still impede such projects, as summarized below.

Marine impacts of nuclear desalination are, generally speaking, a matter of trade-off between intake and discharge impacts on the environment. Compared with other co-location options it does not prove as a solution to the associated adverse environmental impacts due to the intake. It must be remembered that suitable design can solve the problem of adverse marine impacts for any co-location option. On the other hand, when the standard once-through cooling system is applied, as stated earlier, it provides large quantities of seawater necessary for dilution of the rejected brine and it also cools down the warm discharge from the nuclear power plant, which mitigates the largest problems that stand-alone power and desalination facilities have. Yet, large quantities of water for dilution imply large entrainment and impingement effects on the marine ecosystems. Deciding which one is less harmful to the environment is a site specific matter dependant on the intake and outfall locations and techniques. Combined use of indirect and direct intakes is also a mitigating option.

Coastal and atmospheric impacts of nuclear desalination though, can be considered as smaller or even minor, if compared to other co-location options. Especially in the area of mitigating atmospheric impacts from desalination processes, nuclear desalination offers huge opportunities due to the fact that fossil fuel co-located desalination options cannot achieve low levels of atmospheric impact, while renewable energy sources are not the better choice as well. Nuclear power plants, with very low atmospheric impacts, have large heat losses in the power generating process which can be used for seawater desalination with virtually no additional atmospheric impacts. The land use impact by the nuclear desalination facility, from the perspective of production quantity for potable water and energy, is currently the best option available.

In conclusion, nuclear desalination is particularly recommendable as a retrofitting option in existing nuclear power plants. As for building new nuclear desalination plants, for reasons discussed in more detail in the following section, policies addressing energy demands will have to be the main criteria. If then the choice lies with nuclear power while desalination is required to address shortage of good quality water, than a nuclear desalination facility definitely presents environmentally the most benign option for doing so.

4. SOCIO-ECONOMIC IMPACTS OF NUCLEAR DESALINATION

Several factors influence the importance of nuclear desalination as a socio-economic stimulus. The most significant though would be the higher development potential due to availability of energy and water. However, it may change patterns of consumption behavior, and cause major redistribution of people, capital and resources.

At present, owing to the economy of scale which allows for lower specific costs, the typical size of a commercially available nuclear power plant is in the range of about 1000 to 1600 MW(e).[27] For instance, a desalination plant with 100 000 m^3/d capacity will need a fraction of the power produced by such a nuclear unit.[28]Therefore, the key issue when considering nuclear desalination would be the energy demand, rather than the water demand. Consequently, engaging nuclear desalination would require that in addition to water demand, there should be a clear demand for the remaining power from the nuclear power plant as well as a power grid of sufficient size.

Availability of water and energy has profound positive effect on local development. The potential of nuclear desalination to provide the basis for development has its best example in the emerging of Aktau (Kazakhstan), where nuclear desalination was used to support the growing city and industry in the area rich with minerals. The desert-like area was transformed into a developed coast, further stimulating the economic as well as the population growth (from 59 to 155 thousand residents) that occurred between 1970 and 1999 (Figure 25).

This section will focus more on socio-economic impacts caused by water availability rather than the energy implications for growth, as they are a standard part of nuclear power plants' impact assessment. Moreover, compared to power, water distribution is geographically limited and thus water availability impacts may not be as dispersed over large areas as the energy-related ones. Water induced growth impacts may therefore be more intense, with the development surpassing the local or regional plans.

---

[27] It is expected that within the next decade also smaller nuclear reactors will become commercially available. When small and medium sized reactors, now under development, become commercially available as proven designs, i.e. after sufficiently demonstrating economic competitiveness, reliability and safety, nuclear power will also become an option for being used as energy source for desalination in small grids or even as exclusive energy source for a single co-located desalination plant

[28] Presuming the latest technology with high efficiency, this fraction would amount to about 10% of thermal power in the case of a MED plant (if specific energy requirement is 200 MJ/m^3), and in case of a RO plant about 1% of the electric output (specific energy requirement 10 MJ/m^3).

 

Figure 25. Aktau in 1961 and 1975. Source:www.aqtau.kz.

Indeed, the CCC [28] has suggested that growth-inducement related desalination impacts are likely to be “the most significant potential indirect adverse impacts”. Growth due to availability of water from new sources, including desalinated water, or due to water that becomes available since other users found new alternatives, can stimulate new residential and commercial development [50], putting additional (possibly unsustainably high) strain on the local environment and resources.

Although usually water use is the major socio-economic impact factor, the interference of nuclear desalination construction, as well as operation, with other coastal activities must not be neglected when considering the project’s value. These include fisheries, recreational, tourist, navigational and other commercial activities that may be common in the area and which might be affected.

When desalination is applied as a source of fresh water, two cases can be identified for assessment. One would involve the additional water as an augmentation of water supply and the other one would use the desalinated water as a substitute for the depleted or stressed natural water sources.

4.1. SOCIAL IMPACTS

Nuclear desalination in general is expected to have a positive impact on society by making more fresh water available and opening up opportunities for more development related activities. The desalinated water can be intended to bridge the gap between supply and demand as a completely new water source in addition to the already available water. The social impact in such a case will differ in magnitude as well as character on a case specific basis, largely dependant on the water management and development plans that control growth in compliance with other supporting factors.

However, desalination should not conform to a tendency to exceed the natural limitations with water-dependant development. Often, based on the idea that water is available and cannot be exhausted, gaps between supply and demand are addressed with more supply, which in turn encourages higher water consumption. Essentially, water supply and consumption will augment each other if uncontrolled. Therefore, supply-based practices like desalination, while providing water availability, may lead to unsustainable pattern of development or, may initiate an increase in water consumption beyond sustainable levels.

As an example, water availability has been the key to development growth in Spain (which has the largest desalination capacity in the Mediterranean [25]), especially in the southern and interior regions. Desalination capacity growth for its southern region of Almeria went together with development of the region's agricultural industry (27 000 ha of greenhouses), resulting in high water consumption of 3000 L/d per person, in spite the fact that it is naturally one of the driest regions in Europe (see next page, Figure 26). Desalination has thus allowed export of food to regions which are more suitable for producing it in the first place [120].

This seemingly positive economic impact changed the consumption patterns to a point where every natural water supply disturbance may cause severe damage by affecting the local economy as well as the food availability on a larger scale. If such a situation emerges, the perceived best solution is usually sought in more desalination capacities, as can be seen from the plans and contracts for new desalination capacities triggered after the recent drought in Spain, aiming at maintaining the agricultural output and residential life-style [134]. This basic idea that water is endless as a resource if enough desalination capacity is to be deployed is also one of the reasons for the extremely large numbers of properties built in the arid regions of southern Spain. Not only have new residences been built, causing with its spreading further environmental damage to the coastal ecosystems [135], but also golf courses which are very water-intensive. Water conservation and reclamation, which in many cases is a cheaper and less complicated way to obtain water [28] is thus not considered.

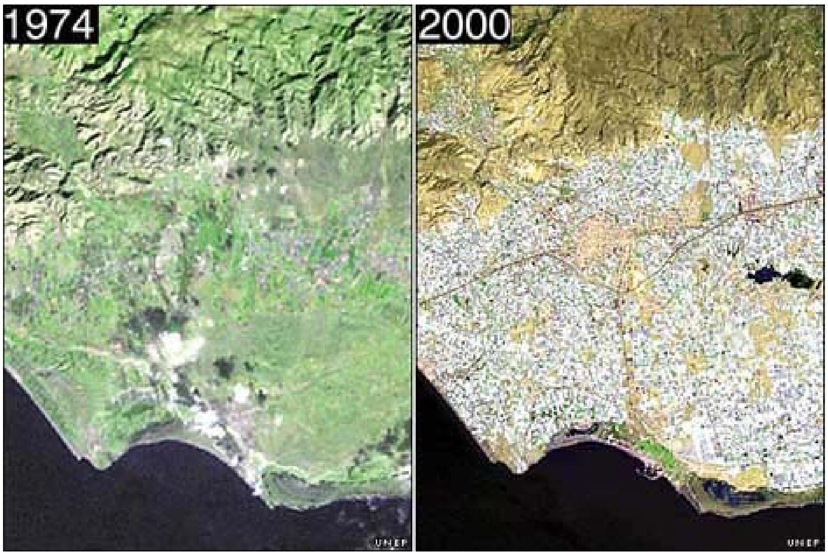

Figure 26. Greenhouse agriculture growth in Almeria, Spain. Source: UNEP.

Another example of water availability contributing to socio-economic impact beyond sustainable limits is the wheat production in Saudi Arabia. Encouraged by the idea of food independence, the agriculture was supported with subsidies and groundwater from aquifers which have a slow replenishment rate. The result was far beyond food independence, with Saudi Arabia becoming in 1992 the world's sixth largest wheat-exporting country although its arid climate required two to three times more water for agriculture than a temperate country [136]. Saudi Arabia now plans to gradually bring to an end its food production by 2016, and although its development was not based on wheat production, this case remains as a reminder of drastic changes that a society may undergo with (sudden) water availability.

Enhanced economic activity after provided water availability due to desalination may cause immigration to the community which enjoys it[29], and as a consequence stimulate residential and industrial development. This may also significantly impact the social balance, affecting the local organization and structure. Population rise beyond local or regional development plans can result in outgrowing of the available capacities of public services and necessary supporting infrastructure (e.g. utility), adding to the social and economic disturbances.

Other impacts from residential development include increase of runoff water, which subsequently degrades the quality of water sources, alteration of land use, which might affect recreation and tourism, increase of traffic and changes in traffic patterns, damages to sensitive coastal ecosystems from the increased population etc. [50].

On the other hand, desalination offers positive effects, such as diversity of supply which mitigates the impacts of prolonged water stress or when dealing with the quality of water, alleviating water scarcity and even may be, as mentioned in the desalination report by the US National Academy of Sciences [23], environmentally less damaging. Severe constraints on socio-economic development are expected if available water resources are below 1000 m^3/y per capita - which is required per capita for a moderately developed country. Additionally, water availability can reduce conflicts over scarce water resources and it can create wealth through tourism, industry and agricultural growth, offering employment [25]. The case of Malta, for instance, shows how desalination combined with measures that prevent water misuse may help the profitable tourist industry [73].

It is noticeable that the same effects of water availability due to desalination may have positive or negative consequences, such as coastal development. In order to apply nuclear desalination in a positive socio-economic way, just as with any other desalination project, there has to be a development plan for the region or area, based on many criteria as well as quantities of water matching the desalination capacity.[30] Such development plans define the growth to a level that can be sustained from environmental, social and economic aspects combined as well as a water management plan that defines the use of water and other measures ensuring availability of water in the long run.

Using desalinated water as a substitute source may happen due to variety of reasons. It could be that the previously used water source has depleted, with possible effects on subsidence or seawater intrusion into the aquifer. Furthermore, if the withdrawal from fresh water resources becomes harmful to the ecosystems, using desalinated water could result in restoring the waterflow levels and the biota dependent on that water, preserving valuable habitats [28]. Some of the proposed desalination plants, like the one in Monterey Bay, California, are envisaged as a substitute for the current sources of fresh water which are degrading the environment, and considered preferable to other water source solutions such as dams [50].

As a substitute source of water, desalination can be applied to avoid the use of contaminated water sources which, although accessible, may be contaminated and responsible for waterborne (transmitted by drinking contaminated water) and water washed diseases (due to lack of water for hygiene) [137]. Such a case for instance would be contamination of traditional water sources due to pesticide intrusion in ground aquifers. Desalination can

[29] Other factors clearly have a role in this issue and water availability cannot be the only problem hindering regional development, although there are cases where this is true.

[30] Of course, in a similar way, the energy from the nuclear power plant would have to match projections for energy supply growth at a national development plan level.

provide water with high quality, helping to prevent waterborne diseases. Water washed diseases' alleviation together with other basic necessities, require minimum 50 liters per day per person (18 m^3 water per year per person) [138].

This case of desalinated water used as a substitute source is very likely not to cause the possible adverse development impacts discussed above, since the quantity of water available to the users remains more or less the same. The improved quality may though influence some changes, but their magnitude and scope will most probably not be large. It must be kept in mind that in this case, the environmental impact of the nuclear desalination plant must be addressed properly so as not to deteriorate the existing social conditions.[31]

It is important in this case to ensure that the environmental benefits will not be short-lived. If a water distribution system, replaces one of its sources with desalination, while another distribution system takes over the released water source for its consumers, essentially the same social challenges that need to be addressed will emerge, with no environmental benefit. What is even more difficult in this case is the larger area of impacts that needs to be assessed.

The use of desalination as an emergency water source is not so common and there are limited experiences with this use of desalinated water. One such example is the SWRO plant of Santa Barbara in California, which was built to be a base supply solution, but after the drought passed, categorized as an emergency water supply. Never being used after that, it demonstrates two important facts: specific emergency water costs can be comparatively higher than surface water supply, thus requiring sound reasons for the project, and water conservation measures can yield substantial savings of water at a lower price than desalination [44]. However, although the economic impact of emergency desalination would probably be adverse[32], possibly the environmental and social impact in this case would be beneficial, since drought effects could be mitigated.

4.2. ECONOMIC IMPACTS

Nuclear desalination raises great concerns among the public as well as experts on the account of the necessity for the product water and energy, from an aspect of initial costs and development plans. However, it can well prove to induce positive economic impacts if, in addition to energy, there is need for supplementary water supplies as well, linking the benefits of nuclear power to water availability as well. Such is the case with Aktau, where the combined needs for energy and water necessary in developing the town have been successfully addressed with the use of nuclear power.

The production costs of desalinated water consist mainly of three cost components: The cost of capital investment, operation and maintenance costs and energy costs. The operation and maintenance costs of MED and SWRO plants are comparable, while the respective MSF costs are higher. However, the capital investment and energy costs differ considerably. The following Table 11 shows the results of a comparative study for specific investment costs and production costs of fresh water for different types of desalination plants [73].

---

[31] Social impacts may be caused by adverse environmental impacts. For instance: loss of employment and tax revenue from tourist and fishing industries because of adverse marine impacts from the nuclear desalination plant.

[32] This is a matter of risk assessment and cost-benefit analysis. If the risk of natural hazards due to lack of water, such as droughts and fires, is considerable enough and has the potential to cause large damage in economic terms – then desalination as an emergency measure would, of course, be beneficial.

Table 11. SPECIFIC INVESTMENT AND COSTS FOR DESALINATION PROCESSES

Specific costs	MED	MSF	VC	RO
Specific investment cost (US$/m^3/day)*****	900 to 1000	1200 to 1500	950 to 1000	700 to 900
Costs of fresh water (US$ per m^3)******	0.75 to 0.85	1.10 to 1.25	0.87 to 0.95	0.68 to 0.82

* Plant capacity 30 000 m^3/day, 7% interest rate, project life 20 years.
** Electricity price 6.5 US cent/kWh, cost of manpower 45,000US$.

Table 11 above clearly shows the superiority of the RO technology in regard to economics. It is to be mentioned that especially distillation plants like MSF and MED, however, can take advantage of the economy of scale, i.e. their specific costs decrease with increased capacity of the plant. Thus, very large desalination plants using MED technology with a capacity of about 340 000 m^3/day achieve specific investment costs comparable to RO plants, i.e. in the range of 780 US$/m^3/day [11]. MED, MSF or VC as distillation processes may also be a preferable choice for producing high quality water from seawater, to be used in industrial purposes for example.

As already mentioned before, to improve flexibility of desalination plants to fulfill changing demand of fresh water quality and volume, and to increase their thermal efficiency combinations of different desalination processes have been considered such as co-location of a MSF or MED plant with a VC or RO plant (called a hybrid plant). One example of such a hybrid plant (MSF/RO) is operating in Kalpakkam, India, with a pressurized heavy water moderated reactor as the energy source (to be discussed further in Appendix V-1.1.).

Preheating of the seawater in a MED plant for a co-located RO plant to about 40^{o}C increases the efficiency of the RO process and was calculated to reduce the specific costs of freshwater production by about 10% [11].

Depending on the distance between desalination plant and the water users, non negligible costs for water transportation have to be taken into account. These costs include the fabrication and erection of the pipe line including necessary pumping stations and the O&M costs of the transportation system. Studies performed [11] determined values of total specific transportation costs in the range of 0.001 to 0.003 US$/m^3/km, e.g. a water transport of 300 000 m^3/day over a distance of 231 km with significant differences in elevation would result in additional (to the values given in Table 11 above) specific costs of fresh water in the range of 0.4 to 0.7 US$/m^3 depending on the interest rate (6-10%).

Additionally, the spin off benefits to national industry by a nuclear power program are numerous and include delivery of new products, increased quality and competitiveness in the industry, higher possibilities for export, and additional higher skilled jobs. Meanwhile the price of the produced energy is rather stable in long terms.

On the more specific subject of water cost from nuclear desalination, the IAEA Coordinated Research Project on economics of nuclear desalination concludes that it is an economically attractive and technically feasible option in a variety of reactor concepts and site conditions

[11]. Combined with the nuclear power plant availability at 83% on average[33], low cost of externalities[34] and lowest operating costs per kWh [124, and in Table 10], the concern over the long-term cost of desalinated water and reliability of supply for that price should be minimal compared to other energy supply options. In comparison, wind turbines have lower availability factor which, range around 0.7 and higher operating costs, though lower external costs per kWh [124]. Fossil thermal power plants appear to provide lower energy availability factor than nuclear – though in the range of 70-90% for large coal, but around 60% for combined cycle gas plants [139][35] while having higher operating and external costs [124].

However, this is not quite the case with new plants: in addition to safety concerns, the huge capital costs for a nuclear desalination plant, longer construction periods, high degree of uncertainty with respect to schedules and finances are enough to spark public opposition. If the government or utility is not committed to the project, these reasons might enhance the investors' reluctance to support the project financially [140]. Indeed, in the USA, all 41 reactors ordered after 1973 were subsequently cancelled on the account of (among other reasons) economic recession, rising capital and fuel costs and environmental concerns among the public [141].

Of course, retrofitting existing nuclear power plants with a desalination facility includes much lower costs, and the desalination project would be able to avoid the risk of a prolonged public debate over its cost, siting and construction schedules or even its cancellation. The nuclear desalination experience in such retrofitting is limited only to the demonstration plant in Kalpakkam and conclusions can not be drawn from this small capacity case. Nevertheless, from the economic impact aspect, it would be interesting to study the possibility of retrofitting nuclear power plants. One such study case could be Koeberg, near Cape Town, South Africa, which is a coastal plant, 30 kilometers outside the city and in a water scarce zone, making it almost ideal for nuclear desalination as a retrofit option.[36]

Water supply reliability in the case of nuclear desalination with reverse osmosis is achieved at even lower costs since it is not connected to the nuclear power plant availability. Reverse osmosis facilities can draw energy from the grid, while for distillation processes backup heat source must be provided. As for distillation processes, the nuclear desalination plant in Aktau had used a gas-driven power plant to supply the necessary heat for the process. On the other hand, a modular nuclear plant design might exclude the need for an extra on-site fossil fuel capacity [140].

Regarding the more localized economic impacts which can be expected from nuclear desalination, Bezdek and Wendling's research [142] on the nuclear power plant effects on local property values, economic growth, tax revenues, public services, community development, jobs and employment, as well as schools, concludes that the effects have largely

---

[33] Half of the reactors in the world have 86% and above availability, quarter of the world's reactors have 91% or above availability [124]. The data for fossil fuel power plants is currently being updated to provide a more accurate picture of the actual availability.

[34] Externalities do not include waste disposal costs, nor decommissioning, since they are usually internalized for nuclear power [198].

[35] This specific data is found from Renewable Energy Research Laboratory at University of Massachusetts at Amherst. The data from WEC is currently being updated.

[36] Cape Town and the immediate region's sustainable water supply is being threatened by a combination of growth and development, uncontained demand and unrealistically low tariffs [143]. These issues must be addressed prior to, or parallel with, a possible nuclear desalination project.

been positive. As pointed earlier, water availability also has a significant influence on development, property values, jobs etc. This indicates that nuclear desalination within the frames of a national, regional or local development plan will most probably have a large and mainly beneficial economic impact, which may strongly influence the public opinion. Of course, as already said, there are situations where the development impacts from nuclear desalination might cause adverse effects. One such case could be the drop in generated revenues due to lowering of the scenic value of the tourist site - if the plant is sited on an intact beach.

4.3. PUBLIC ACCEPTANCE

The application of nuclear desalination does not depend solely on resolving technical and regulatory issues. Just as with other development projects, public acceptance of nuclear desalination is a major factor in its successful implementation since the local citizens and nongovernmental organizations can influence the regulatory bodies which in turn can place various impediments in the permitting process [23]. Therefore identifying the issues that affect the public opinion and acceptance is very important.

In general though, it may be expected that for nuclear desalination the issues burdening nuclear power as well as the issues that affect desalination will add up, instead of mitigating each other (as with the marine impacts). Combined, these include safety and public health issues, environmental justice and impacts, necessity of water and energy supply, as well as financial concerns.

The matter of safety and public health is mainly due to the use of nuclear energy. Concerns about reactor safety, radioactive waste disposal and nuclear proliferation, are always associated with nuclear power. The main risk of a co-located nuclear power plant and a desalination plant (DP) clearly rests with the nuclear unit. Safety issues of the nuclear power plant itself though, are handled within a so-called nuclear safety case which forms the detailed basis of licensing guaranteeing an adequate safety level. Whether the DP influences the safety of a nuclear power plant depends on the coupling between the two facilities.

If the DP is coupled via electricity supply only, e.g. in case of a RO plant, there is practically no additional safety risk associated with the co-location.

If the DP plant is coupled to the nuclear unit via heat, e.g. in case of a MED or MSF plant some additional minor safety issues are to be addressed, which, however do not lead to any significant additional risk. A thermally coupled DP is part of the heat sink of the nuclear plant and a shutdown of the DP results in a partial loss of heat sink of the nuclear unit. This transient is already covered in the safety base of the nuclear plant itself; however, the frequency of occurrence of this incident could be increased by frequent shutdowns of the DP. To avoid such an increase of frequency specific design measures of the DP plant have to be taken, such as splitting the DP plant in a sufficient number of small modules. To summarize, thermal coupling does not induce any significant additional safety risk to the nuclear power plant, since such risks can be completely eliminated by appropriate design measures.

This of course needs to be clearly communicated to the public. Low public acceptance is known to have reversed decisions and halted nuclear power projects. One such example is the plant at Zwentendorf, Austria, which was rejected in a public referendum although it was prepared to start operating – and this was prior to the incident at the NPP Three Mile Island. However, most of the public has reacted negatively after two specific incidents: the previously mentioned at Three Mile Island and Chernobyl. Despite the safety record of nuclear power, which is second to none in the industry, the two major accidents still have an impact on public acceptance of nuclear. Three Mile Island has effectively stopped new nuclear power plants in the USA [144] and the public opposition after the Chernobyl accident due to doubts about safety issues has influenced the stagnation of nuclear power on a global level (Figure 27).

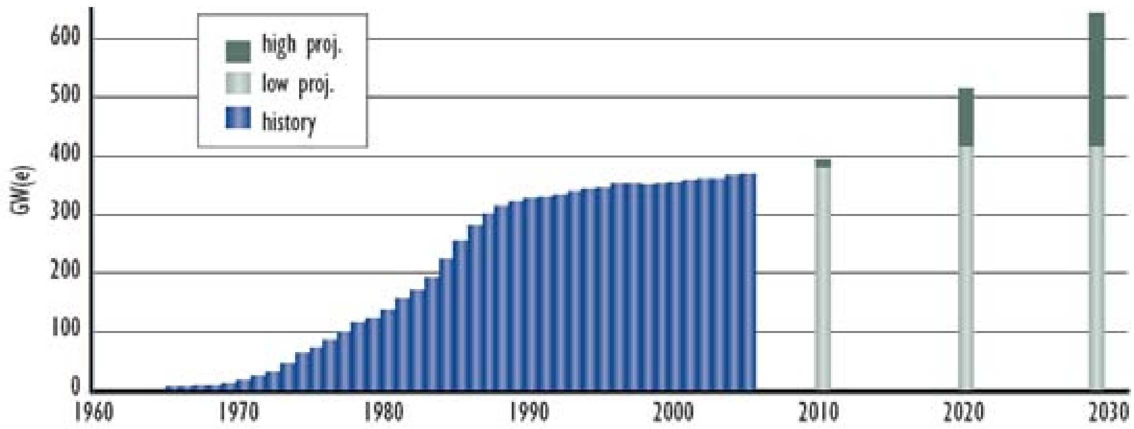

Figure 27. Nuclear power growth 1960 – 2005 with projections to 2030.

As seen on Figure 27, there are expectations for growth of nuclear power in the near future. This predicted rise is not only based on the need for energy which has a low carbon footprint, but also on the fact that many countries have experienced a change in the level of public acceptance of nuclear power. As an example, Figure 28 depicts the support levels among the public for nuclear in the EU. This goes parallel with the construction of new nuclear reactors in Western Europe - after 14 years, since 1991 [145]. Similarly, the US Energy Information Administration in its 2008 Annual Energy Outlook [146], estimates a 15% rise in the US nuclear power output mainly due to new capacities.

The Eurobarometer report 297, "Attitudes towards radioactive waste", [147] states that a significant increase of support for nuclear power was recorded in 17 out of 27 EU countries, while a significant decrease of support was noticed in only two countries. The survey noted that people who consider themselves well informed on the topic of radioactive waste are considerably more positive about nuclear energy production than those who feel poorly informed, according to this report. Record high public support for nuclear power was noted in the USA as well [148], in addition to the high safety ratings for nuclear power (Figure 29).

These results indicate that diminishing public fears concerning nuclear power are closely linked to information made available and presented to the public: the more informed the public is, the more confidence about its safety and more support will be shown for nuclear power and of course, nuclear desalination.

As for the public acceptance of desalination, few studies were done so far. On the other hand, it seems from the large number of projects (more than 14 000 [77]) and the estimates for doubling of the current production capacity till 2016 [149], that water availability as a benefit for the community is, in general, a strong enough argument in the eyes of the public to accept a desalination plant in their proximity.

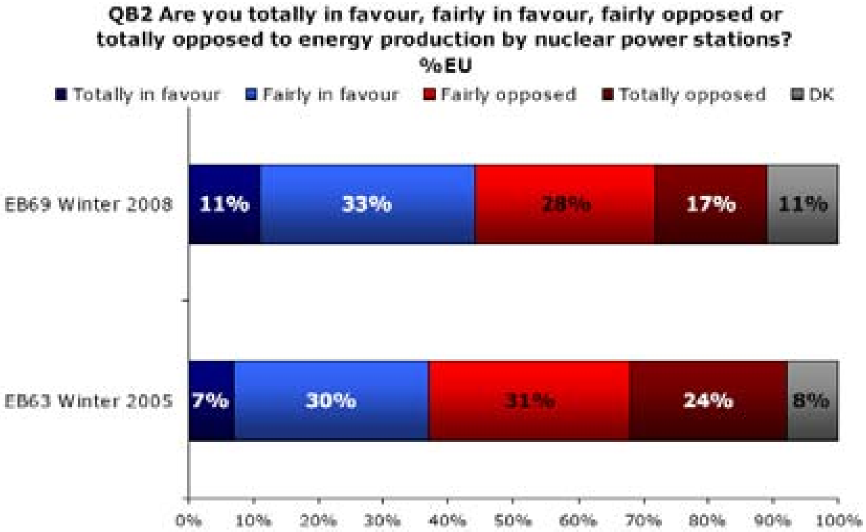

Figure 28. Support growth for energy production from nuclear power plants in the EU.

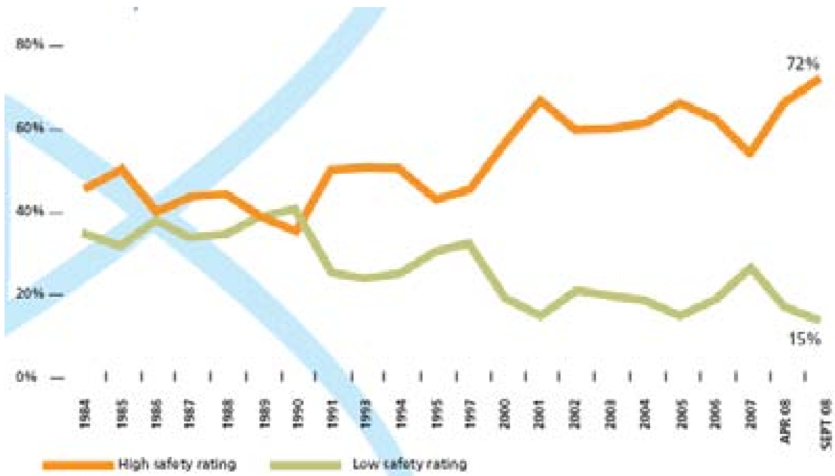

Figure 29. Public opinion on nuclear power safety in the USA.

Desalinated water, by its inherent perception as a drought-proof measure, is easier to be accepted by the public. The previously mentioned case of Santa Barbara desalination plant, was set up because of the public fear of possible drought [44]. However, the high public acceptance of desalination seams to be tested on many occasions when desalination plants are announced as concrete projects, especially in Europe and North America. Such specific desalination plans often reveal the public concern with environmental impacts of desalination projects and it may not be much different for nuclear power, or more specifically, nuclear desalination.

As for the public perception of desalination health impact, one survey that compared public perception on recycled and desalinated water, conducted in Australia, shows that 69% of the respondents consider desalinated water as healthy and 79% perceive it as drinkable [150]. Yet seawater desalination with reverse osmosis does raise health concerns, such as the levels of boron and bromide [23, 34] that are originally higher in the seawater than the levels suitable for consumption and agricultural use. Even after the seawater passes through the membranes, the levels of these substances may remain unsuitably high for use and special treatments are considered for the removal of most of them, including double pass and higher pH of the process [23].

The public health concerns however, in the specific case of nuclear desalination, will additionally have to address the issue of suitability of desalinated water for safe public use. Tritium, as the main concern for public health, would need to be addressed more thoroughly in an information campaign in order to eliminate possible negative reaction from the public, regardless of the radiation safety experiences so far. More details on this issue are provided in the Appendix III.

According to the experience so far, nuclear desalination was accepted for use by the public. For instance, based in a water-scarce region, the facility in Kalpakkam is experiencing growth of demand for desalinated water [20]. The other applicable experience of nuclear desalination is even more convincing: founded in a desert, Aktau’s development and population growth were supported with water supplied mostly from the nuclear desalination plant [151]. This plant was shut down in 1999, but new NPP is being planed in the area [152]. These two cases, as well as the relatively high public acceptance of desalination, imply that nuclear power will attract more public support when applied in arid regions in combination with desalination i.e. nuclear desalination will be, in all likelihood, more acceptable to the public rather than just nuclear energy.

Other aspects of nuclear desalination public acceptance include environmental justice. As of the last decade, this is an important issue against which projects are scrutinized in the developed, and increasingly more so in the developing world. It means that the positive and negative environmental (ecological, financial and social) consequences should be proportionally distributed among groups of stakeholders which differ in their income, education, race and nationality. Therefore, it is necessary to carefully review the stakeholders and the impacts that nuclear desalination will have on them, mitigating the adverse impacts in time.

Issues of environmental justice have been reflected in the Aarhus Convention, signed by 40 parties, mainly in Europe [153]. This Convention, stemming from the UN Conferences on environment and sustainable development, is a legal instrument linking environmental rights with basic human rights, and granting all stakeholders (including NGOs as well) access to relevant information, decision-making power and justice. The right to information access is especially interesting in this case, since information provided to the concerned public, as previously indicated, may add to the sustainability of the project and shorten the time of its implementation.

As more nuclear desalination project take place, it is likely that their scrutinizing against such issues will be increasingly detailed. The reason for this is that such facilities tend to be built on cheaper coastal properties, closer to less prosperous communities. If the price paid for the property does not reflect the true costs which include externalities[37] and fails to deliver the benefits of water, energy and jobs that other, more affluent communities enjoy, serious social conflicts might emerge based on violated environmental justice. Another serious environmental justice issue is the user group to which the desalinated water is intended, even if no other issues exist. Distribution that excludes specific social, racial or ethnic groups will likely be impeded due to environmental justice concerns, either on the basis of existing regulations or on the basis of negative public response.

[37] These might include visual, noise, air and marine pollution causing adverse impacts on local industries, as well as diminishing of the cultural, historical, commuting or aesthetic significance of the site.

4.4. CONCLUSION ON SOCIO-ECONOMIC IMPACTS OF NUCLEAR DESALINATION

The socio-economic impacts of nuclear desalination will most probably be differently dispersed on a national level for a country which is introducing nuclear power and for one which is already a nuclear power user. In the first case, the benefits would require the scope assessment to deal much more with impacts on a national level since the nuclear energy issues will be introduced for the first time: energy availability, radioactive waste handling, socio-economic impacts due to nuclear power etc. In case a nuclear power is already used or a plant is retrofitted with a desalination facility, the scope of the Assessment will be based more on issues such as water availability and socio-economic impacts on a more local scale.

The preliminary review of possible impacts suggests that the energy and water availability due to nuclear desalination would not result in adverse socio-economic impacts if a development plan is in place (national, regional, local). The magnitude of the beneficial impact would likely be higher than other desalination co-location options, due to:

- Lower overall costs,

- Higher availability, and

- Larger capacity of the nuclear desalination plant.

It is not expected that the general public reaction would be more radical than for the available fossil fuel alternatives. It seems that the increasing support for nuclear power in this age of combating the climate change will be carried over for a nuclear desalination project with even less criticism than for nuclear power alone, since typical desalination is burdened with the use of fossil fuels. Retrofitting a nuclear plant with desalination facility is also not expected to be publicly opposed. It should be remembered though that nuclear power is very sensitive to public acceptance which is quite easy to loose.

On the other hand, if the alternatives include renewable energy coupled desalination, the public acceptance of nuclear desalination is likely to be not as high. Though the socio-economic benefits will not be emphasized to the extent of nuclear desalination, renewables have a very positive image in the public and decision makers do have the tendency to conform to public expectations. Therefore, a nuclear desalination plant would require:

- Need for energy and water, aiming to solve the shortage,

- Proper information campaign is needed prior to such a project,

- An open public debate ensuring the sustainability of the nuclear desalination project, if decided upon.

5. CHALLENGES TO NUCLEAR DESALINATION

Nuclear desalination faces several major challenges especially in the case of introducing the first nuclear unit in a country, i.e. the high capital investment needed upfront, risks associated with nuclear power operation, i.e. accidents, proliferation and radioactive waste, and last not least the significant effort needed to install and maintain an adequate nuclear infrastructure. Establishing a pool of human resources that are capable of dealing with the mentioned specific issues is also among the preconditions that need to be met for nuclear power/desalination.

All of these challenges have to be taken into consideration when nuclear desalination is assessed for suitability in addressing water and energy shortages, comparing it to the available alternatives.

5.1. ISSUES AND PRECONDITIONS RELATED TO NUCLEAR POWER

As nuclear power has large upfront costs, one of the issues of nuclear desalination is the financial capability of the investor. The high investment costs (see Table 12 for specific investment costs) of nuclear power are primarily caused by the highly sophisticated design of nuclear technology that requires special materials and manufacturing processes of highest quality, and elaborate measures taken in the design to assure safe and reliable performance during operation.

Table 12. OVERNIGHT COSTS[38] OF POWER PLANTS [154]

Type of plant	Nuclear	Coal	Gas	Oil	Hydro	Wind	Solar PV
Specific costs (US$/kW(e))	1074 to 2614	719 to 2347	424 to 1262	2520	1541 to 6985	976 to 2622	3363 to 10164

Additionally, the typical large size of a nuclear power plant with around 1000 MW(e) (or more) and the relatively long duration of the construction (up to 6 years) resulting in high capital cost (interest) increases the necessary total investment. To enable the financing of such high investment special financial instruments are to be used. Nevertheless, as mentioned before (see Table 10), the production costs of electricity using nuclear power are still competitive due to the relatively low fuel costs.

Another main challenge is public perception of risks associated with nuclear power, first of all the possibility of a severe accident causing extreme damage to the public and environment. The two major accidents that happened in the 1970s and 1980s in nuclear power plants in the USA (with no impact on the environment) and former Soviet Union (with a major impact on people and environment) respectively, had major consequences on nuclear power development. Yet, the lessons learned form these accidents have led to retrofitting of operating nuclear units and improved new designs thereby excluding the possibility of reoccurrence of such accidents.

Another risk frequently discussed in public is the possibility of nuclear proliferation, i.e. the misuse of a peaceful application of nuclear energy for development of nuclear weapons. However, based on the international treaty of Non Proliferation (NPT) the international regime of safeguards in the responsibility of the IAEA has been successfully preventing non proliferation worldwide (in its Member States).

It is common understanding in regard to the risk of a terrorist attack on nuclear power plants that they are the least suited targets of terrorist attacks due to their extremely high security measures in comparison to other sensitive facilities. The concrete dome of a nuclear power plant, designed to prevent an accident spill over to the environment, is also capable to withstand a plane crash.

---

[38] Overnight cost is the amount that would be paid out if all capital expenses occurred simultaneously. It includes no interest charges.

The treatment of radioactive waste including spent fuel is a specific issue of nuclear power, also perceived as a high risk in public discussions. Some of the nuclear waste produced needs planning and execution of long term measures to solve this issue, e.g. the installation of a final depository of spent fuel and other nuclear waste containing long lived radioactive fission products and transuranics.[39] Low and medium level radioactive waste has to be taken care of usually in the country of origin, but for spent fuel and high level waste international solutions seem to become reality in a not to distant future. The Appendix briefly discusses in more detail the management of nuclear waste.

It is a well known fact that the scientific definition of risk, expressed by frequency of an incident multiplied by its consequences, and the common perception of risk by people is very different [155]. Technically speaking, nuclear power is one of the safest industries and has for instance a much better record than fossil power regarding impact on human health. This is the result of intensive measures in design and operation of a nuclear power plant assuring the safe operation during the lifetime of the plant. However, still in many countries the public perceives nuclear power to be associated with a high risk. Perception of any kind of risk by the public is influenced by several factors such as level of knowledge of risk, possibility to control risk, amount of benefit received and level of willingness in taking the risk: the lower the value of those factors the higher the level of perceived risk. This leads to necessary actions to achieve and maintain public acceptance (of any technology): provision of relevant, sufficient, and understandable information to society and opportunity for public participation in decision making.

Finally a major challenge, especially for introducing nuclear power into a country, is the corresponding infrastructure needed to guarantee an effective, safe and secure operation of a nuclear unit. The infrastructure to be established and maintained consists primarily of an adequate legal framework and competent institutions with corresponding human resources. Primarily, detailed and comprehensive planning is needed to establish an adequate nuclear infrastructure, and appropriate institutions to maintain it.

In order to introduce a nuclear power plant into a country, especially the first one, a wide range of infrastructure issues need to be addressed. Figure 30 illustrates a systematic approach how to establish an adequate infrastructure for nuclear power. According to [156] the installation of a first nuclear power plant should be performed in three steps, called milestone 1 to 3: The first milestone is reached when the country is ready to make a knowledgeable commitment to a nuclear power program, the second when it is ready to invite bids for the first NPP and the third one when it is ready to commission and operate the first NPP.

The main issues are the establishment of an adequate legal and institutional infrastructure in regard to safety and liability, non-proliferation and security, identification of suitable financing, clarification of technical issues such as compatibility of the nuclear power plant with the national grid, and assurance of needed human resources.

[39] Transuranics are chemical elements with higher number of protons and electrons produced by neutron capture in the nuclear fuel (uranium) during operation of the nuclear power plant. Examples are neptunium, curium, and americium.

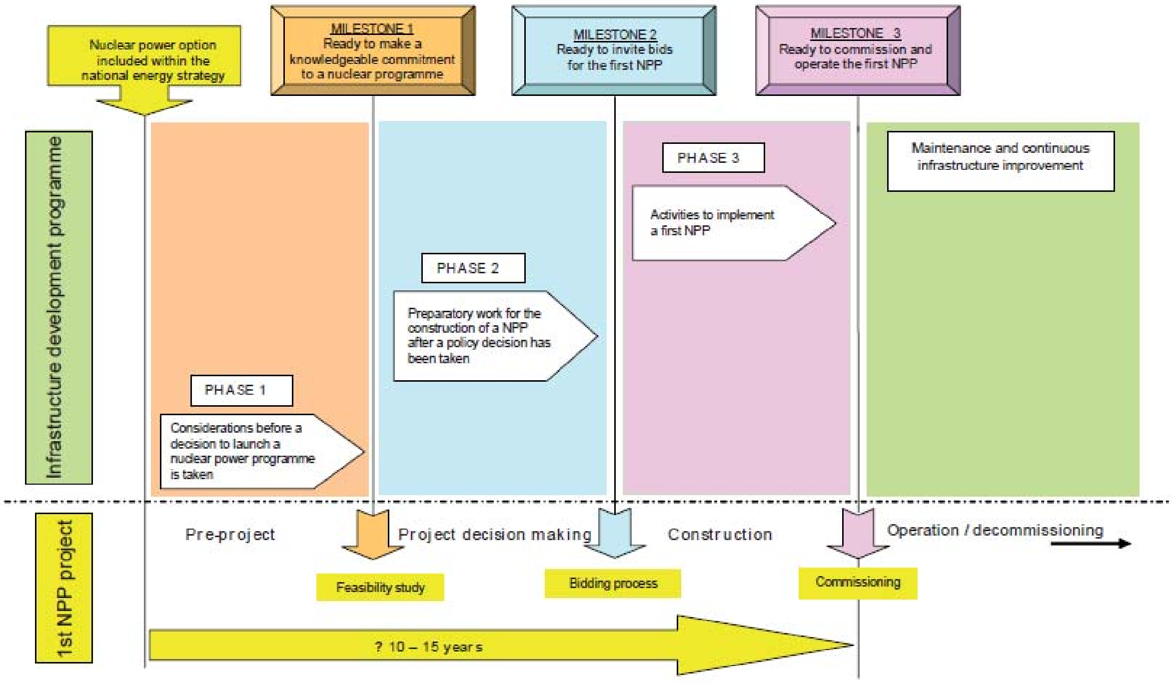

Figure 30. Milestones for establishment of national nuclear infrastructure [156].

5.2. ADDRESSING THE CHALLENGE

Nuclear power faces several challenges as discussed above, but all of them can be mitigated by appropriate technical or institutional measures. One of the biggest issues however, is the public perception of risks associated with nuclear power. As suggested, establishing public acceptance right from the beginning of a nuclear project requires that the public to be informed and involved accordingly. The financing of a nuclear project needs special financial instruments. Last not least the construction and safe operation of a nuclear power plant needs a special infrastructure to be maintained during the life time of the plant and for nuclear waste long term measures have to be taken.

Nuclear power has accumulated an impressive base of experience with more than 10,000 reactor years of operation. It can therefore certainly be called a mature technology. Due to economy of scale, currently, the typical size of a commercially available nuclear power plant is in the range of about 1000 to 1600 MW(e). Although from the aspect of costs per product they can be considered very cheap, the upfront costs are a huge impediment for the deployment of nuclear power.

Addressing this very important issue, a large number of smaller nuclear units is under development, though none of them has fully reached the status of a proven design. It is expected that within the next decade also smaller nuclear reactors will become commercially available.

About 60 concepts of small and medium sized reactors (SMR) are under development in 13 IAEA Member States with different levels of maturity of the design. Those concepts are presented in detail in [157, 158].

The following Figure 31 shows an optimistic view of possible dates of deployment of SMR designs [159]. On the left side of Figure 31 designs are presented with conventional on-site refueling during shut down of the plant, and on the right side designs without on-site refueling schemes i.e. with replacement of complete long-term cores after several years of operation without refueling, thus offering also simplicity of operation.

The brown colored name of designs indicates progress towards advanced design stages, licensing or deployment. However, by mid-2008, from all those concepts shown below, only of the gas cooled pebble bed reactor PBMR in South Africa (his counterpart HTR-PM should start in China in 2009), and the integral non stationary PWR called KLT-40S first prototype is currently under construction.

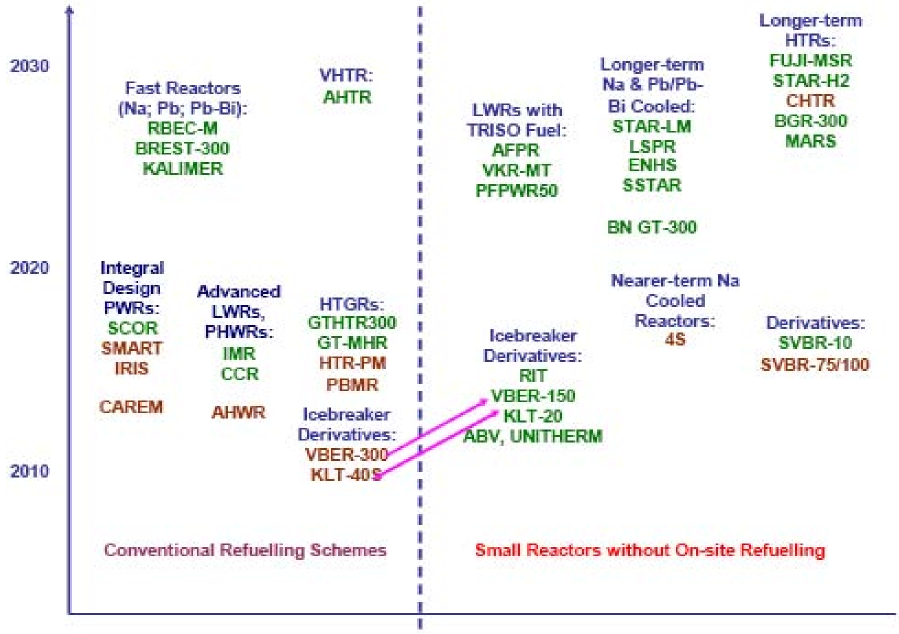

Figure 31. Potential of deployment of small and medium sized reactor concepts [159].

Most of SMR designs presented above are designed for cogeneration, i.e. production of electricity and heat that can be used for non electrical applications such as desalination.

Of course, the development of such reactor types is expected to increase the attractiveness of nuclear desalination to investors due to smaller costs and simpler operation. The easier and inherently safer operation practices are likely to increase public acceptance, providing even higher safety of operation as well as reduced proliferation risks.

Nevertheless, a significant progress in that direction remains to be seen.

6. CONCLUSIONS AND FURTHER RESEARCH

The objectives set for this report were to: (1) review the experiences with the environmental impacts of nuclear desalination so far, (2) identify the possible impacts and mitigation measures on the air, marine, coastal and socio-economic environment, and (3) present some challenges that nuclear desalination faces today.

The main conclusions are:

- Experiences show that sufficient knowledge is gathered for the specific operation and maintenance practices in nuclear desalination. Radiation safety of the desalinated water, just as the environment, is guaranteed by these practices. Other safety aspects of a nuclear desalination plant are resolved to a satisfactorily high level.

- Adverse environmental impacts on marine habitats are not prevented or enhanced with nuclear desalination. Just as with other co-located plants, the use of direct intakes will likely cause entrainment and impingement, and even at a higher rate than other co-located plants. On the other hand, brine discharge in the sea may harm the marine ecosystems if not diluted with the coolant discharge from the power plant. The mitigation solutions for these issues are site specific and basically the same as with any other co-located or stand-alone desalination plant.

- Coastal[40] environmental impacts of nuclear desalination, when leveled with the minimal average capacity of 1 GW for a nuclear power plant, are smaller than for other co-located plants, regardless of the energy source.

- Compared with desalination coupled with other thermal power plants, nuclear desalination is able to mitigate the adverse environmental impacts on the atmosphere to a large extent. If properly done, in this respect it might even be cleaner than renewable energy driven desalination. This is by far, the greatest advantage nuclear desalination can offer.

- The socio-economic impacts of nuclear desalination, compared with other co-located plants, have the potential to be enhanced when a new plant is deployed. This is mainly due to the economic competitiveness of its products: water and electricity. Whether these impacts will be beneficial or adverse, will depend on how is the desalinated water and generated electricity used. If a desalination facility is added to an existing plant, the socio-economic impacts can be reviewed in the same manner as for a stand-alone desalination plant.

- The limited data on the specific topic indicates that the public support of nuclear desalination will be positive. Whether the support given by the public for nuclear power is high or low, public acceptance of nuclear desalination is expected to be always higher than that level. On the other hand, it will likely contribute to an increase in public acceptance of nuclear power.

- Challenges for nuclear desalination generally involve infrastructure, human resources, financial capital and public acceptance. Development of smaller and simpler reactor designs may overcome these challenges in a positive way, allowing for broader application of nuclear desalination.

As mentioned earlier, this report is a preliminary overview of environmental impacts originating from nuclear desalination plants. Therefore, all the topics covered leave open possibilities for more detailed research which can further assure decision makers, experts and members of the public that nuclear desalination can be applied with environmentally and socio-economically beneficial results. As most urgent ones though, the issues influencing public acceptance should be addressed first. These include public health issues as well as environmental impacts and therefore the subsequent research should be focused on:

[40] Referring to land use, noise and construction.

- Identifying environmental indicators and developing models for their application, in order to provide a more detailed perspective on nuclear desalination’s environmental impacts. The models should preferably assess the competitiveness of the alternative desalination solutions as well.

- Detailed assessment on tritium migration and technologies for its limitation, with overview of applicable experiences, which should identify consequences on public health and ability to conform to the most stringent health regulations.

- Feasibility of various nuclear desalination plant layouts which influence the marine impacts and their attributed environmental impacts.

- Whole effluent toxicity research, which would assert no adverse cumulative impacts originating from the brine and radioactive release.

Appendix I

METHODOLOGY FOR ASSESSMENT OF ENVIRONMENTAL IMPACTS ON MARINE HABITATS

I-1. METHODOLOGY FOR ASSESSING ENTRAINMENT AND IMPINGEMENT

As previously noted, the following methodologies can provide estimates on the entrainment and impingement impacts, but do not represent the meaning of those impacts on the whole ecosystem or the species' population. They are however capable of providing a general idea of the possible environmental impacts.

I-1.1. Methodology for evaluating entrainment impacts

The potential adverse impacts require initial assessment in order to be able to mitigate them in time. Any such assessment of the intake system impact should involve several consecutive steps.

Since not all the species can be monitored for entrainment, the first and practical step would be determining target species (ones that are expected to suffer most from entrainment). Endangered and threatened species must be on that list. The selected target species will influence the sampling frequencies and equipment.

The second step would be performing preliminary sampling in the estimated area of impact which will help determine the most appropriate sample volume of seawater. Ocean and tidal currents should be used to determine the appropriate sampling areas for estimating daily entrainment mortality.

Subsequently, at least one year of baseline studies should be performed for the assumed source water area and the involved habitats, as indicated by several authors, in order to include all the variations in species' spawning and migrating habits as well as hydrological and meteorological conditions [55, 160].

Following the baseline study of the area, the results can be used for assessing the impacts of the seawater intake systems with several methodologies. These are simple as an idea, yet they can be complex to perform [55]. One of the most used and recommended ones is the empirical transport model (ETM). Both, the California Energy Commission and the California Coastal Commission, have required the ETM approach in recent studies [160]. The model estimates the number of organisms entrained and compares it to the source population i.e. number of organisms at risk of entrainment. The ratio of these two numbers represents the proportion of organisms expected to be lost due to entrainment or simply - proportional mortality (Pm).

Another factor required for this modeling approach is the estimated time during which larvae are subjected to entrainment. It can be obtained either by calculating the average age of the entrained organisms or, the more strict method, by taking into consideration the maximum age of entrained organisms. This is important because the age of the entrained larvae combined with the sea currents velocity and direction is used to determine the source area (or distance) that holds risk of entrainment for the marine organisms. This area, multiplied by the average density of organisms in the seawater, will represent the source population at risk in the assessment study. The two calculation methods differ in the following presumptions:

- the mean ETM calculation considers the risk of entrainment lower for older larvae as their size and swimming ability increase.

- the maximum ETM calculation takes into account the area from which, not the average, but the actual larvae came from.

The age of the larvae can be estimated based on their length variations and the reported growth rate for the species [55, 160, 161]. Finally, in order to take the so far neglected effects of water motion on larvae entrainment, an upgrade model of the ETM was being developed for the California Energy Commission, due in fall 2008 [162].

Habitat production foregone (HPF) is a further indicator of the entrainment impact can be obtained by multiplying the source area at risk and the mortality proportion due to entrainment (Pm). HPF represents habitat that needs to be added to the endangered one in order to neutralize the impact to the population entrained. Several species' HPFs can be combined in one average HPF. [55] This method is used as most appropriate when restoration measures have to be implemented [160].

Entrainment losses can be also estimated using fecundity hindcast (FH) and adult equivalent loss (AEL) which are demographic approaches, converting larvae loss into adult loss. For each species that is being assessed with these models, information about the maturation and mature age, survival rates per age groups, fecundity etc. is needed. Estimating losses of adult organisms can also be done by AEL and FH aligning at fishery age [163]. The variations from the calculations' results can be either calculated or a standard 30% coefficient of variation can be used to estimate the sample variance. [161]

For further information on the methodology and guidelines for assessing the impacts of entrainment, refer to California Energy Commission's report: "Assessing power plant cooling water intake system entrainment impacts" [160].

I-1.2. Methodology for evaluating impingement effects

Impingement calculating models have not been found in the literature. However, intake velocity has been identified by the US EPA as a key factor affecting the impingement of marine organisms and this is confirmed by other studies, that found a correlation between intake volume and impingement rates [31, 36, 164, 165]. Pisces Conservation Ltd. derived a simple function describing the impingement rate by collecting full seasonal impingement data from 28 US power plants withdrawing estuarine or seawater:

$$I = 0.1704 \times V^{1.5943}$$

$$V = V_1 / 0.0283$$

I represents the number of fish impinged, V_1 is the volume extracted in [m^3/s].

Impingement rate formula was also derived by Henderson [165] from the impingement records of 18 coastal power plants in North East Atlantic:

$$I = 9 \times 10^{-7} G^{3.055}$$

$$G = G_1 / 0.00378$$

Where G_1 is the water extracting rate in [m^3/s].

To support assessing impingement impacts, setting up a pilot plant can be of great significance. A small scale intake can verify the entrainment estimates and indicate the full scale facility's effect on impingement for different target species, as well as their mortality rate due to impingement. This is usually done by backwashing the screens into a confined area where the mortality of the marine organisms for the first 24 or 48 hours can be observed and used when assessing the impingement losses.

I-2. METHODOLOGY FOR ASSESSING DISCHARGE IMPACTS

When sea discharge is considered for brine disposal, the environmental impacts may be predicted, and consequently optimized, using mathematical models for predicting the behavior of the discharge plume. In fact, one of the requirements in licensing processes is environmental impact modeling [23]. Since the mixing efficiency depends not only on the brine properties, various models take other important parameters into consideration as well. These site specific parameters are: fresh surface water inflows, water depth, ambient density with seasonal variations, wind and density driven currents, tidal regime, diameter and depth of the outfall, effluent velocity and volumes [23, 25]. All modeling techniques will therefore require detailed study of the proposed site for discharging at least one year in advance, while the data gathered could be later used as baseline for the follow up and monitoring activities.

IAEA Safety Guide No. NS-G-3.2 [70] describes three basic groups of models for radionuclide dispersing and they can be applied for the discharges of the co-located plants or even for the desalination discharge alone, though only after being verified for the particular case. Two of these are commonly used in site evaluation for a nuclear power plant:

1. Box type models treat the entire body of water, or sections thereof, as composed of homogenous compartments. In this type of model, average concentrations are computed for each compartment and transfer constants are set up to relate the variables for one compartment to those in adjacent compartments. Most models dealing with the interactions between radionuclides and sediment are of this type.

2. Calculational models solve the basic equitations describing radionuclide transport with major simplifications made for the geometry of the water body and the dispersion coefficients. These models are the ones most frequently used in surface hydrological analysis.

In addition, Monte Carlo methods are allowed to model water body geometry and to simulate particles.

Some of the computer models that are available for assessing impacts of various designs of desalination outfalls are CORMIX and visual plumes, based on the Gaussian Dispersion techniques. The CORMIX series developed for the US EPA comprises of CORMIX1 for single port outfalls, CORMIX2 for multi-port diffusers, CORMIX3 for surface level discharges, and D-CORMIX for negatively buoyant (desalination) discharges. Visual Plumes is a plume software package for simulating jets and plumes, and for assisting in the preparation of mixing zone analyses and other water quality applications developed for the US EPA. For more sophisticated plume analysis, various computational fluid dynamics software packages are available [37].

It is also very important to assess the impact of toxicity of the whole effluent (desalination discharge combined with other effluents) on the marine organisms that inhabit the discharge site. This should be performed through laboratory tests after the modeling calculations indicate composition and behavior of the discharge, and for various conditions regarding duration of toxicity peaks, temperature, oxygen solubility, light penetration, current speed etc. All of the model results, regardless of the chosen approach, should be compared with the field and laboratory data so that the estimates from the calculations could be verified.

Appendix II

ALTERNATIVE COOLING OPTIONS FOR NUCLEAR POWER PLANTS

The environmental impact on marine organisms of a power plant co-located to a desalination plant depends strongly on the cooling system used by the power plant. Therefore, firstly, the cooling system of a power plant is being shortly discussed. In general there are three different types of cooling modes possible: once through cooling, wet cooling tower and air cooled condenser. Also combinations of the latter two systems – air cooling and wet cooling tower – are installed. The following Figures 32 to 34 show a sketch of these cooling modes.

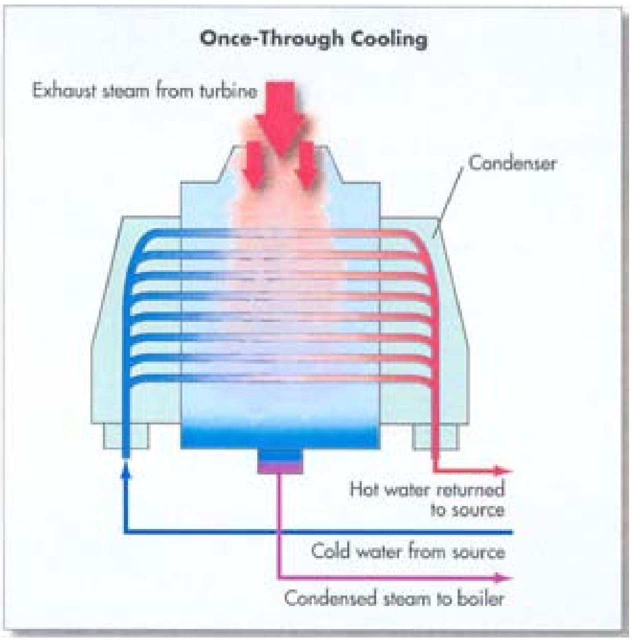

Figure 32. Principle of a once through cooling system [166].

Figure 32 above shows the principle of a once through cooling system. In this system cooling water taken from an external source – a river or the sea – condenses the exhaust steam from the turbine in the condenser tubes and then returns the cooling water to the original source about 15 degrees C warmer. A 1000 MW(e) power plant needs about 3 millions m^3 of cooling water (heated 15 C) per day to remove its waste heat, which is about an order of magnitude more than a large desalination plant (several 100 000 m^3 per day feed water). This system is the cheapest of all cooling systems and most widely used.

Figure 33 shows the principle of a wet cooling tower system. The hot water from the plant's condenser is pumped to the top of a cooling tower and rains downward (in small droplets) through fill material being cooled and partly evaporated by ambient air blown upwards by a fan or natural convection. A portion of the water has to be discharged as blow down to limit the concentration of solids (salts) and prevent the formation of mineral deposits that could interfere with the heat transfer in the condenser. Addition of makeup water is necessary to replace water lost by evaporation in the cooling tower and by blow down. The amount of makeup water in a wet cooling tower system is about an order of magnitude smaller compared to the cooling water in a once through cooling system.

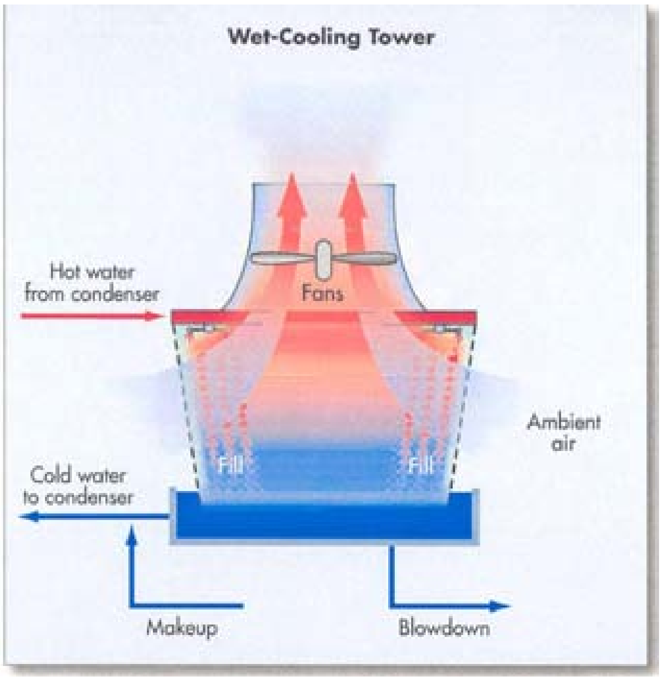

Figure 33. Principle of a wet cooling tower system [166].

Figure 34 shows the principle of a dry cooling system (air cooled condenser). The turbine exhaust steam is fed into the large ducts at the top of the air cooled condenser. As the steam passes down through the condenser's finned tubes it is cooled and condensed by ambient air blown through upwards the structure by fans working similar like an automobile radiator. Typically the capital cost of dry cooling systems is about 3 to four times higher than wet cooling tower systems, and dry systems can also cause a penalty of the plant's annual efficiency of about 2%.

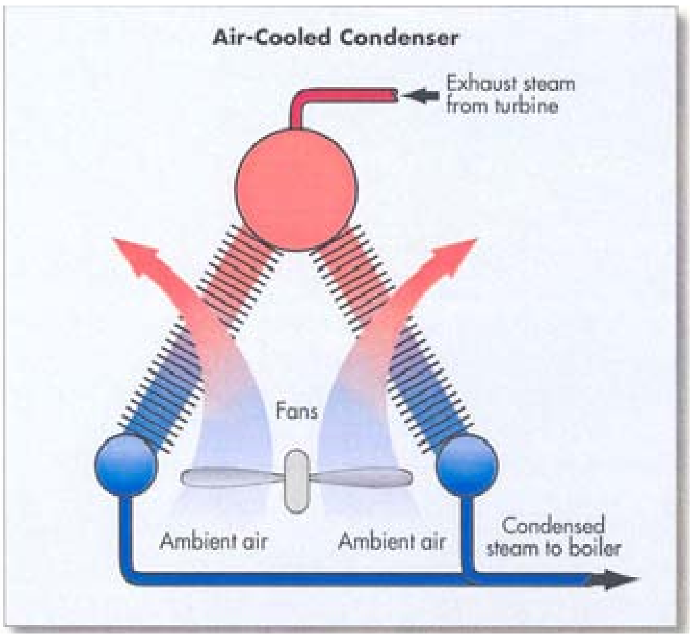

Figure 34. Principle of a dry cooling system [166].

Wet and dry cooling systems can be combined into hybrid systems as shown in Figure 35. These hybrid systems gain the advantages of both systems and offset the disadvantages of each. Typically, to minimize the use of cooling water a power plant with a hybrid system runs primarily with the dry cooling system and only on very hot days would turn on the wet cooling tower in addition to avoid loss of efficiency.

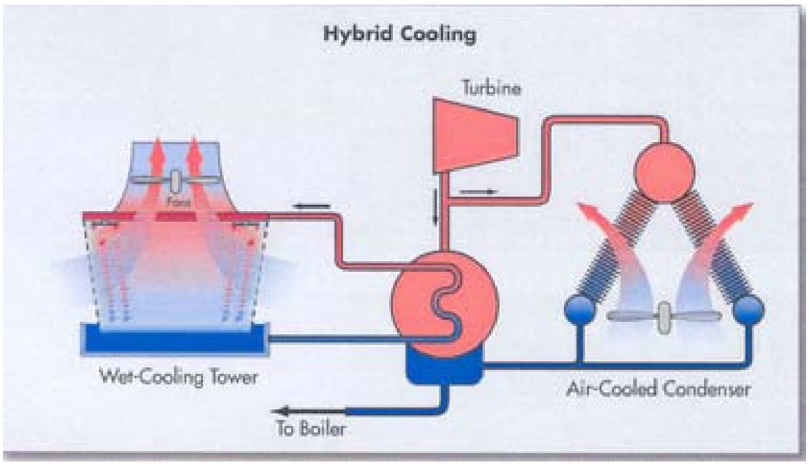

Figure 35. Principle of a hybrid cooling system [166].

Regarding the environmental impact of a co-located power plant on the marine organisms it is clear that similar to a desalination plant it will be the intake and outtake structures that are responsible for damage to the marine environment.

The environmentally worst cooling mode of a power plant is of course the once through cooling system. The cooling flow in its intake system – generally only direct intakes are feasible due to the large amount of cooling water needed – of a power plant with about 1000 MW(e) output is about an order of magnitude bigger than the feed water flow of a large desalination plant causing corresponding much higher suction forces and flow velocities. If not properly designed, impingement and entrainment in such an intake system can cause severe damage to marine organisms. The outtake system of a once through cooling system with surface or submerged discharge can lead to environmental impact due to the elevated water temperature and chemicals added to the cooling water to protect components of the cooling system. Mitigation measures for the intake and outtake system of such a power plant are the same as discussed above for desalination plants with direct intake systems and surface or submerged discharge systems.

For a power plant with wet tower cooling the environmental impact is already significantly reduced in comparison to a once through cooled plant, and a dry cooling system obviously avoids completely any impact on marine organisms.

Both the once through cooling and the wet tower cooling system can provide some relief of the environmental impact of a co-located desalination plant by enabling dilution of the brine by mixing it with discharged cooling water.

Appendix III

QUALITY ISSUES OF NUCLEAR DESALINATED WATER

The objective of this Appendix is to shed more light on tritium, its properties and meaning for nuclear desalinated water. It has been added due to the great deal of concern with the public about possible radioactivity contamination of the product water, while only a few detailed sources provide comprehensive information on the issue.

Desalinated water must comply with the quality standards for drinking water. However, seawater and potable water differ not just in their solids' content, but also the composition of it, thereby complicating the desalination processes. For instance, a great concern in reverse osmosis desalination is higher concentration of boron in seawater which is transferred to the product water due to the low rejection level of the RO membranes. On the other hand, if intended for human consumption, distillation also holds a hindrance in providing water with very low mineral content. Desalination therefore, has to incorporate additional steps such as second membrane pass or minerals adding in order to insure safe public use of desalinated water. These concerns are based on the properties of seawater, not on the energy source, and are common for every desalination plant.

As mentioned, nuclear desalination also involves the issue of product water radiation safety. Radionuclide contamination of the desalination loop must be prevented in all circumstances and operating regimes. In that context, the high permeability of tritium, combined with the difficult removal from gases, liquids and solids [15], is the principal concern in nuclear desalination.

III-1. TRITIUM AND ITS PROPERTIES

Tritium (^3H or T, 1p+2n) and deuterium (^2H or D, 1p+1n) are isotopes of hydrogen (^1H or protium, 1p). Unlike the stable deuterium, tritium is a radioactive isotope. Naturally, it is a reaction product of nitrogen (^{14}N) or oxygen (^{16}O) with cosmic rays in the upper layers of the atmosphere [167]. Since precipitation removes some of the tritium from the atmosphere, accumulating it in surface waters, it can be found in water as well as air.

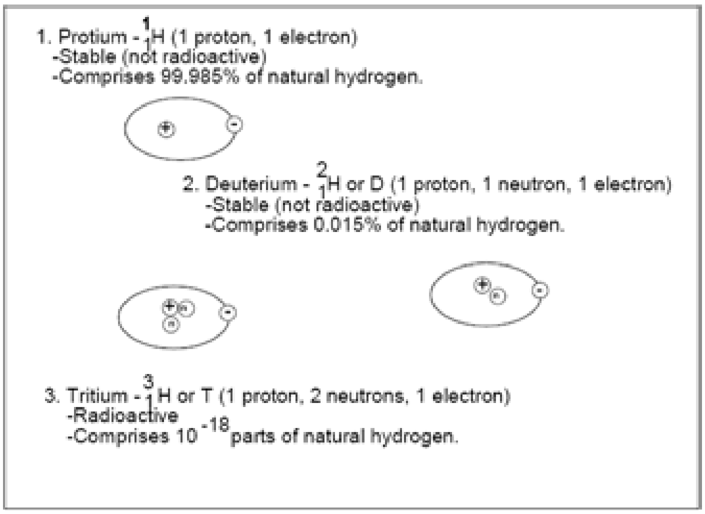

Figure 36. Hydrogen isotopes.

As an instable isotope, with a half-life of approximately 12.3 years and a decay constant of 0.056 a^{-1} [168], tritium undergoes a radioactive decay emitting a beta particle to form the more stable ^{3}He isotope:

$$^{3}H \rightarrow {}^{3}He + e^{-}$$

The tritium beta particle's track length is very short, about 6 µm, but the size of the tritium atom allows it to be close to chemical bonds. Similarly, the energy of the beta particle varies between 0 and 18.6 keV with an average of 5.7 keV [16]. Although its energy is small, it is more than one thousand times the energy required to break chemical bonds. Therefore many chemical reactions that would not occur with deuterium or hydrogen are radiolytically catalyzed in the presence of tritium [15, 16].

Other physical and chemical properties of tritium are similar as hydrogen. For instance, it can replace hydrogen in organic compounds and it forms tritiated water with oxygen: either HTO or T_2O. Tritiated water pathways through the environment are essentially the same as natural water, and accordingly it can be considered as very mobile. However, tritiated water has a higher mass compared with natural water (20 or 22 vs 18 atomic mass units), so consequently its boiling point is higher and vapour pressure is lower. This allows for slightly higher surface evaporation rate of natural water [168]. Furthermore, although chemical reaction rates and diffusion rates of tritium compounds are often slower than those of hydrogen compounds, tritium gas is difficult to contain, diffusing through container walls, especially plastic walls [167].

Just as hydrogen, tritium dissolved in metallic materials, can cause embritllement which is accentuated by the resulting ^{3}He from tritium decay. Yet, at low temperatures and pressures, penetration of tritium in barrier walls as well as material embritllement is not a significant issue [16].

Table 13. OTHER CHARACTERISTICS OF TRITIUM

Specific activity		3.59×10^{14} Bq/g
Diameter of atom		~ 1.1 angstroms
Beta particle	maximum energy	18.6 keV
	maximum track length in water	6.0 µm
	maximum track length in air	5 mm

III-2. TRITIUM IN NATURE

Tritium is very rare, with a trace-level concentration of 1×10^{-18}%. The steady-state global inventory is estimated to be approximately 2.6×10^{18} Bq and a global production of 0.15×10^{18} Bq/a [169]. It is distributed in various quantities in air, water and soil. Its environmental, or background, levels also vary according to the location. Most of it though, 99%, is found in the hydrosphere as HTO, with the remaining 1% is distributed in the atmosphere as HTO vapour or HT gas [170]. The tritium quantities produced in the Earth's crust from neutron activation of ^{6}Li in rocks is considered negligible [171]. Of course prior to its ending, the '60s and '70s nuclear testing has increased tritium background levels, but they have been steadily declining since [168].

The atmosphere usually has very low tritium concentrations. For instance, it has been found that in Fukuoka, Japan the tritium in the atmospheric components is at the following concentration levels [172]:

Methane	13-15 mBq/m^3
Water vapour	19-23 mBq/m^3
Hydrogen gas	33-47 mBq/m^3

The Swiss Division of Radiation Protection states 1.4 Bq/m^3 as the normal background tritium level [173]. Mean values of 80±24 mBq/m^3were found in air humidity in Romania prior to the construction of the Cernavoda NPP [174].

Similarly low levels may be found in precipitation. The natural occurring tritium contributes a few tenths of a Bq/L [173]. However, US EPA records [175] presenting tritium levels in precipitation for various cities show higher values. As an example, Seattle and Pittsburgh have a maximum value of 11.1 and 18.5 Bq/L respectively. Average tritium activity values in the precipitation for Japan are lower and amount to 0.5 to 1.7 Bq/L [167].

Background tritium activity in river water is reported to be only a few Bq/L with slightly higher values for ground water [167, 173]. Environmental levels of tritium activity in seawater and rivers are estimated by the US DoE to be between 0.037 and 3.7 Bq/L [16], which is in line with the pre-1952 values provided by Weaver et al., ranging from 0.6 to 1.3 Bq/L [176], as well as EPA’s reported values for surface- and groundwater samples average in the USA of 0.1 Bq/L [177]. Many of the measurements in UK for tritium concentrations in foodstuffs have shown levels at 5 Bq/kg or less [178].

In conclusion, regardless of the specific value, average background tritium concentrations are often higher compared to levels prior to the atomic age. Yet, it is important to note that even these levels are insignificant from the aspect of health hazard.

III-3. RELEVANT REGULATIONS ON TRITIUM

As a potential hazard to public health, tritium is regulated by various national and international standards, while also addressed in a number of non-mandatory guidelines. Drinking water is especially in their focus due to the nature of beta activity. However, most of the regulatory limits set for tritium activity in drinking water differ among them. This section will give an overview as well as an explanation for some of the most stringent and most relevant guidelines and standards currently applied.

III-3.1. Guidelines on tritium in drinking water

First of all, it has to be noted that the international guidelines, such as the ones from ICRP and WHO, do not specifically address tritium but rather ionizing radiation. Second, the international guidelines in principle refer to human-made radiation exposures in excess to natural radiation sources. This of course includes beta emitters such as tritium and is applicable in nuclear desalination water quality assessment.

Based on the evidence gathered so far, for protection of the members of the public the ICRP recommendation is an effective dose limit of 1 mSv per year for any combination of internal and external radiation doses [179]. In the publication on prolonged exposure, ICRP deems prudent to constraint the dose to less than this value, for example to no more than 0.3 mSv per year or even 0.1 mSv in any given year of the exposure [180]. Nonetheless, the 1 mSv value is the basis for many national and international regulations. On the other hand, in the USA the legally enforceable dose limit is set by the EPA at 0.04 mSv per year [181].

Another figure that requires attention is the dose conversion coefficient for tritium. This coefficient relates the activity concentration (in Bq/L) with an effective dose per year (in mSv/a). Its value depends on the age and sex of the population. Usually though, the calculations are based on the value for an adult male, because the higher coefficients for infants are related with much lower water intakes [182]. Despite being argued [183], the dose coefficient for ingestion of tritium by an adult member of the public is widely accepted to be ICRP's 1.8×10^{-11} Sv/Bq. The US NRC uses the more stringent 2.8×10^{-11} Sv/Bq value [184] for the effective dose calculations in the USA.

The WHO regulatory recommendation logic is based on the ICRP figures and starts with a 10% of the ICRP's effective dose limit of 1 mSv. Given the fact that other radiation sources will contribute to the committed effective dose[41], 0.1 mSv per year through drinking water is a reasonable value. The guideline level GL of tritium activity concentration is calculated as:

$$GL = \frac{RDL}{DCF \times q}$$

Where:

RDL is the reference dose level (= 0.1 mSv)

DCF is the dose conversion factor for ingestion by adults (= 1.8×10^{-11} Sv/Bq)

q is the annual ingested volume of drinking-water (= 730 L/a).

The consequent guideline level of 7610 Bq/L is rounded up to 10 000 Bq/L, referring to the total activity in a water sample and not just tritium. It is used by many of the WHO member states as a basis for regulation as well as other UN agencies [182]. The limit though, does not exclude the ALARA principle in efforts to further reduce the level of radionuclides in drinking water [18].

III-3.2. Regulation specifics on tritium in drinking water

As mentioned, most of the WHO member countries have accepted the WHO guidance reference level of 10 000 Bq/L for drinking water as an upper regulatory limit. Switzerland also accepts this limit to define water that is unfit for human consumption but with a 1000 Bq/L radiation limit which defines water of lesser quality. Similarly, Russia and Kazakhstan (7700 Bq/L) as well as Canada (7000 Bq/L) set their regulatory limits at a level much closer or slightly below the calculated value of 7610 Bq/L [18].

On the other hand, Australia and Finland follow the same approach used by WHO but with different reference dose levels (instead of 0.1 mSv - 1mSv in Australia and 0.5 mSv in Finland) and changed water intake volumes (2.2 litres in Finland). Thus, the regulatory limits in those countries are set at 76 103 Bq/L and 30 000 Bq/L respectively [18].

---

[41] As an example, 200 hours per year of flights at altitudes of 12 km is approximately equivalent to a dose of 1 mSv [164].

The EU and most of its members have chosen the value of 100 Bq/L as an indicative value for the presence of other much more dangerous radionuclides. The EU Council Directive 98/83/EC is a typically a guideline which was transposed into EU members' national legislatives. As an example, the drinking water regulation in Northern Ireland includes tritium in the indicator parameters and not in the prescribed concentrations and values [185]. Curiously, Japan and R. of Korea have no specific limits for tritium in drinking water [18].

The US maximum contaminant level (MCL) for tritium is set at 740 Bq/L. Not accepting the ICRP's concept of effective dose equivalent, the EPA has calculated the maximal permissible dose of tritium in water based on the "total body or organ dose equivalent". Furthermore, the dose would not be higher than 0.04 mSv on a total body basis instead of the ICRP's 0.1 mSv. Although the EPA calculation includes ingestion of 2 litres of water, it also assumes that an extra dose resulting from organically bound tritium (equal to 20% increase of the worker exposure dose in Handbook 69) should be included. This EPA methodology was to be updated in 1997, using the "effective dose equivalent" concept, which would have increased the permissible tritium dose level at 3200 Bq/L. However, according to the 1996 Amendments of the Safe Drinking Water Act, the revision of standards resulting in increased health risk is precluded and subsequently, the older, more stringent federal standard of 740 Bq/L was kept [16]. Yet, in addition to this dose, the public health goal in California is established at 15 Bq/L [168].

These are the most relevant and stringent regulations against which nuclear desalination will be scrutinized. The risk estimates derived from these tritium activity concentrations will be presented in more detail further in this document.

III.4. TRITIUM SOURCES

In nuclear desalination the main source of tritium is the facility's nuclear reactor. Depending on the type of the reactor, during its operation the tritium production occurs, at different rates, due to ternary fission as well as with neutron activation of isotopes such as ^{2}H, ^{3}He, ^{6}Li and ^{10}B [170, 186, 187]. The table below presents the nuclear reactions that result in tritium formation in light water reactors, but in different proportions they occur in heavy water reactors as well.

Nuclear reactions resulting in tritium formation in reactors would also include the neutron activation of the ^{3}He isotope present in the helium coolant [22].

The most important factors in tritium production would be fuel integrity, boron control and lithium purity. Other factors such as: type of reactor, operating power, fuel cladding, burnable poison assemblies, primary chemistry controls and operating strategies, also influence the specific tritium production rate [187]. The following sections will therefore give a general overview of tritium sources and rates for various reactor types.

III-4.1. Light water reactors

Currently, most of the nuclear power reactors in the world are the light water type reactors [188], divided into boiling water (BWRs) and pressurized water reactor (PWRs). The primary tritium production mechanism in LWRs is the ternary fission (Table 14, reaction 10), estimated to be between 5.55×10^{8} to 9×10^{8} MBq/(GW(e) a) [17, 189, 190]. However, the tritium release to reactor coolant is minimized at approximately 0.1-1%, while the rest of it remains in the fuel elements and the zircaloy fuel cladding [187, 189, 191].

Table 14. SIGNIFICANT NUCLEAR REACTIONS IN LWRs

Nuclear Reaction		Target Isotopic Abundance (%)	Neutron Reaction	Cross-Section (barns)
^{1}H (n, γ) ^{2}H	(1)	99.99	Thermal	0.332 b
^{2}H (n, γ) ^{3}H	(2)	0.015	Thermal	0.52
^{10}B (n, α) ^{7}Li	(3)	19.9	Thermal	3840 b
^{10}B (n, ^{3}H) ^{8}Be	(4)	19.9	Fast	42 mb
^{10}B (n, 2α) ^{3}H	(5)	19.9	Fast	45 mb
^{11}B (n, ^{3}H) ^{9}Be	(6)	80.1	Fast	15 mb
^{6}Li (n, α) ^{3}H	(7)	7.6	Thermal	941 b
^{7}Li (n, nα) ^{3}H	(8)	92.4	Fast	330 mb
^{7}Li (n, ^{5}He) ^{3}H	(9)	92.4	Fast	55 mb
^{235}U (n, fission) ^{3}H	(10)	---	Thermal	0.01% of fission rate

Concerning the reactor coolant and moderator as sources of tritium, neutron activation of isotopes is estimated to be less than 37 × 10^{6} MBq/(GW(e) a). Tritium concentration in the coolant and moderator are below 37 MBq/kg [170].

In BWRs the activation of deuterium is a major tritium source, with estimated 37 × 10^{4} MBq/(GW(e) a) [17, 170]. Deuterium can be naturally found in the coolant as it has a 0,015% concentration in natural water or, some of it may be created with neutron activation of hydrogen (Table 14, reaction 1).

On the other hand, tritium production in PWRs is mainly due to activation of boron (reaction 5) and lithium (reactions 3 and 8), which are used in the primary coolant for chemistry and reactivity control, while activation of deuterium contributes less than 5% [17, 187]. Boron is the primary contributor to tritium inventory in PWRs and the reduction of its production rate over a fuel cycle is roughly equal to the percent of boron reduction in the coolant [187].[42] Additionally, the presence of lithium hydroxide, used for pH control in the primary coolant, introduces a source of tritium production via the reaction (7) as well as, to a lesser degree, (8) and (9). Consequently, tritium control is achieved through control of ^{6}Li levels in the lithium hydroxide, which usually consists of 99.96% ^{7}Li and contributes 37 × 10^{4} MBq/(GW(e) a) [192]. For comparison, the use of 98.4% ^{7}Li in lithium hydroxide would result in 16 fold increase in tritium production from this reaction [187].

Presented in Table 15, are the different sources and their contributions to tritium production in LWRs and fast breeder reactors (FBRs) [15].

[42] Reduction of boron would lead to higher burnable poison loading hence higher enrichment requirements for the fuel and therefore result in higher fuel costs [187].

Table 15. RATES OF TRITIUM PRODUCTION [MBq/(MW(t) day)]

Sources of generation	*WWR-440*	*WWR-1000*	*BN-350*	*BN-600*	*BWR*	*PWR*	*LMFBR*
Nuclear fuel	470	480	1040	1065	610	610	1210
Control rods	1.83	–	637	215	67	–	482
Heat carrier	21.5	66.2	3	3	0.13	27.4	5
Construction materials	–	–	15	22.7	–	–	–
Total	493	546	1695	1306	677	637	1692

III-4.2. Heavy water reactors

Heavy water reactors use deuterium as a moderator and as a coolant, for neutron efficiency. Tritium production in HWRs occurs through the same nuclear reactions that result in formation of tritium in LWRs. However, since the deuterium is much more abundant in heavy water reactors, the tritium production with neutron activation of this isotope accounts for a much larger proportion of the tritium formed in such reactors. The quantities of tritium are hundreds times greater than in LWRs, typically around 5.42×10^{10} MBq/(GW(e) a) [168, 190]. Most of this tritium activity originates from the heavy water moderator and to a lesser degree, the heavy water coolant (see Table 16.) This difference in tritium production reflects in a steady rise of tritium concentration in the heavy water inside the moderator. The calculations suggest a value of 3640 GBq/kg after 40 years, while in the coolant heavy water it is only 81 GBq/kg, for the same operation time, based on a capacity factor of 90% [193]. Tritium due to neutron activation of boron and lithium is negligible [170].

III.4.3. Other types of reactors

Tritium production rates in other reactors types, notably gas cooled reactors (GCRs), high temperature reactors (HTRs), fast breeder reactors (FBRs), pebble bed modular reactors (PBMRs) etc., are all in the same range compared with LWRs, and considerably lower than HWRs.

Table 16. TYPICAL TRITIUM PRODUCTION [GBq/(GW(e) a)]

	Fuel	Coolant	Moderator	Total
LWR–PWR	5.18×10^5	3.70×10^4	NA	5.55×10^5
LWR–BWR	5.18×10^5	Low	NA	5.18×10^5
HWR	5.18×10^5	1.85×10^6	5.18×10^7	5.42×10^7
GCR	5.18×10^5	Low	$(0–1.85) \times 10^5$	$(5.18–7.03) \times 10^5$
GCR–HTGR	5.18×10^5	1.85×10^5	$(0.18–7.40) \times 10^4$	$(5.2–5.9) \times 10^5$
FBR	7.40×10^5	7.40×10^4	NA	8.14×10^5

NA: data not available.

The tritium source in FBRs can be identified in the core and the breeder fuel due to lithium and boron impurities [194].

For PBMR of 500 MW(t), tritium sources and formation per type of reaction demonstrated that the ternary fission is the source for 84% of the tritium formed, with isotope neutron activation accounting for the remainder of it [195]. The total production rate for the unit was 8.5×10^5 GBq/(GW(e) a).

On the other hand, in GCR a large contribution of tritium is due to lithium impurities in the graphite moderator and the presence of water vapor in the core [190]. Table 16 illustrates the typical tritium contributions for these types of reactors.

HTRs also include the helium coolant as a source, as well as the lithium impurities in the graphite moderator [194].

III-5. TRITIUM PATHWAYS

Tritium migration from the source to the receptors, which in this case are the users of desalinated water, starts from the fuel. Approximately 10^{13} atoms of tritium are produced each second per megawatt of electrical energy generated or1850 MBq/(MW(e) day) [176]. The cladding material around the fuel has the role of containing fission products, preventing primary coolant contamination.

That said, it has been found that tritium diffuses through stainless steel cladding at a significantly higher rate than through zirconium alloys. Tritium also reacts with the zirconium alloy cladding to form a hydride, lessening the release of tritium to the reactor coolant [190]. Nevertheless, due to various reasons resulting in material structure flaws, unequal corrosion rates or temperature gradients, the zircaloy cladding may develop pinhole failures or defects through which tritium and other fission products may escape into the coolant [176]. For GCRs and HTRs further tritium release into the coolant originates from the graphite moderator due to corrosion [194]. The proportion of HTO to HT in the LWR coolant is expected to be in favour of the tritiated water, with an approximate value of 10 to 1 [17], lowering thus the quantity of tritium which can migrate to the next loop only to potential leaks and gaseous tritium diffusion.

The tritium migration pathways in the Liquid Metal Fast Breeder Reactor (LMFBR) BN-350, which was used for nuclear desalination in Aktau, Kazakhstan, were described by Muralev [15]. The generated tritium from the core diffuses into the primary coolant inside the reactor vessel. According to McKay [194], the tritium quantity diffusing into the primary coolant may be up to a rate of 95%. Muralev reports 99% tritium diffusing into the coolant. Part of it gets into the reactor blanket, while the other part remains in the primary circuit and passes on the secondary cooling circuit through the surface of the intermediate heat-exchanger. From there, again through the surface of the heat-exchanger, diffuses to the water-steam circuit. Diffusing and penetrating through reactor vessel walls, heat-exchanger and stem-generator surfaces, machinery and pipelines, small portion of tritium is transferred into the desalination loop.

Tritium migration in a process heat HTR does not differ greatly from the above described pathways [22].

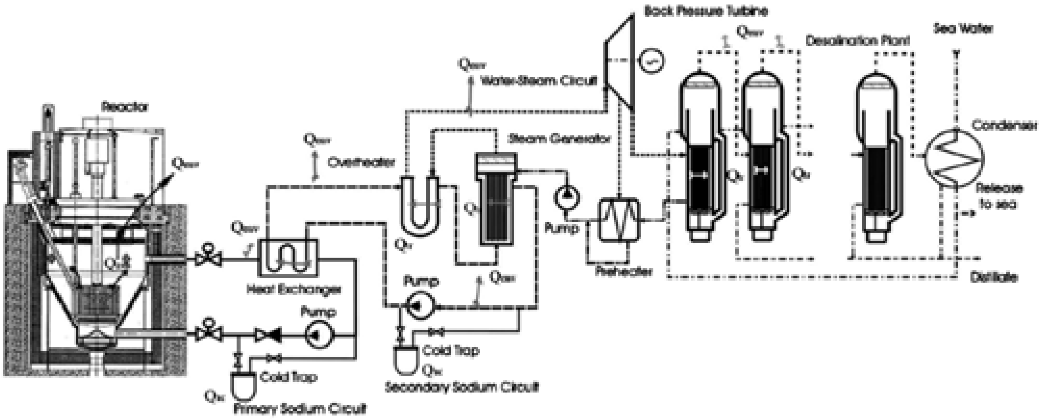

Figure 37. Schematic flow diagram in the nuclear desalination plant with BN-350 reactor.

Indeed, with FBRs the sodium loop is separated from the desalination loop by two heat-exchangers and the steam circuit has a higher pressure than the secondary sodium pressure, while cold traps remove substantial quantities of tritium from the two sodium loops, allowing the nuclear desalination plant in Aktau to achieve its product safety record.

In general, although the tritium pathways would be basically the same in all nuclear reactors, the quantities of migrating tritium would not be the same. Apart FBRs and AGRs (or GCRs), tritium usually stays in the fuel of most thermal reactors [194].

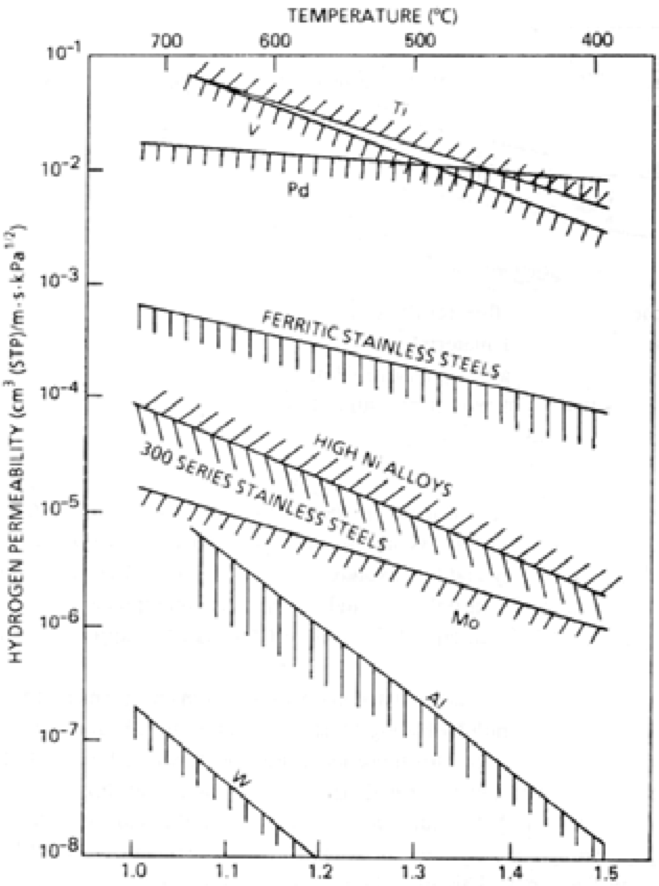

Figure 38. Hydrogen permeability as a function of temperature for selected metals and alloys.

In BWRs, the coolant cycle involves steam generation in the core, steam transport through turbine and condenser systems, and back to the core through the feedwater system [17]. The tritium migration due to leaks in the coolant circle [187] makes steam from BWRs unsuitable for direct use in desalination processes, and apart from few tests, it was never deployed as an energy source for desalination. PWRs have a similar tritium pathway, apart from the fact that a secondary cooling loop is applied. However, the pressure in the first reactor cooling loop is usually higher, which is why isolation heat-exchangers are used in preparation of desalinated water [12].

Leaks of coolant or moderator from the reactor are of particular concern for HWRs, which may lose from 0.5-3% of their heavy water per annum [194]. For this reason, given the price of heavy water, special systems for recovery of heavy water are deployed in nuclear plants with HWRs, lowering the level of tritium releases well below the regulation limits. In addition, detritiation of heavy water is also performed, keeping the tritium concentration in the coolant at controlled levels [190].

Concerning tritium permeation through physical barriers, it primarily varies based on the type of material, pressure and temperature. At the same pressure the temperature increase has a dramatic effect on the increase of tritium permeability. For instance, at 300 K temperature for 3 mm thick 304 stainless steel with 1000 cm^2 surface area exposed on one side with T_2 gas under 1 bar pressure, the tritium permeation will have a steady rate of 5.9 MBq/d. At 800 K temperatures though, the permeation rate within a few hours can reach 20 TBq/d [196]. Tritium permeability through some materials is presented in Figure 38.

Tritium permeability has been noticed to vary under the influence of surface conditions as well, or more specifically the presence of metal oxides layer. For the same temperature, metal oxides reduce tritium permeability by orders of magnitude [197, 198].

The available data on tritium permeability is usually sufficient to estimate the rate of permeation. These estimates are then used to determine whether additional purging and stripping systems are required to remove permeated tritium or whether the material, its thickness and coating should be replaced [16].

Once tritium reaches the desalination loop, for the purpose of a conservative estimate, we can assume that it is transformed to HTO 100%. Through the water distribution network and subsequent consumption, it is ingested into human bodies where it quickly spreads more or less uniformly. Fraction of HTO, 1-5%, becomes organically bound tritium (OBT) and its retention in the human body will depend on the metabolism of the specific tissues that have incorporated HTO or OBT. Generally, it can be estimated that the biological half-life of HTO is 9 days, exchangeable OBT (or OBT-1) is 30 days and non-exchangeable OBT (OBT-2) is 450 days [199].

III-6. HEALTH IMPACTS OF TRITIUM

From the experiences so far, no adverse health effect has been noticed in Kazakhstan as well as in India or Japan. In all those cases the product water from nuclear desalination complied with the WHO guidelines. Moreover, the tritium activity values in drinking water, which were reported for those nuclear desalination facilities, are orders of magnitude below the WHO guideline limit, close to the background values. Nevertheless, the possible adverse health impacts should be kept in mind when the quality of the product water is being set against technically and economically optimal solutions.

The regulations and guidelines on tritium content in drinking water were already presented with their basic logic (see III-3.2.). In this section, the specific impacts will be presented, based on animal studies and experiments as well as the health risk calculations.

As already mentioned, tritium decay emits beta particles with a maximal energy of 18.6 keV and a maximal track in water of 6 μm. The transmutation to ^{3}He has a negligible energy of 0 to 11 eV, so health impacts are mostly associated with beta radiation [167].

Tritium beta radiation cannot cause any adverse health effects outside the human body, since the maximal track is shorter than the thickness of the human skin epidermis. However, ingested tritium can be exchanged with hydrogen in many body molecules, including ribonucleotides, proteins and others. Due to the fact that tritium can be easily exchanged out of (as well as into) biological molecules, which prevents damage to the organisms, so far, it has not been associated with significant health impacts on humans [168]. Still, inside the body, decaying tritium atoms can be close enough to inflict damage on critical molecules and human DNA, which might cause chromosome aberrations and induce cancer. The consequent ^{3}He as a decay product of tritium may still cause further adverse impacts as point mutation [200]. Furthermore, tritium beta rays have generally a higher biological effectiveness compared to X rays and gamma rays [201], meaning that smaller tritium activity can result with the same harm to organisms which can be achieved with higher gamma activity. It should also be remembered that per dose, lower tritium doses can cause more harm to the organisms than higher tritium doses [202].

Possible health effects can be divided into acute toxicity, chronic and subchronic toxicity, genetic effects, development and reproductive effects, carcinogenic effects, immunological etc. [168]. The impacts on humans have not been recorded through experiments but rather by using models which translate gamma- or X ray effects into tritium beta radiation effects or, using results from experiments with animals which have similar tissues, water content in the tissues or metabolism. However, it has to be remembered that human and animal organs can have very different susceptibility to carcinogenic effects of ionizing radiation [200, 201]. Other factors that have to be taken into consideration when assessing the health impacts of tritium intake include: the age, the gender, base-line cancer risks and cancer latency.

Balonov [200] reported on several experiments with continuous HTO ingestion. The findings indicated that there is an apparent adaptive response in cases of lower doses of tritium intake for chromosome aberrations. On the other hand, the total frequency of malignant tumors was similar for all of the tested tritium activity doses (3.7 kBq/g to 370 kBq/g), although the tumor spectrum showed considerable variation.

The doses that were used in the experiments reported by Balonov were at least 3.7 kBq/g[43] per day and continuously given for 200 days. Therefore, the used tritiated liquid had a minimal value for tritium activity much higher (around 1500 times) than the tritium ingestion possible within the limits suggested by the WHO, but the corresponding minimal absorbed dose by the experimental rats was 0.24 Gy. For purposes of conservative estimate, we can accept that 0.24 Gy absorbed dose equals[44] 0.24 Sv of equivalent dose given to the experimental rats in 180 to 200 days. For comparison, humans are not be exposed to doses higher than 0.1 mSv per year (2400 times smaller dose), under normal circumstances.

[43] 3.7 kBq per gram of bodyweight for the tested animals. The rats had average bodyweight of 35 grams.

[44] Some researchers [203] suggest a tritium quality factor Q = 2, which means that the equivalent dose would be twice the absorbed dose.

Other experiments with tritium include studies with mice subjected to drinking water starting from levels of 11.1 MBq/L, with no significant biological effects found at this lowest experiment level but without studying the carcinogenesis [204]. The Californian EPA [168], summarized the findings from several studies in the following Table 17:

Table 17. **NOAEL** AND **LOAEL** FINDINGS SUMMARY

Exposure or Effect	**Doses (MBq/kg-day)**	**NOAEL (MBq/kg-day)**	**LOAEL (MBq/kg-day)**	**Comment**	**Reference**
Survival - mice	25.4	25.4		Assumed daily water intake of 8 mL/day and average weight of 0.035 kg	Carsten et al., 1989
Hemopoietic effects	3.7 to 370	37	370	Rats and mice	Balonov et al., 1993
Survival - rats	3.7 to 370	37	192.4	6 month exposure	Balonov et al., 1993
Reproductive effects - rats	0.63 to 63	6.3	63	2 generations of dosing	Laskey et al., 1980

Primates were rarely used in tritium health impact experiments. One such experiment [205] reported health impact findings for squirrel monkeys. They were given drinking water with 16 to 1000 times higher tritium activity than the one suitable for human use, throughout their gestation period. The results indicated no adverse health impact which can clearly be linked with tritium in the drinking water except for a dose-response pattern with the number of oocytes. Unlike rats though, no effect was observed on the body weight and dimensions, organ weight, hematologic patterns, and histology of organs and tissues even at those increased levels.

The quantity of tritium in the drinking water is not the only factor which can cause serious adverse impacts. According to the Chairman of BEIR-III, Dr. Radford from the US National Academy of Sciences, tritium in the drinking water may be much more dangerous for a female embryo in the early stages of pregnancy, because the DNA of the ova will be labelled with the level of tritium concentration in the mother's body, which might remain for the whole reproductive lifespan of the female [206]. Yet, exposure to smaller doses of radiation, according to the United Nations Scientific Committee on the Effects of Atomic Radiation [207], showed evidence indicating activation of DNA and cellular repair, protecting in that way from carcinogenic diseases.

In general though, according to the precautionary principle, the health risk estimates project a linear relationship between tritium doses and adverse health reactions. Thus the accepted opinion is that there is no tritium threshold or safe dose. For instance, the US EPA considers the cancer mortality risk to be 9.44×10^{-13} per Bq, and the cancer morbidity risk 1.37×10^{-12} per Bq ingested with drinking water [208]. The ICRP [180] agrees with these values[45]: 5×10^{-5} per mSv for fatal cancers, but 2.3×10^{-5} per mSv for non-fatal cancers and severe hereditary effects. The later value is almost three times smaller than the one suggested by EPA, probably due to the fact that the EPA includes a broader scope of effects into the risk assessment. ICRP also assumes 30 IQ points downward shift per Sievert dose to the fetus between the 8th and

[45] ICRP expresses the health risk in lives per Sievert. EPA risk values divided by the dose conversion factor for tritium activity amount to the same figure for ICRP risk estimates.

15^{th} week after conception. UNSCEAR [209] estimates no more than 200 malformations per 10^6 liveborn, after in utero exposure to small doses which can be compared to the nonirradiated population risk of 60 000 per 10^6 liveborn.

Confirming the UNSCEAR estimate, the naturally high background radiation in certain parts of the world, such as Kerala in India and Pocos del Caldas in Brazil – of up to 10 times the usual exposure dose of 2.4 mSv – have no detected deleterious health effects [210].

Compared to these values, the WHO recommendation for doses below 0.1 mSv annually through drinking water is negligible, and as such, it is the basis for many national regulations. The WHO derived a limit for tritium in drinking water of 10000 Bq/L concluding that “no deleterious radiological health effects are expected from consumption”. The existing experience of the operation of nuclear desalinization plants show that tritium levels in desalinated water are orders of magnitude below this value.

III-7. CONCLUSION AND RECOMMENDATIONS

It should be noted that despite the current regulations based on these calculations, there is an emerging trend to lower the regulatory limits for tritium activity even further. One such example is the alarm levels set in the EU of 100 Bq/L. Even more stringent, California has already set a public health goal of no more than 15 Bq/L [168]. These values are still not regulatory limits, but must be kept in mind when assessing the technical and economic feasibility of a nuclear desalination facility.

To achieve as low as possible tritium activity levels in the desalinated water, the technical solution must be based on several factors.

First, regarding the nuclear reactor, it would be recommendable that it has a low tritium production. Such reactors are usually the PWRs, although in India heavy water reactor has proven to be successfully applied for in nuclear desalination, while in Kazakhstan a FBR has also proven as a suitable energy source for desalination.

Second, based on that production, the choice of coatings, protective materials, removal mechanisms and measurement equipment must be selected. Materials with oxidized layers manage to contain tritium more successfully and cold traps for removal of tritium in the MAEC nuclear desalination plant have proven capable of removing more than 3.7×10^{15} Bq during the operating time of the plant. New technological developments are emerging from the ITER project which will likely result in materials and coatings that will prevent tritium migration much more successfully.

Third, safety measures should to be taken, especially pressure barriers and hold-up reservoirs which will allow for a precise measurement of the tritium activity in the water, as well as prevention of the water’s release in the distribution network in case of contamination. Also, operating practices which avoid the reactor’s higher tritium production at start up should be implemented.

These factors and measures have so far prevented tritium contamination in nuclear desalination. Recent improvements and developments allow for even safer coupling designs and practices in nuclear desalination facilities. It can be thus concluded that, although it will always be a safety concern, the radiation safety of the desalinated water is ensured by the practices and technologies used.

Appendix IV

SMALL AND MEDIUM SIZED REACTORS SUITABLE FOR NUCLEAR DESALINATION

In the following the design of the two SMR under construction, the PBMR and the KLT-40, will be shortly outlined. More information on other SMRs can be found in IAEA-TECDOC-1326 [7].

IV-1. PEBBLE BED MODULAR REACTOR (PBMR)

This reactor is under construction in South Africa. The power plant incorporates a closed cycle primary coolant system using helium to transport heat energy directly from the modular pebble bed reactor to a recuperative power conversion system with a single shaft turbine/compressor/generator (see Figure 39 and 40).

The nuclear fuel consists of TRISO particles (also called pebbles) with a UO_2 fuel kernel in graphite coated fuel spheres (also called balls), each containing about 15 000 particles. They are loaded continuously during operation into the top of an annular core (see Figure 41) with a fixed central reflector; spent fuel is continuously removed from at the bottom of the core.

Detailed design data of the PBMR are documented in IAEA-TECDOC-1485 [157].

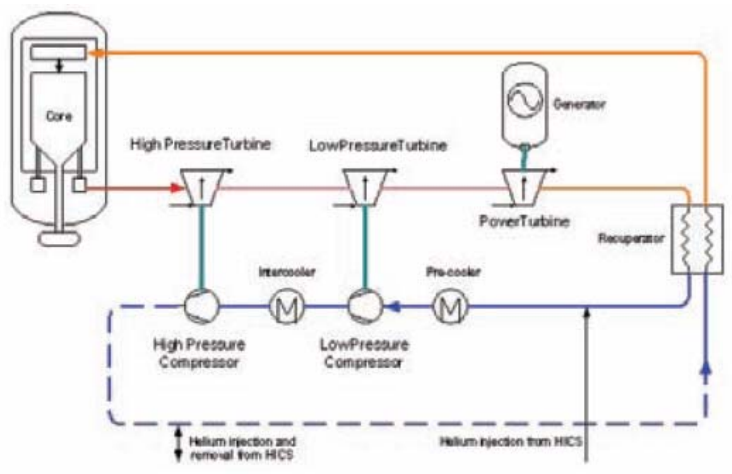

Figure 39. Power conversion system of PBMR [157].

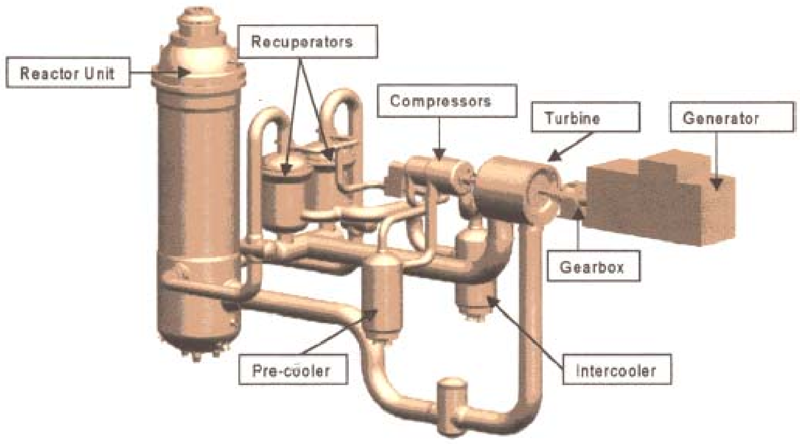

Figure 40. Layout of PBMR plant [157].

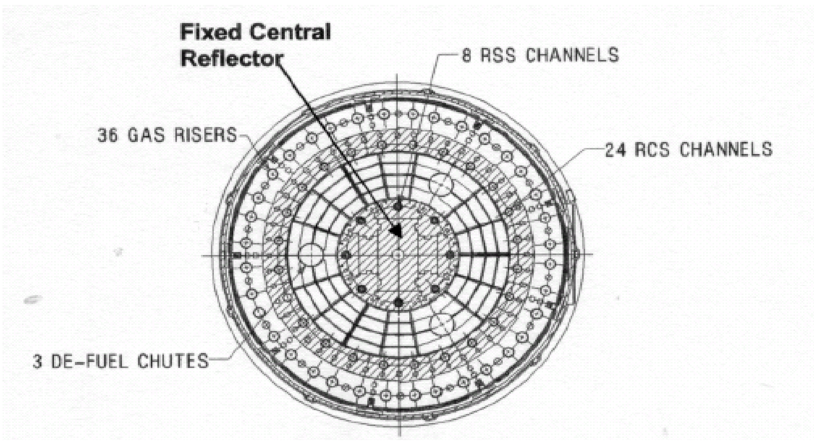

Figure 41. Horizontal cross section of core of PBMR [157].

IV-2. BARGE MOUNTED KLT-40

This reactor is under construction in the Russian Federation. It is a two loop plant with a pressurized water reactor connected to coil type steam generators (see Figure 42).

The KLT-40 design is based on proven technology used in ice breakers under severe environmental conditions of Far North. The accumulated operating experience of such reactor types is more than 275 years. Two identical reactor units are to be installed on a barge (see Figure 43) that can be towed to its final destination.

Technical data of the KLT-40 are documented in IAEA-TECDOC-1326 [7] and IAEA-TECDOC-1561 [11].

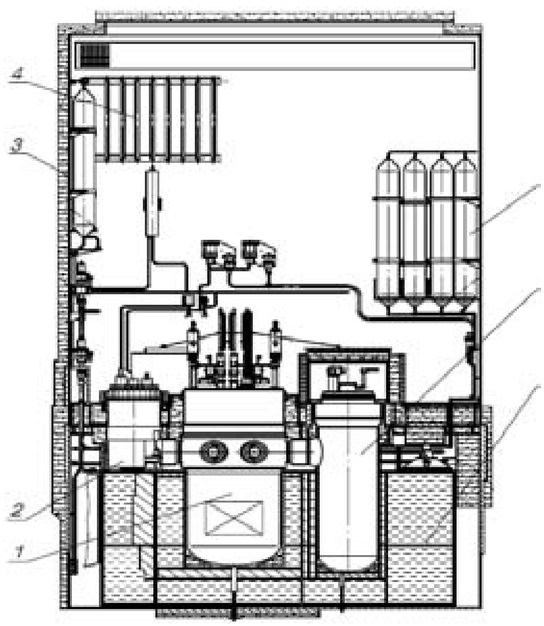

Figure 42. Cross section of KLT-40 reactor [7].

Legend: 1 – reactor, 2 – primary circuit circulation pump, 3 – protective shell, 4 – emergency condensation system, 5 – high pressure gas cylinders, 6 – steam generator, 7 – metal water shielding tank,

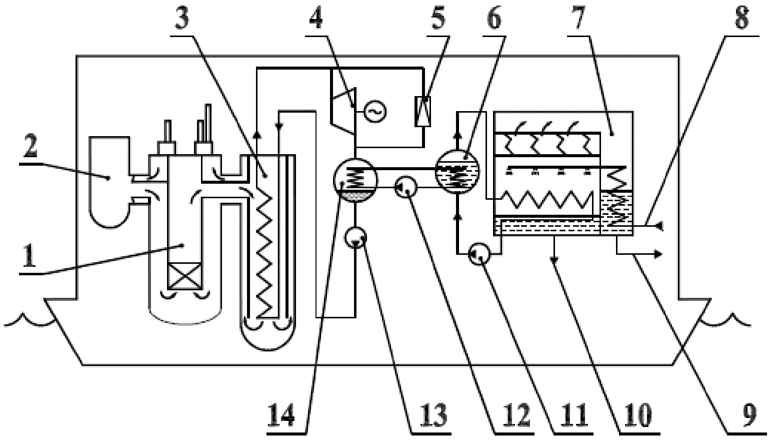

Figure 43. Flow diagram of KLT-40 with thermal desalination plant [7].

Legend: 1 – reactor, 2 – primary circuit circulation pump, 3 – steam generator, 4 – turbo generator , 5 – reduction cooling set, 6 – intermediate heat exchanger, 7 – distillation desalination plant, 8 – sea water inlet, 9 –product water outlet, 10- brine outlet, 11 – pump, 12 – intermediate circuit pump, 13 – secondary circuit pump, 14 – condenser.

Appendix V

EXPERIENCE WITH NUCLEAR DESALINATION

In this Appendix additional information will be presented on installed desalination plants using nuclear power as their energy source. Additionally, an overview on international studies on technical and economic issues performed by IAEA Member States will be laid out.

V-1. EXPERIENCE WITH THE NUCLEAR DESALINATION PLANT IN AKTAU

V-1.1. Short history of nuclear desalination at the Caspian Sea

In 1961 development of seawater desalination technology began in the former USSR with the erection of a desalination testing facility in the eastern deserted Caspian seashore. The first distillation unit had an output of fresh water of 70 up to 120 m^3 per day.

Based on the results achieved in this testing facility, in 1963, two fossil boilers, a backpressure turbine and a desalination unit (MED) with an output of 5000 m^3 of desalinated water per day was installed to satisfy growing needs for water for the nearby city of Aktau (formerly Shevchenko) and its developing industries at the sea shore of the Caspian sea.

The next step was to construct a fossil (gas/oil) power station (750 MW(t)) , a nuclear reactor, three MED plants of five effects, each with a capacity of 12 000 m^3 per day, coupled to three backpressure turbines with 50 MW each, and a potable water preparation facility. The nuclear reactor started up in 1973. Till 1990, ten MED plants of 10 effects were erected with a capacity of 8000 to 14 500 m^3 per day leading to a total design capacity of the desalination plant of 145 000 m^3 per day.

V-1.2. Description of the nuclear desalination facility at MAEC

The site of the nuclear desalination plant is called Mangyshlak Atomic Energy Complex (MAEC). The location of MAEC at the Caspian Sea is shown in the following Figure 45.

Figure 44. Distillation units at Mangyshlak Atomic Energy Complex (MAEC), Aktau, Kazakhstan.

Figure 45. Location of MAEC at the Caspian Sea.

The seawater intake channel is about 2 km long; the brine discharge (outfall) channel feeds into an artificial shallow lake (Kara-Kol) that is connected to the sea. The intake channel is used to purify the seawater from silt, and the artificial lake provides aeration of the brine and suspended particle clean up.

The main components and flow diagram of the nuclear desalination plant within MAEC are shown in the following Figure 46.

As shown in the Figure 46, steam from the fossil power plant ("fossil fired boilers") and from the nuclear power plant's steam generators is supplied parallel to a condensation turbine and to (three) backpressure turbines, and directly after a temperature and pressure reduction to industrial consumers located about 7 km away from MAEC in Aktau.

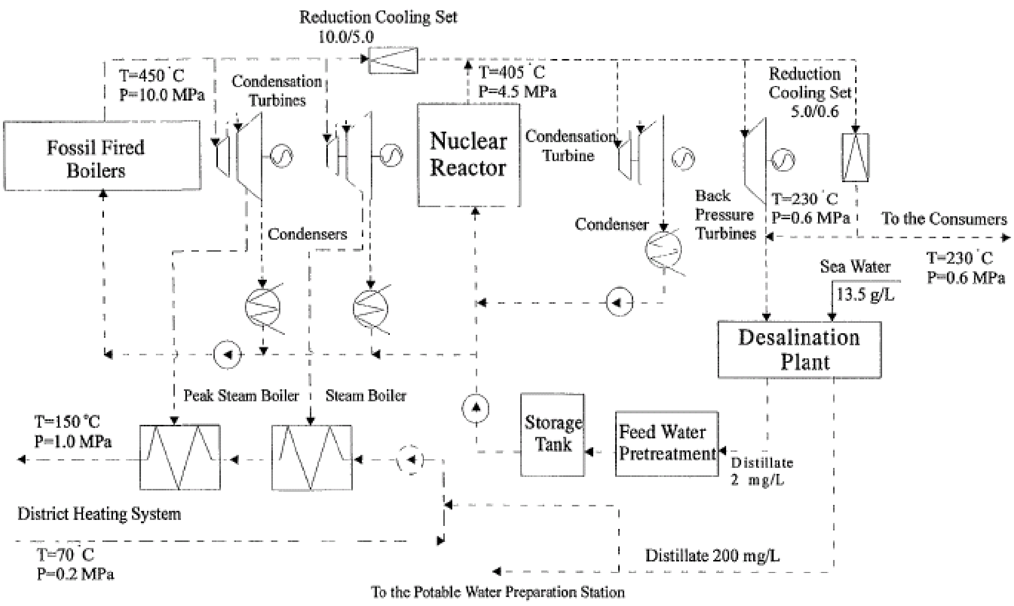

Figure 46. Principle flow diagram of MAEC [14].

The exhaust steam (0.6 MPa) of the backpressure turbines is fed into the first effects of the MED desalination plant. The distillation plant produces two qualities of desalinated water, the one with less purity (distillate A with a salinity of 200 mg/L) being fed to the potable water preparation station and the one with high purity (distillate G with a salinity of 2 mg/L) to the feed water pre-treatment facility. Part of the distillate A with lower purity is also fed into a district heating system for the city of Aktau thereby using extraction steam from the condensation turbine to heat the water up to 150 C (at 1.0 MPa) in separate steam boilers.

V-1.3. Characteristics of the sea water and product water at MAEC

The seawater supplied from the Caspian Sea to the MED plant has the following characteristics (Table 18):

Table 18. CHARACTERISTICS OF THE SEAWATER SUPPLIED TO MAEC [211]

Characteristic	Dimension	Value
Calcium	mg/L	338.6 + 8.2
Magnesium	mg/L	772.6 + 7.8
Sodium	mg/L	3337.8 + 29.4
Potassium	mg/L	84.0 + 0.7
Chloride	mg/L	5571.2 + 59.0
Sulphate	mg/L	3192.3 + 23.4
Bicarbonate	mg/L	213.1 + 7.1
Total Dissolved Solids	mg/L	13 489 + 99
Seasonal variation in temperature	°C	2 to 24

Two different types of product water were prepared at the MAEC nuclear desalination plant: distillate G, with very low solids content, suitable for industrial purposes, and distillate A which was used in the preparation of potable water.

The two types of desalinated water produced in the MED plant – type G and A – and the potable water delivered by the potable water preparation station have the following characteristics as presented in Table 19.

As laid out in the Table 19, the potable water delivered to Aktau clearly meets the World Health Organization (WHO) requirements for drinking water quality. An analysis of tritium in distillate A and G of desalination plant has shown that it is at background level, i.e. close to that of the sea or groundwater.

V-1.4. Technical description of reactor BN-350 at MAEC

The BN350 is a loop type fast breeder reactor (FBR) cooled with liquid sodium. It has six primary loops, each loop has a pump and an intermediate sodium-sodium heat exchanger connected to a second sodium loop. The reactor core is surrounded by a blanket of depleted uranium. The negative power and temperature reactivity coefficient of the core provide self stability of the reactor. The low pressure of the sodium coolant and the absence of noticeable corrosion ensure the leak tightness of sodium piping and components. The following Table 20 depicts an overview on the main technical parameters of BN-350.

Table 19. CHARACTERISTICS OF THE DESALINATED WATER IN MAEC [211]

Characteristics	Distillate G	Distillate A	Potable water	WHO guideline values
Total Dissolved Solids (mg/L)	1.96	198.6	389.4	< 1000
Temperature (°C)	45	28	26	NG
Colour (total colour units)	-	-	2	15
Turbidity (formazin turbidity units)	-	-	1.7	5
Conductivity (mS/cm)	4.05	326.7	691.2	NG
pH	8.46	8.07	8.2	6.5 – 8.5
Total hardness ($CaCO_3$ mg/L)	0.78	66.0	126.0	500
Chloride (mg/L)	0.48	55.6	138.8	250
Sulphate	0.31	33.2	91.7	400
Calcium	0.08	7.6	25.2	ng
Magnesium	0.09	8.2	10.0	ng
Sodium	0.18	48.5	105.4	200
Aluminium	-	-	0.1	0.3
Copper	0.013	0.06	0.05	1.0
Iron	0.033	0.09	0.27	0.3
Zinc	-	-	0.028	5.0
Fluoride	-	-	0.1	1.5
Nitrate	-	0.27	0.44	10.0
Alpha activity (Bq/L)	-	-	0.012	0.1
Beta activity (Bq/L)	-	-	0.09	1.0

NG = not defined.

Table 20. MAIN TECHNICAL DESIGN PARAMETERS OF BN-350

Reactor thermal power	750 MW(t)
1. Electric output	125 MW(e)
Inlet/outlet sodium temperature of the primary loops	288/437°C
Inlet/outlet sodium temperature of the secondary loops	260/420°C
Steam outlet temperature	405°C
Steam pressure	4.5 MPa
Steam flow	1070 t/h
Fuel burnup	11.8% at

The reactor had been in operation since 1973 and achieved more than 160 000 hours of operation. It was shut down in 1999 mainly due to political reasons and is currently under decommissioning.

No sodium leaks occurred in primary and secondary loop and cavitation damage in the pumps was insignificant. The steam generators were reconstructed after a couple of years of operation to eliminate failures of the steam generator tubes. Shut down of the reactor was done regularly twice every year for twenty days to perform maintenance and refuelling. During this period the heat for the desalination plant was supplied exclusively by the fossil power station. The following Figure 47 shows a vertical cross-section of BN-350.

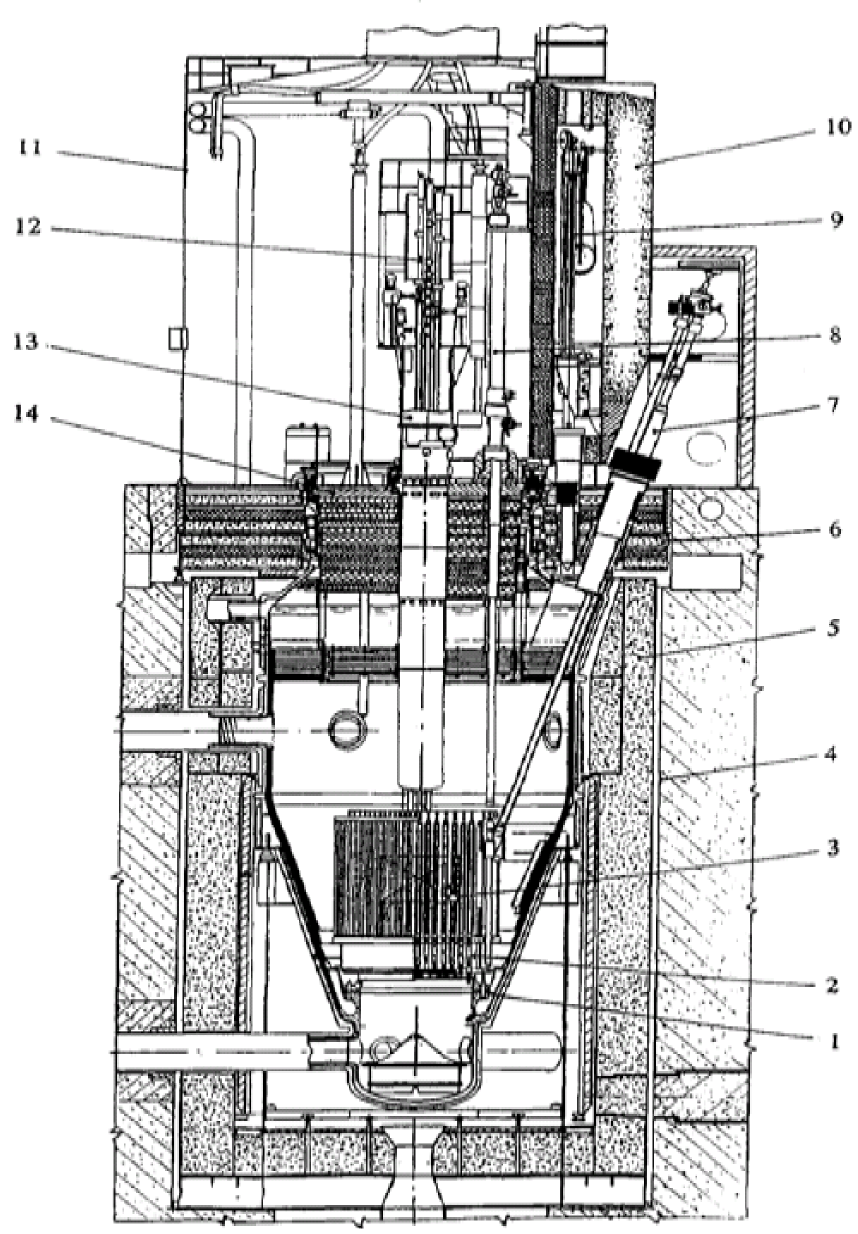

Figure 47. Vertical cross-section of BN-350 [212].

1 – reactor vessel, 2 – core diagrid, 3 – reactor core, 4 – reactor well liner, 5 – lateral shield, 6 – upper-stationary shield, 7 – elevator, 8 – refueling mechanism, 9 – FAa transfer mechanism, 10 – fuel transfer cell, 11 – protective dome, 12 – control rod drive mechanism, 13 – above core structure, 14 – rotating plugs.

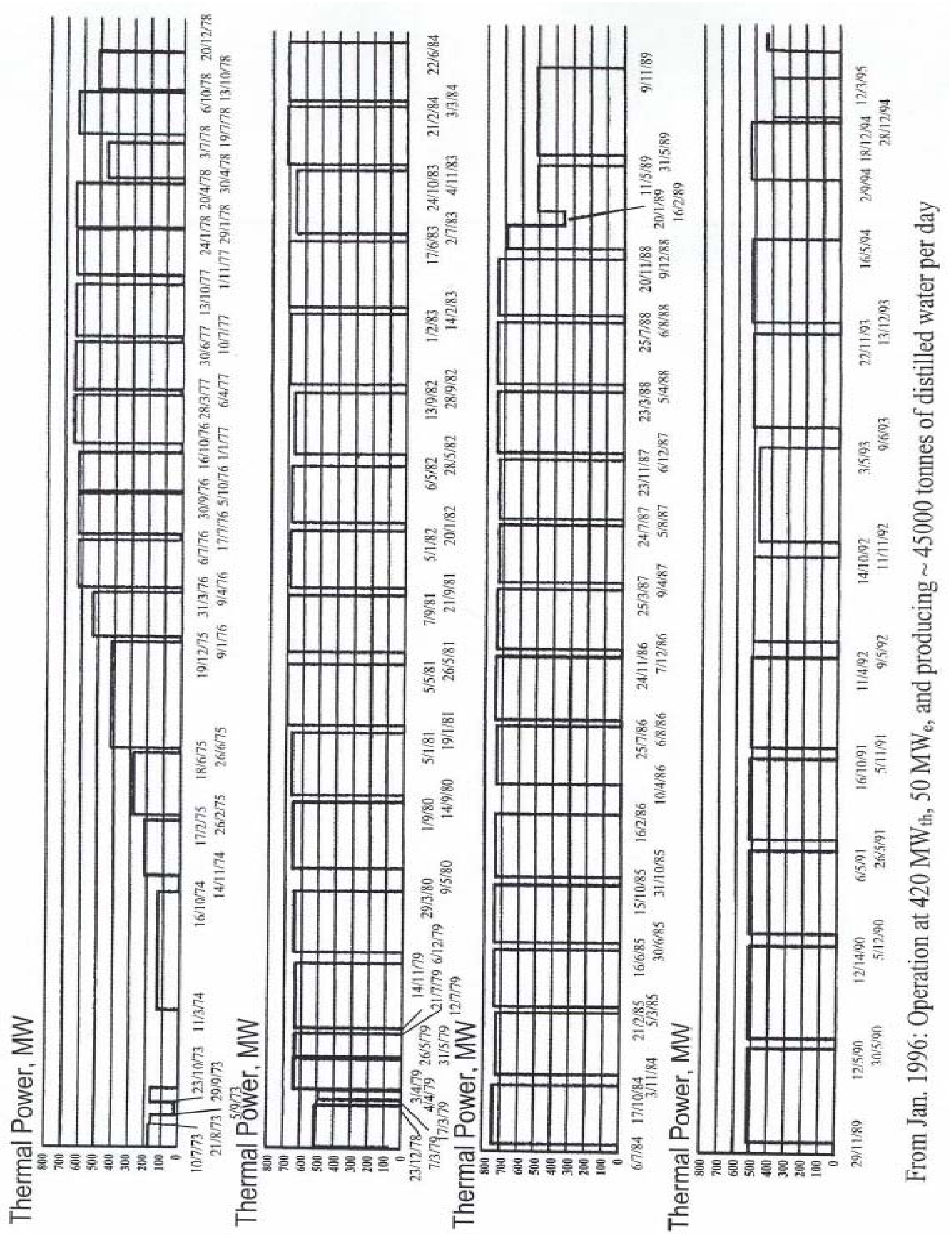

Figure 48. Operational history of BN-350 [212].

V-1.5. Technical description of desalination plant at MAEC

The desalination plant consists of three MED vertical tube distillation units with five effects and seven units with ten effects. The technical data of the desalination plant are presented in Table 21.

The nuclear desalination plant at MAEC near Aktau has shown high reliability and flexibility due to the combination of a nuclear reactor and a fossil plant as its energy source. No contamination of the steam and water and no adverse effect on the environment were observed during 27 seven year of operation.

Table 21. TECHNICAL DATA OF DESALINATION PLANT (ONE UNIT) [211]

TECHNICAL CHARACTERISTICS	
No. of effects	10
Heat exchange area evaporator regenerative pre-heater	 1760 m^2 550 m^2
Length of tubes	5 m
Outer/inner diameter	38/33.5 mm
Recycled brine in the evaporator	18 000 t/h
DISTILLATE	
Daily production	14 500 t/d
Temperature	30°C
Maximum salinity (tds)	200 mg/L
Performance ratio	8.4 kg/kg
SEA WATER	
Total flow	1500 – 4500 t/h
Required pressure	0.3 MPa
Concentration ratio	3.3
Maximum brine temperature	105°C
STEAM TO EVAPORATOR	
Pressure	0.4 MPa
Flow	67 t/h
Specific consumption of heat energy	295 kJ/kg
Condensate salinity	< 2 mg/L
STEAM TO VACUUM EJECTOR	
Pressure (absolute)	1.2 MPa
Flow (approximate)	1.3 t/h
ELECTRICITY	
Consumption per tonne of distillate	3.9 kWh/t

V-2. EXPERIENCE WITH NUCLEAR DESALINATION IN JAPAN

All 55 nuclear power plants in Japan are located at seaside using the sea as their ultimate heat sink. Some of them are equipped with seawater desalination plants to ensure the supply of fresh water needed for boiler feed (make up) water and for households.

The first nuclear seawater desalination plant (MSF) started up in Japan in 1974 at the Ohi nuclear power plant (PWR type). Currently, there are eight[46] nuclear seawater plants in operation at four different utilities, i.e. Kansai, Tokyo, Shikoku and Kyushu Electric Power Company. The capacity of these desalination plants ranges between 1000 and 1300 m^3 per day (per unit). Three types of desalination processes are used in Japan: MSF, MED and RO. Originally, MSF plants were installed but later MED and RO were chosen, mainly due to their higher efficiency.

Table 22 and 23 presents the technical specification of the desalination plants.

In 2003, at Takahama nuclear power plant a new MED plant replaced the old (built in 1983) MSF plant. This new MED plant has a thermal vapour compressor for the first two effects; instead of tubes in the MED effects, pressed vertical plates made of titanium [214] are used.

In addition to make up water used for the power plant, the RO plants in Ohi (III and IV) and Ikata (III) are producing potable water and household water, respectively.

The nuclear desalination plants in Japan have shown excellent operational performance for more than 30 years. They have been free of any serious problems related to migration of radioactive material into the desalted water.

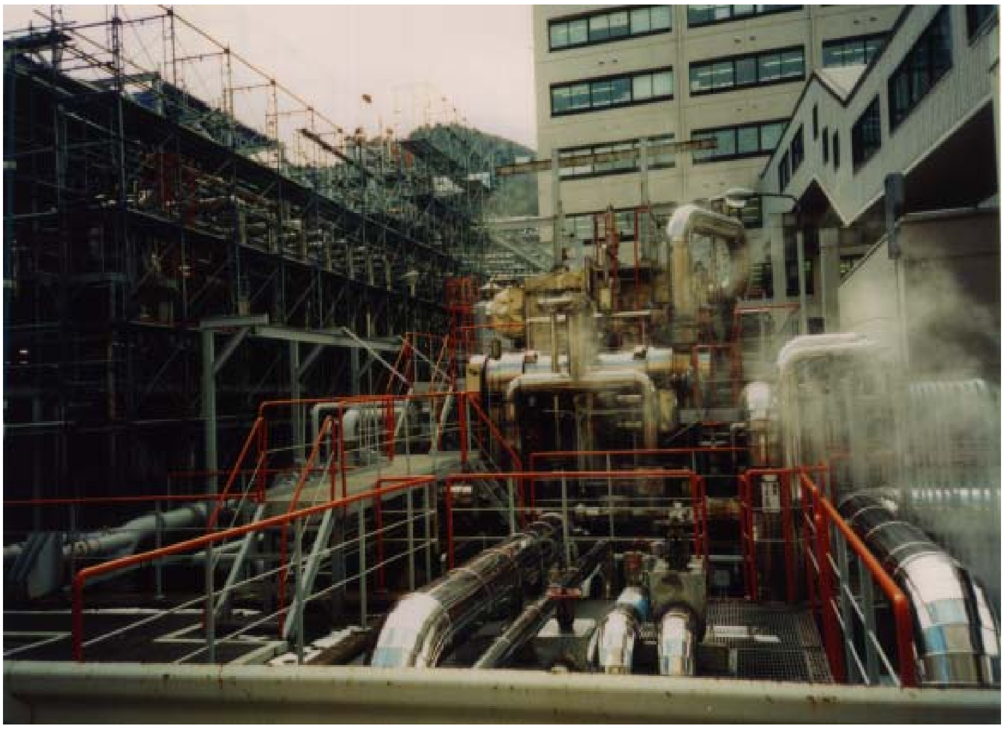

Figure 49. Desalination plant at the nuclear power plant Ohi, Japan.

[46] All operating eight desalination plants are at PWR sites. One additional desalination plant at a BWR site, Kashiwazaki, is not operated as the needed water is supplied via the local community.

Table 22. SPECIFICATION OF THE MED AND MSF DESALINATION IN JAPAN [213]

	Ohi-I, II	Ohi-I, II	Takahama	Ikata-I, II	Genkai-III, IV
Process	med	msf	med/vc	msf	med
No. of stages/effects	8	18	8	27	8
Total capacity (m^3/d)	2600	1300	2000	2000	1000
Train (unit) capacity (m^3/d)	1300	1300	1000	1000	1000
Gained output ratio	6	6	6	8	6
Inlet seawater temperature (°C)	6 - 31	6 - 31	6 - 31	6 - 31	6 - 31
Salinity of seawater TDS (mg/L)	35 000	35 000	35 000	35 000	35 000
Brine temperature (°C)	118	104	94	116	94
Product water tds (mg/L)	10	10	5	5	5

Table 23. SPECIFICATION OF RO IN JAPAN [213]

	Ohi-III, IV	Ikata-III	Genkai-III, IV
Membrane type	Cellulose acetate Hollow fibre	Cellulose acetate Hollow fibre	Cross linked polyether Spiral wound
Total capacity (m^3/d)	2600 (at 10°C)	2000	1000
Train (unit) capacity (m^3/d)	1300 (at 10°C) 1700 (at 31°C)	1000	1000
No. of modules	95 × two lines (1st stage = 65, 2nd stage = 30)	36 × two lines	54
Inlet pressure (MPa) first stage second stage	6.5	6.8 4	6.5
Recovery ratio (%)	28 (at 10°C) 37 (at 31°C)	33.3 (at 10°C) 40 (at 17°C)	25 - 40
Inlet seawater temperature (°C)	6 - 31	6 - 31	6 - 31
Salinity of seawater TDS (mg/L)	35 000	35 000	35 000
Product water salinity TDS (mg/L) conductivity (μS/cm)	15 30 (at 30°C)	350 700	150 300

V-3. EXPERIENCE WITH NUCLEAR DESALINATION IN INDIA

In India two nuclear desalination plants are in operation: The Nuclear Desalination Demonstration Project (NDDP) at Kalpakkam and at the nuclear research reactor at BARC at Trombay.

V-3.1. Experience with the Nuclear Desalination Demonstration Project in Kalpakkam

Based on operational experience with several types of desalination plants such as multi-stage flash (MSF) and reverse osmosis (RO), Bhabha Atomic Research Centre (BARC) has designed, developed and constructed a nuclear desalination demonstration plant (NDDP) at Kalpakkam based on hybrid technology (see Fig. 50). It is a 6300 m^3/day hybrid MSF-RO desalination plant comprising of 4500 m^3/day Multi-stage flash (MSF) and 1800 m^3/day reverse osmosis (RO) plant coupled to Madras Atomic Power Station (MAPS). The requirements of seawater, steam and electricity for the desalination plant are met from MAPS.

Figure 50. Desalination plant at nuclear power station Kalpakkam, India.

The hybrid technology, developed by BARC, has several advantages. It has provision for redundancy and production of two qualities of desalinated water for best utilization. MSF pant uses low pressure steam from the MAPS as energy input. The desalinated water produced from MSF is of distilled quality which is good for industrial use. The desalinated water produced from MSF can be blended with RO water for giving better quality of drinking water close to rain or river water, as opposed to well water.

The RO plant with a capacity of 1800 m^3 water per day was commissioned in 2003 and the MSF plant with a capacity of 4500 m^3 water per day was commissioned in 2008. The salinity of seawater is normally around 33 000 to 38 000 ppm TDS, with a high of 41 000 ppm TDS in summer times and a low of 26 000 ppm TDS in the rainy season [215]. Due to this high variability of seawater salinity, the RO plant was operated within safe recovery limits so that it does not lead to membrane scaling. The plant has demonstrated a high reliability and safety since its start up. The product water has been found to be safe for drinking, totally conforming to WHO standards.

The coupling of the PHWR to the desalination plant is done via an intermediate heat exchanger. The reject seawater with about 40°C from the MSF plant is fed into the RO plant, thereby increasing the efficiency (i.e. higher flux at same pressure) of the RO process. The technical specification of the MSF plant is provided in Table 24. The technical specification of the RO plant of the NDDP at Kalpakkam is shown in the following Table 25.

Table 24. MSF PLANT TECHNICAL SPECIFICATION AT NDDP KALPAKKAM

Product water capacity	4500 m^3/d
Product water quality	< 20 ppm TDS
Top brine temperature	121°C
Blow down temperature	40°C
Performance ratio	9
Seawater flow	1450 m^3/h
Steam consumption	20.6 t/h
Pumping power consumption	600 kWe
Power loss to power station due to steam withdrawal for desalination plant	2.4 MW(e)
Scale control	Acid treatment
Flash evaporator	Rectangular, long tube design
No. of recovery modules	9
No. of flash stages/modules	4
No. of reject module	1
No. of stages	3
Total number of flash stages	39
Tube material	Cupronickel 90/10
Material of centrifugal pumps	SS316

Table 25. RO PLANT TECHNICAL SPECIFICATION AT NDDP KALPAKKAM

Product water capacity	1800 m^3/d
Product water quality	< 500 ppm
Seawater flow	215 m^3/h
Seawater salinity tds	35 000 ppm
Membrane element	TFC spiral wound, 22 m^3/day/element
Product recovery	35%
Design pressure	55 kg/cm^2
No. of elements	156
No. of elements per module	6
Total no. of modules	26

As presented above the MSF plant is designed for production of water with a quality of < 20 ppm TDS and the RO plant with 350 to 500 ppm TDS; blending of both types of product water will produce a quality of 125 to 175 ppm TDS.

The production costs of the desalinated water were estimated [52] to be 0.95 US$/$m^3$ for the RO plant, 1.18 US$/$m^3$ for the MSF plant and 1.10 US$/$m^3$ for the blended product water.

The RO system of the NDDP has shown excellent performance since its start-up producing desalinated water of constant high quality at competitive costs. No contamination with radioactive products from the nuclear power station has ever happened.

V-3.2. Experience with nuclear desalination at Trombay

CIRUS, located at BARC, Trombay, is a heavy water moderated reactor of 40 MW(t) with natural uranium metallic fuel and demineralised water as primary coolant, and seawater as the secondary coolant. In order to demonstrate the utilisation of nuclear waste heat for seawater desalination, a Low Temperature Evaporation (LTE) desalination plant was coupled to the nuclear research reactor at BARC in (see Figure 51 and 52) for utilizing a part of its waste heat for producing desalinated water from seawater to meet the make-up water requirement of the reactor. The following Figure 52 shows the flow diagram of the desalination plant coupled to CYRUS.

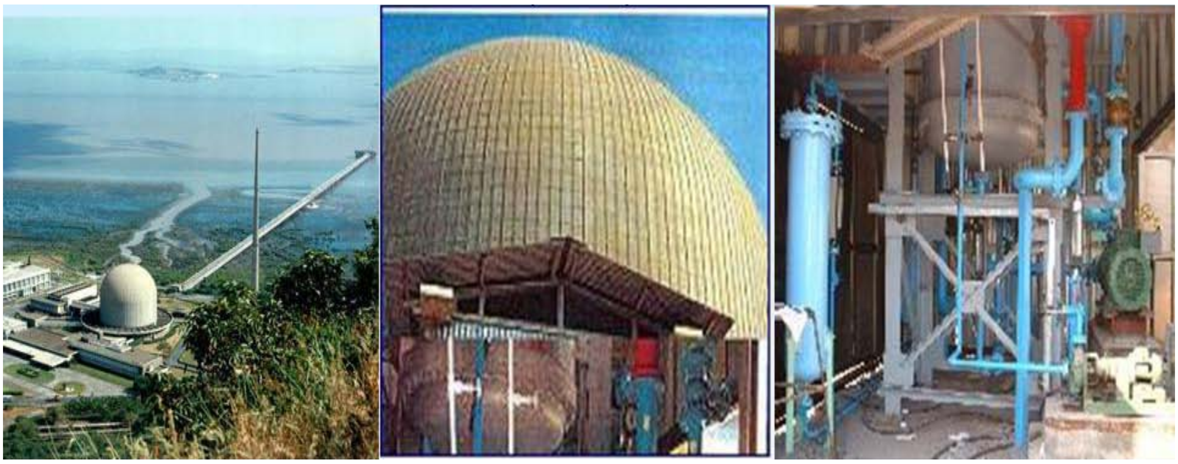

Figure 51. Desalination plant at CIRUS research reactor, Trombay, India.

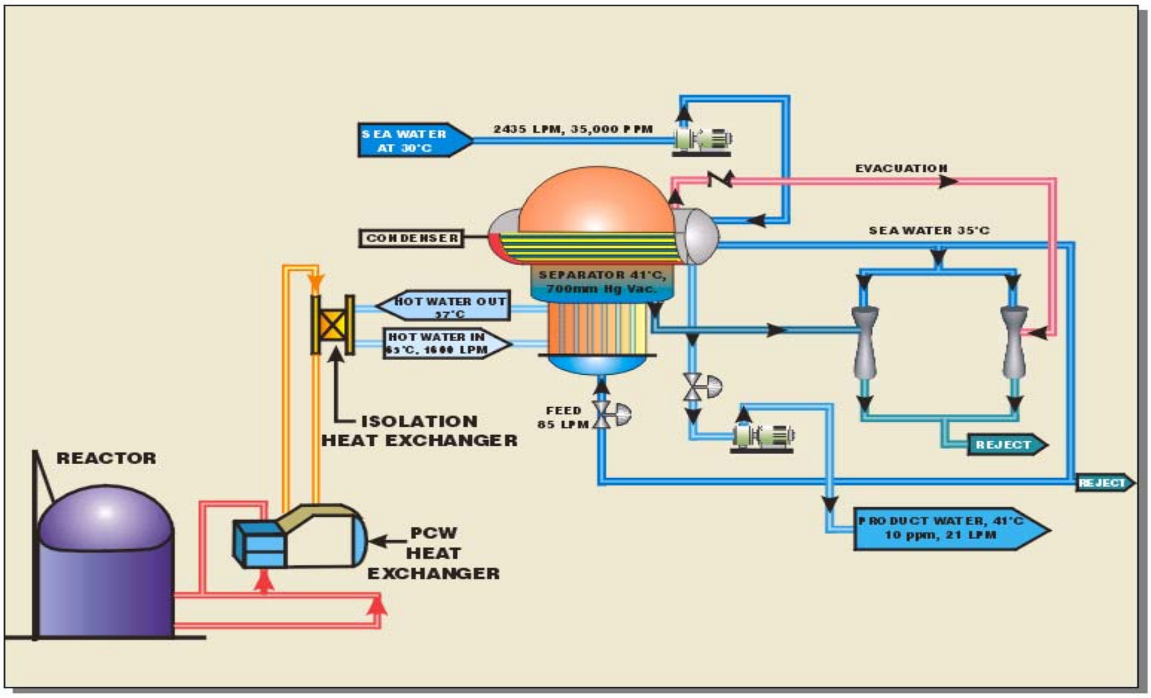

Figure 52. Flow diagram of the LTE desalination plant coupled to the nuclear research reactor at Trombay [52].

Table 26. TYPICAL PERFORMANCE DATA OF THE LTE PLANT COUPLED TO THE NUCLEAR RESEARCH REACTOR AT TROMBAY

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

Since 2004, the waste heat of the research reactor is used to supply heated water to the LTE plant for seawater desalination. The capacity of the plant is 30 m^3 of desalinated water per day which is sufficient to satisfy the make-up requirement of demineralised water for the research reactor. The successful operation of this small desalination plant has demonstrated high reliability, safety and economics.

The integrated system has been successfully operated and demonstrated the technical feasibility of coupling a LTE plant to a nuclear research reactor. The product water of the desalination plant meets the make up water requirement of the nuclear research reactor.

V-4. Experience with nuclear desalination in USA

The Diablo Canyon power plant at Avila Beach in California utilizes seawater as cooling water in its direct cooling system and for the production of make up water for its steam system, but also for potable water.

The desalination process used is RO; the plant was commissioned 1992 and has a capacity of 4500 m^3 per day in two parallel units [217]. The product water of the desalination plant is pumped to a set of twin reservoirs with a combined capacity of about 20 million liters. Flow to this reservoir is supplemented by water from a seasonally available well and creek with chemical treatment (pH adjusted and chlorinated). Water from these reservoirs is fed into the water treatment system, where it is processed to produce make up water or drinking and domestic water.

The RO plant (Figure 53) has a pre-treatment system with chemical additions (e.g. ferric sulphate and polyelectrolyte as anti scaling), several types of filters (including UF, ultra filtration) to remove suspended particles and bio mass and ultraviolet lamps to kill bacteria and reduce fouling of the membranes. Typical operating pressure of the high pressure pumps is 5.5 MPa. The RO elements are of type Filmtec SW30 8040HR; they are operated at a 45% recovery rate with about > 99% salt rejection. The product water of the RO facility has an average conductivity of 400 µS/cm. Energy consumption is constant at about 4.5 kWh/m^3.

Figure 53. Desalination plant at nuclear power plant Diablo Canyon, USA.

Online availability of the RO system has been 100%. The excellent performance is achieved by an appropriate design and by careful control and (preventive) maintenance procedures, primarily, of the pre-treatment system.

V-5. RESULTS OF STUDIES ON NUCLEAR DESALINATION PERFORMED WITHIN AN IAEA COORDINATED RESEARCH PROJECT

The results of site specific techno-economic studies on nuclear desalination performed during 2002 to 2006 within an IAEA coordinated research project[47] (CRP) are well documented [11]. In the following only a short overview of the results will be presented.

Within the IAEA CRP the following countries participated: Argentina, China, Egypt, France, India, Republic of Korea, Pakistan, Russian federation, Syrian Arab Republic, and USA.

Several types of desalination systems were evaluated: RO, HT-VTE-MED, LT-HTE-MED, MED/VC, MSF, and hybrids MSF/RO and MED/RO. The corresponding co-located nuclear power plants included PWRs of various sizes, ranging from about 70 MW(e) (KLT-40S) to 1000 MW(e) (French and US design), PHWR (Indian and Canadian design), and the new generation of gas cooled high temperature reactors such as the GT-MHR and the PBMR. In the Chinese study the heating reactor NHR-200 (with 200 MW(t)) was chosen as power source.

For MSF plants coupled to nuclear power plants the levelised costs of desalinated water were calculated to be in the range of 1.18 to 1.28 US$ per m^3. The studies showed a high sensitivity of the water costs to the discount rate and to the power (steam and electricity) cost.

For MED plants coupled to nuclear power plants the levelised water costs were determined to be in the range of 0.6 to 0.96 US$ per m^3; for the MED/VC plant coupled to a PWR water costs of 0.5 US$ per m^3 were estimated. MED plants coupled to gas cooled reactors (e.g. GT-MHR or PBMR) were found to produce water cheaper compared to MED plants coupled to

[47] An earlier IAEA CRP on nuclear desalination ran from 1999 to 2003 and is documented in Ref. [20].

other nuclear reactors. MED plants coupled to combined cycle gas turbine (CCGT) plants as power source showed systematically higher water costs of about 20% compared to MED desalination plants coupled to nuclear power plants. Similar to MSF, also water costs of nuclear desalination plants using MED showed high sensitivity to the discount rate, but also to the availability of the plant, and to the desalination base cost (US$/$m^3$/day). Water costs were rather insensitive to a variation of capacity.

For RO plants coupled to nuclear power plants desalination costs vary from 0.5 to 0.94 US$ per m^3. Water costs using a CCGT as power source for RO desalination were determined to be much higher compared to nuclear desalination. Sensitivity of the water costs to discount rate, power cost and availability was calculated to be high. A comparison of water costs using RO and MED showed 16-31% lower costs for RO.

The overall conclusion was that nuclear options will remain competitive against fossil power sources including CCGT as long as the gas prices stay above 150 $/toe and discount rates below 10%.

REFERENCES

[1] INTERNATIONAL ATOMIC ENERGY AGENCY, Introduction of Nuclear Desalination, Technical Reports Series No. 400, Vienna (2000).

[2] INTERNATIONAL ATOMIC ENERGY AGENCY, Market potential for non-electric applications of nuclear energy, Technical Reports Series No. 410, Vienna (2002).

[3] INTERNATIONAL ATOMIC ENERGY AGENCY, Potential for nuclear desalination as a source of low cost potable water in North Africa, IAEA-TECDOC-917, Vienna (1996).

[4] INTERNATIONAL ATOMIC ENERGY AGENCY, Non-electric applications of nuclear energy, IAEA-TECDOC-923, Vienna (1997).

[5] INTERNATIONAL ATOMIC ENERGY AGENCY, Floating nuclear energy plants for seawater desalination, IAEA-TECDOC-940, Vienna (1997).

[6] INTERNATIONAL ATOMIC ENERGY AGENCY, Thermodynamic and economic evaluation of co-production plants for electricity and potable water, IAEA-TECDOC-942, Vienna (1997).

[7] INTERNATIONAL ATOMIC ENERGY AGENCY, Status of design concepts of nuclear desalination plants, IAEA-TECDOC-1326, Vienna (2002).

[8] INTERNATIONAL ATOMIC ENERGY AGENCY, Desalination Economic Evaluation Program (DEEP), User's Manual, IAEA Computer Manual Series No. 14, Vienna (2000).

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

[10] INTERNATIONAL ATOMIC ENERGY AGENCY, Optimization of the coupling of nuclear reactors and desalination systems, Final report of a coordinated research project 1999 -2003, IAEA-TECDOC-1444, Vienna (2005).

[11] INTERNATIONAL ATOMIC ENERGY AGENCY, Economics of nuclear desalination: New developments and site specific studies, Final results of a coordinated research project 2002-2006, IAEA-TECDOC-1561, Vienna (2007).

[12] INTERNATIONAL ATOMIC ENERGY AGENCY, Safety aspects of nuclear plants coupled with seawater desalination plants, IAEA-TECDOC-1235, Vienna (2001).

[13] CHIEN, C.L., Radiochemistry in nuclear power reactors, Nuclear Science Series NAS-NS-3119, National Academy Press, Washington, DC (1996).

[14] INTERNATIONAL ATOMIC ENERGY AGENCY, Nuclear heat applications: Design aspects and operating experience, IAEA-TECDOC-1056, IAEA, Vienna (1998).

[15] MURALEV, E.D., Tritium migration in nuclear desalination plants, International Journal of Nuclear Desalination **1** 1 (2003) 104.

[16] UNITED STATES DEPARTMENT OF ENERGY, DOE Handbook: Tritium Handling and Safe Storage, US DOE, Washington DC (1999).

[17] LIU, C.C., CHAO,J.H., LIN, C.C., Tritium release from nuclear power plants in Taiwan, Health Physics **84** 3 (2003) 361-367.

[18] CANADIAN NUCLEAR SAFETY COMMISSION, Standards and guidelines for tritium in drinking water. Available at: http://www.nuclearsafety.gc.ca/eng/readingroom/healthstudies/tritium/

[19] MURALEV, E.D., "Experience in the application of nuclear energy for desalination and industrial use in Kazakhstan", Nuclear heat applications: Design aspects and operating experience, IAEA-TECDOC-1056, IAEA, Vienna (1998) 361-368.

[20] Private Communication to V.Anastasov from P.K.Tewari (BARC), India Concerning the Environmental Impact of the Nuclear Desalination Facility, IAEA, Vienna (2008).

[21] HÜBNER, E., Nordostschweizerische Kraftwerke AG (NOK), pers. comm. (2008).
[22] KIRCH, N., SCHEIDLER, G., "Control of the Tritium Path in Process Heat HTR's", International Working Group on Gas-Cooled Reactors 13: Fission product release and transport in gas-cooled reactors, Berkeley Nuclear Laboratories, Berkeley (1985) 236-249.
[23] NATIONAL RESEARCH COUNCIL, Desalination: A National Perspective, The National Academies Press, Washington DC (2008).
[24] WORM, B., et al., Impacts of Biodiversity Loss on Ocean Ecosystem Services, Science **314** (2006) 787.
[25] UNITED NATIONS ENVIRONMENT PROGRAMME/MEDITERRANEAN ACTION PLAN, Sea Water Desalination in the Mediterranean, Assessment and Guidelines, UNEP/MAP, Athens (2003).
[26] PANKRATZ, T., An overview of seawater intake facilities for seawater desalination, The Future of Desalination in Texas **2**: Biennial Report on Water Desalination, Texas Water Development Board, (2004).
[27] MIRI, R., CHOUIKHI, A., Ecotoxicological marine impacts from seawater desalination plants, Desalination **182** (2005) 403-410.
[28] CALIFORNIA COASTAL COMMISSION, Seawater Desalination and the California Coastal Act, Staff Report (2004). Available at: http://www.coastal.ca.gov/energy/14a-3-2004-desalination.pdf
[29] CALIFORNIA DEPARTMENT OF WATER RESOURCES, California Desalination Planning Handbook (2008). Available at: http://www.owue.water.ca.gov/recycle/docs/Desal_Handbook.pdf
[30] BURGE, M.,. Making the case for desalination. In: Sun On San Diego. November 11th 2007. Available at: http://www.signonsandiego.com/news
[31] UNITED STATES ENVIRONMENTAL PROTECTION AGENCY, Cooling Water Intake Structures – Section 316(b). Final Regulations for Cooling Water Intake Structures at Large Power Plants (Phase II), Office of Water Fact Sheet (2004). Available at: http://www.epa.gov/waterscience/316b/phase2/phase2final-fs.pdf
[32] UNITED STATES ENVIRONMENTAL PROTECTION AGENCY, National Pollutant Discharge Elimination System: Suspension of Regulations Establishing Requirements for Cooling Water Intake Structures at Phase II Existing Facilities; Final Rule, 40 CFR Parts 122 and 125, US Govt Printing Office, Washington, DC (2007).
[33] UNITED STATES ENVIRONMENTAL PROTECTION AGENCY, National Pollutant Discharge Elimination System: Regulations Addressing Cooling Water Intake Structures for New Facilities; Final Rule, 40 CFR Parts 9, 122, et al., US Govt Printing Office, Washington, DC (2001).
[34] WORLD HEALTH ORGANISATION, Desalination for Safe Water Supply Draft Paper, WHO Press, Geneva (2007).
[35] INTERNATIONAL ATOMIC ENERGY AGENCY, Use of Nuclear Reactors for Seawater Desalination, IAEA-TECDOC-574, IAEA, Vienna (1990).
[36] SUPER, R., "An Overview of Flow Reduction Technologies for Reducing Aquatic Impacts at Cooling Water Intake Structures", A Symposium on Cooling Water Intake Technologies to Protect Aquatic Organisms, Proc. Symp., US EPA, Washington DC, (2003).
[37] CALIFORNIA WATER DESALINATION TASK FORCE, Management Practices for Feedwater Intakes and Concentrate Disposal for Seawater Desalination, Draft Issue Papers (2003). Available at: http://www.owue.water.ca.gov/recycle/desal/Docs/IssuePapers.htm
[38] GILLE, D., Seawater Intakes for Desalination Plants. Desalination **156** (2003) 249-256.

[39] UNION OF CONCERNED SCIENTISTS, Got Water?, Issue Brief (2007). Available at: www.ucsusa.org/clean_energy/nuclear_safety/got-water-nuclear-power.html
[40] CALIFORNIA ENERGY COMMISSION, Issues and Environmental Impacts Associated With Once-Through Cooling at California's Coastal Power Plants, Staff Report (2005). Available at: http://www.energy.ca.gov/2005publications/CEC-700-2005-013/CEC-700-2005-013.PDF
[41] HASSAN, A.M., JAMALUDDIN, A.T.M., ROWAILI, A., ABART, E., LOVO, R., Investigating intake system effectiveness with emphasis on a self-jetting well-point (SJWP) beachwell system, Desalination **123** (1999) 195-204.
[42] PETERS, T., PINTO, D., Seawater intake and pre-treatment/brine discharge – environmental issues, Desalination **221** (2008) 576-584.
[43] JONES, A.T., Can we reposition the preferred geological conditions necessary for an infiltration gallery? The development of a synthetic infiltration gallery, Desalination **221** (2008) 598-601.
[44] COOLEY, H., GLEICK, P.H., WOLFF, G., Desalination, With a Grain of Salt. A California Perspective., Pacific Institute, Oakland (2006).
[45] JINKS, S., "A Review of Impingement Survival Studies at Steam-Electric Power Stations", A Symposium on Cooling Water Intake Technologies to Protect Aquatic Organisms, Proc. Symp., US EPA, Washington DC, (2003).
[46] ELECTRIC POWER RESEARCH INSTITUTE, Water & Sustainability (Volume 3): US Water Consumption for Power Production – The Next Half Century, EPRI, Palo Alto (2002).
[47] UNITED STATES ENVIRONMENTAL PROTECTION AGENCY, Technical Development Document for the Final Regulations Addressing Cooling Water Intake Structures for New Facilities, US Govt. Printing Office, Washington, DC (2001).
[48] McLEAN, R., "State of Maryland Perspectives on Cooling Water Intake Technologies to Protect Aquatic Organisms", A Symposium on Cooling Water Intake Technologies to Protect Aquatic Organisms, Proc. Symp., US EPA, Washington DC, (2003).
[49] EINAV, R., HARUSSI, K., PERRY, D., The footprint of desalination processes on the environment, Desalination **152** (2002) 141-154.
[50] DAMITZ, B., FURUKAWA, D., TOAL, J., Desalination Feasibility Study in the Monterey Bay Region, Report prepared for AMBAG (2005). Available at: http://cdm266301.cdmhost.com/cdm4/item_viewer.php?CISOROOT=/p267501ccp2&CISOPTR=24
[51] BRINING, D.L., et al., Development of environmental standards for combined desalination/power generating stations in the Arabian Gulf region. Desalination **39** (1981) 255-260.
[52] INTERNATIONAL ATOMIC ENERGY AGENCY, Status of Nuclear Desalination in IAEA Member States, IAEA-TECDOC-1524, IAEA, Vienna (2007).
[53] CALIFORNIA ENERGY COMMISSION, Environmental Performance Report of California's Electrical Generation System, Staff Report (2005). Available at: http://www.energy.ca.gov/2005publications/CEC-700-2005-016/CEC-700-2005-016.PDF
[54] Private Communication to V.Anastasov from O.Orininskaya (MAEC), Kazakhstan Concerning the Environmental Impact of the Nuclear Desalination Facility, IAEA, Vienna (2008).

[55] RAIMONDI, P., Cooling Water System. Findings Regarding Clean Water Act Section 316(b). Diablo Canyon Power Plant. NPDES Permit Order RB3-2003-0009., Testimony to the California Regional Water Quality Control Board (10 Jul 2003). Available at: http://www.waterboards.ca.gov/centralcoast/water_issues/programs/diablo_canyon/docs/07_10_03_hearing/testimony/071003dr_raimonditestimony.pdf
[56] DAVIS, N., RAIMONDI, P., YORK, R., REINHARDT, J., Huntington Beach Units 3&4 Entrainment and Impingement Study Results, Mitigation Options, Staff and Working Group Recommendations, and AES's Response and Objections to the Recommendation, (2006). Available at: http://www.energy.ca.gov/sitingcases/huntingtonbeach/compliance/2006-07-14_STAFF_ANALYSIS.PDF
[57] LATTEMANN, S., HOEPNER, T., Environmental impact and impact assessment of seawater desalination, Desalination **220** (2008) 1-15.
[58] CLEAN AIR TASK FORCE, EPA's Decision to Exempt Older Power Plants from New Water-using Technology Requirements, Fact Sheet (2004). Available at: http://www.catf.us/publications/factsheets/20040216-EPA_PP_Decision.pdf
[59] YOUNOS, T., Environmental Issues of Desalination, Journal of Contemporary Water Research & Education **132** (2005) 11-18.
[60] TAFT, E., COOK, T., "An Overview of Fish Protection Technologies and Cooling Water Intake Structures", A Symposium on Cooling Water Intake Technologies to Protect Aquatic Organisms, Proc. Symp., US EPA, Washington DC, (2003).
[61] SAN FRANCISCO BAY CONSERVATION AND DEVELOPMENT COMMISSION, Desalination and San Francisco Bay, SFBCDC, San Francisco (2005).
[62] RAIMONDI, P.A., The Science of Mitigation, California State Water Resources Control Board Academy Course (2007). Available at: http://www.swrcb.ca.gov/academy/courses/coastalpp/item11_thescienceofmitigation_raimondi.pdf
[63] PURNAMA, A., Al-BARWANI, H.H., SMITH, R., Calculating the environmental cost of seawater desalination in the Arabian marginal seas, Desalination **185** (2005) 79-86.
[64] BLENINGER, T., JIRKA, G.H., Modelling and environmentally sound management of brine discharges from desalination plants, Desalination **221** (2008) 585-597.
[65] Convention on the protection of the Mediterranean Sea against pollution (Barcelona Convention), Official Journal of the European Union **L 240** (1977) 3-11.
[66] UNITED STATES ENVIRONMENTAL PROTECTION AGENCY, National Pollutant Discharge Elimination System: Criteria and Standards, 40 CFR Part 125, US Govt Printing Office, Washington, DC (2008).
[67] WORLD BANK, Pollution Prevention and Abatement Handbook 1998: toward cleaner production, WB, Washington, DC (1999).
[68] JIRKA, G.H., BLENINGER, T., BURROWS, R., LARSEN, T.,. Environmental Quality Standards in the EC-Water Framework Directive: Consequences for Water Pollution Control for Point Sources, European Water Management Online (EWMO) (2004). Available at: http://www.ewaonline.de/journal/2004_01h.pdf
[69] UNITED STATES ENVIRONMENTAL PROTECTION AGENCY, Allocated Impact Zones For Areas Of Non-Compliance, US Govt. Printing Office, Washington, DC (1995).

[70] INTERNATIONAL ATOMIC ENERGY AGENCY, Dispersion of Radioactive Material in Air and Water and Consideration of Population Distribution in Site Evaluation for Nuclear Power Plants, Safety Guide, Safety Standards Series No. NS-G-3.2, IAEA, Vienna (2002).
[71] LATTEMANN, S., HOEPNER, T., Seawater Desalination – Impacts of Brine and Chemical Discharge on the Marine Environment, Desalination Publications, L'Aquila (2003).
[72] MINATO, A., Present and future activities of nuclear desalination in Japan, Int. J. Nuclear Desalination **1** 2 (2004) 259.
[73] WORLD BANK, Seawater and brackish water desalination in the Middle East, North Africa and Central Asia, A review of key issues and experience in six countries, Final report, WB Working Paper (2004). Available at:
http://www-wds.worldbank.org/
[74] SAUVET-GOICHON, B., Ashkelon desalination plant – A successful challenge, Desalination **203** (2007) 75-81.
[75] HODGKIESS, T., OLDFIELD, J.W., HOEPNER, T., AHMED, M., Assessment of the Composition of Desalination Plant Disposal Brines, MEDRC, Muscat (2003).
[76] HOEPNER, T., A procedure for environmental impact assessment (EIA) for desalination plants, Desalination **124** (1999) 1-12.
[77] GLOBAL WATER INTELLIGENCE/INTERNATIONAL DESALINATION ASSOCIATION, IDA Desalination Plant Inventory. Available at:
http://www.desaldata.com/projects
[78] SADHWANI, J.J., VEZA, J.M., SANTANA, C., Case studies on environmental impact of seawater desalination, Desalination **185** (2005) 1-8.
[79] ALAMEDDINE, I., El-FADEL, M., Brine discharge from desalination plants: a modelling approach to an optimized outfall design, Desalination **214** (2007) 241-260.
[80] BOYER, T.P., et al., "World Ocean Database 2005", NOAA Atlas NESDIS 60 (LEVITUS, S., Ed.), US Government Printing Office, Washington, DC (2006) DVDs.
[81] FERNANDEZ-TORQUEMADA, Y., SANCHEZ-LIZASO,J.L., GONZALEZ-CORREA, J.M., Preliminary results of the monitoring of the brine discharge produced by the SWRO desalination plant of Alicante (SE Spain), Desalination **182** (2005) 395-402.
[82] PEREZ TALAVERA, J.L., QUESADA RUIZ, J.J., Identification of the mixing processes in brine discharges carried out in Barranco del Toro Beach, south of Gran Canaria (Canary Islands), Desalination **139** (2001) 277-286.
[83] SATIN, M., A Glass Half Full, Water Conditioning & Purification Magazine **49** 4 (2007).
[84] TSIOURTIS, N.X., Desalination and the Environment, Desalination **141** (2001) 223-236.
[85] LE DIRACH, J., NISAN, S., POLETIKO, C., Extraction of strategic materials from the concentrated brine rejected by integrated nuclear desalination systems, Desalination **182** (2005) 449-460.
[86] FRANCO, J., IES technology produces potable water out of seawater brine, Khaleej Times (7 Jul. 2007).
[87] MONTAGUE, C.L., LEY, J.A., A Possible Effect of Salinity Fluctuation on Abundance of Benthic Vegetation and Associated Fauna in Northeastern Florida Bay, Estuaries **16** 4 (1993) 703-714.
[88] ISO, S., SUIZU, S., MAEJIMA, A., The lethal effect of hypertonic solutions and avoidance of marine organisms in relation to discharged brine from a desalination plant, Desalination **97** (1994) 389-399.

[89] VOUTCHKOV, N., Innovative Method to Evaluate Tolerance of Marine Organisms, Desalination & Water Reuse **16** 2 (2006) 29-34.
[90] DEL BENE, J.V., JIRKA, G., LARGIER, J., Ocean Brine Disposal, Desalination **97** (1994) 365-372.
[91] KINNE, O., ”Marine Ecology”, Environmental Factors Part 1 Vol. 1 (KINNE, O., Ed.), Wiley, New York (1970) 321-363.
[92] J.L. Sanchez-Lizaso, J. Romero, J. Ruiz, E. Gacia, J.L. Buceta, O. Invers, Y. Fernandez Torquemada, J. Mas, A. Ruiz-Mateo, M. Manzanera, "Salinity tolerance of the Mediterranean seagrass Posidonia Oceanica: recommendations to minimize the impact of brine discharges from desalination plants", Desalination, No.221, pp. 602-607, 2008.
[93] CALIFORNIA REGIONAL WATER QUALITY CONTROL BOARD, Waste Discharge Requirements Order No. RB3-2003-0009. NPDES No.CA0003751 for PG&E Company. Diablo Canyon Power Plant 1 and 2, CRWQCB, San Luis Obispo (2003).
[94] COOPERATIVE RESEARCH CENTRE REEF RESEARCH CENTRE, The temperature tolerance of corals, CRC Reef Research Centre Brochure (2005). Available at:
http://www.reef.crc.org.au/publications/brochures/temperaturetolerance.htm
[95] KADYRZHANOV, K.K., LUKASHENKO, S.N., LUSHCHENKO, V.N., “Assessment of Environmental Impact of Reactor Facilities in Kazakhstan”, Safety Related Issues of Spent Nuclear Fuel Storage, NATO Security through Science Series, Springer Netherlands, Dordrecht (2007).
[96] BINDOFF, N.L., et al., ”Observations: Oceanic Climate Change and Sea Level”, Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (SOLOMON, S., et al., Eds.), Cambridge University Press, Cambridge and New York (2007) Ch. 5.
[97] GATTUSO, J.P., ALLEMAND, D., FRANKIGNOULLE, M., Photosynthesis and calcification at cellular, organismal and community levels: a review on interactions and control by carbonate chemistry, Am. Zool 39 (1999) 160-183.
[98] LANGDON, C., et al., Effect of calcium carbonate saturation state on the calcification rates of an experimental coral reef, Global Biogeochem. Cycles 14 (2000) 639-654.
[99] LANGDON, C., et al., Effect of elevated CO_2 on the community metabolism of an experimental coral reef, Global Biogeochem. Cycles 17 (2003) 1-14.
[100] MARUBINI, F., FERRIER-PAGES, C., CUIF, J.P., Suppression of skeletal growth in scleractinian corals by decreasing ambient carbonate-ion concentration: a cross-family comparison. Proc. R. Soc. Lond. B 270 (2003) 179-184.
[101] MAUGUIN, G., CORSIN, P., Concentrate and other waste disposals from SWRO plants: characterization and reduction of their environmental impact, Desalination **182** (2005) 355-364.
[102] GAZEAU, F., et al., Impact of elevated CO2 on shellfish calcification, Geophys. Res. Lett. 34 (2007) L07603.
[103] EUROPEAN COMMISSION SCIENTIFIC COMMITTEE ON HEALTH AND ENVIRONMENTAL RISKS, Scientific Opinion on the Risk Assessment Report on Sodium Hypochlorite. Environmental Part, European Commission, Brussels (2008).
[104] SUNDA, W.G., Trace metal interactions with marine phytoplankton, Biol. Oceanogr. 40 (2001) 1404-1417.
[105] JONES, R.J., HOEGH-GULDBERG, O., Diurnal changes in the photochemical efficiency of the symbiotic dinoflagellate of corals, Plant Cell Environ. 24 (2001) 89-99.

[106] HASHIM, A., HAJJAJ, M., Impact of desalination plants fluid effluents on the integrity of seawater, with the Arabian Gulf in perspective, Desalination **182** (2005) 373-393.
[107] SAFRAI, I., ZASK, A., Reverse osmosis desalination plants - marine environmentalist regulator point of view, Desalination **220** (2008) 72-84.
[108] BAY, S., GREENSTEIN, D., Toxic Effects of Elevated Salinity and Desalination Waste Brine, Southern California Coastal Water Research Projects Annual Report (1993). Available at: ftp://ftp.sccwrp.org/pub/download/DOCUMENTS/AnnualReports/1992_93AnnualReport/ar14.pdf
[109] MOHAMED, A.M.O., MARAQA, M., Al HANDHALY, J., Impact of land disposal of reject brine from desalination plants on soil and groundwater, Desalination **182** (2005) 411-433.
[110] CAMPBELL, R.L., JONES, A.T., Appropriate disposal of effluent from coastal desalination facilities, Desalination **182** (2005) 365-372.
[111] XU, J., et al., A pilot study of UF pretreatment without any chemicals for SWRO desalination in China, Desalination 207 (2007) 216-226.
[112] PETERSON, P.F., Roles and needs for simulation for the development of new reactors, presentation at the Nuclear Fuel Cycle Workshop, Lawrence Livemore National Laboratory, 2005.
[113] AUSUBEL, J.H., Renewable and nuclear heresies, International Journal of Nuclear Governance, Economy and Ecology, **1** 3 (2007) 229.
[114] LAUGHTON, M.A., Renewable Energy Sources: Watt Committee: report number 22, Elsevier Applied Science, London (1990).
[115] NUCLEAR ENERGY AGENCY, INTERNATIONAL ENERGY AGENCY, ORGANISATION FOR ECONONOMIC CO-OPERATION AND DEVELOPMENT, Projected Costs of Generating Electricity: 2005 Update, OECD Publishing, Paris (2005).
[116] MRW & ASSOCIATES INC., AB 1632 Assessment of California's Operating Nuclear Plants. Appendices (2008). Available at: http://www.energy.ca.gov/2008publications/CEC-100-2008-005/CEC-100-2008-005-F.PDF
[117] STOVER, R., CRISP, G., Environmentally sound desalination at the Perth seawater desalination plant, Energy Recovery Inc., paper presented at Enviro08: Australia's Environmental and Sustainability Conference and Exhibition, Melbourne (2008). Available at: http://www.energyrecovery.com/news/pdf_ThePerthSaltwaterDesalinationPlant.php
[118] SHIKLOMANOV, I.A., World water resources and their use, International Hydrological Programme Database (1999). Available at: http://webworld.unesco.org/water/ihp/db/shiklomanov/part'3/HTML/Tb_18.html
[119] MINTON, J., presentation at the Panel Discussion: Ocean Water Desalination in California: Needs versus Wants, Conference on California and the World Ocean '06, Long Beach (2006).
[120] MEERGANZ VON MEDEAZZA, G.L., "Direct" and socially-induced environmental impacts of desalination, Desalination **185** (2005) 57-70.
[121] INTERNATIONAL ENERGY AGENCY, Key World Energy Statistics 2007, OECD/IEA, Paris (2007).
[122] MISRA, B.M., Alternative energy sources for seawater desalination, International Journal of Nuclear Desalination **2** 4 (2007) 372-382.

[123] INSTITUTO NACIONAL DE ESTADISTICA, Survey on Water Supply and Treatment. Year 2006, Press release (2008). Available at: http://www.ine.es/en/prensa/np511_en.pdf
[124] WORLD ENERGY COUNCIL, Performance of Generating Plant: Managing the Changes, WEC, London (2007).
[125] ROGNER, H.H., Let the Market Decide, IAEA Bulletin **49** 1 (2007) 29.
[126] NUCLEAR ENERGY AGENCY, ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT, Nuclear Electricity Generation: What Are the External Costs?, OECD Publishing, Paris (2003).
[127] AUSTRALIAN ASSOCIATED PRESS, Desalination plant claims questioned, The West Australian (26 Jun. 2008).
[128] UNITED STATES GEOLOGICAL SURVEY, Radioactive Elements in Coal and Fly Ash: Abundance, Forms, and Environmental Significance, U.S.G.S. Fact Sheet FS-163-97 (1997). Available at: http://pubs.usgs.gov/fs/1997/fs163-97/FS-163-97.pdf
[129] GABBARD, A., Coal Combustion: Nuclear Resource or Danger, ORNL Review **26** 3&4 (1993) 24-33.
[130] INTERNATIONAL ATOMIC ENERGY AGENCY, Site Evaluation for Nuclear Installations, Safety Requirements, Safety Standards Series No. NS-R-3, IAEA, Vienna (2003).
[131] HOEPNER, T., WINDELBERG, J., Elements of environmental impact studies on coastal desalination plants, Desalination **108** (1996) 11-18.
[132] UNITED STATES ENVIRONMENTAL PROTECTION AGENCY, Mangrove Swamps, Wetlands Fact Sheets (2001). Available at: http://www.epa.gov/owow/wetlands/types/mangrove.html
[133] SKOWRONSKI, M., pers. comm., cited in CALIFORNIA COASTAL COMMISSION, Seawater Desalination in California (1993). Available at: http://www.coastal.ca.gov/desalrpt/dtitle.html
[134] KEELEY, G., Drought ignites Spain's 'water war', The Observer (6 Apr. 2008). Available at: http://www.guardian.co.uk/world/2008/apr/06/spain
[135] DICKIE, P., Making Water. Desalination: Option or Distraction for a Thirsty World?, WWF, Gland (2007).
[136] ELHADJ, E., Saudi Arabia's Agricultural Project: From Dust to Dust, Meria **12** 2 (2008). Available at: http://www.meriajournal.com/en/asp/journal/2008/june/elhadj/index.asp
[137] WORLD HEALTH ORGANIZATION/UNITED NATIONS CHILDREN'S FUND, Global Water Supply and Sanitation Assessment 2000 Report, WHO/UNICEF (2000). Available at: http://www.who.int/docstore/water_sanitation_health/Globassessment/GlobalTOC.htm
[138] GLEICK, P., The human right to Water, Water Policy **1** (1999) 487-503.
[139] RENEWABLE ENERGY RESEARCH LABORATORY, Wind Power: Capacity Factor, Intermittency, and what happens when the wind doesn't blow?, Community Wind Power Fact Sheet 2a (2006). Available at: http://www.ceere.org/rerl/about_wind/RERL_Fact_Sheet_2a_Capacity_Factor.pdf
[140] MEGAHED, M.M., An overview of nuclear desalination: history and challenges, International Journal of Nuclear Desalination **1** 1 (2003) 2-18.
[141] LIDSKY, L.M., MILLER, M.M., Nuclear Power and Energy Security. A revised Strategy for Japan, paper presented at PARES Workshop: Energy Security in Japan, Tokyo, 1998.

[142] BEZDEK, R.H., WENDLING, R.M., The impacts of nuclear facilities on property values and other factors in the surrounding communities, International Journal of Nuclear Governance, Economy and Ecology **1** 1 (2006) 122-144.

[143] CITY OF CAPE TOWN, Five Year Plan for Cape Town. Integrated Development Plan (IDP) (2007). Available at: http://www.capetown.gov.za/en/IDP/Documents/idp/Previous_IDP/coct_IDP_20072008.pdf

[144] BIEDSCHEID, J.A., DEVARAKONDA, M., How Far Are We from Public Acceptance?, Nuclear Plant Journal **23** 3 (2005).

[145] SOKOLOV, Y., McDONALD, A., Nuclear Power–Global Status and Trends (2006). Available at: http://www.iaea.org/OurWork/ST/NE/Pess/assets/nuclear_energy_Alan_Sokolov06.pdf

[146] ENERGY INFORMATION ADMINISTRATION, Annual Energy Outlook 2009 Early Release Overview, EIA (2009). Available at: http://www.eia.doe.gov/oiaf/aeo/

[147] EUROPEAN COMMISSION, Attitudes towards radioactive waste, Special Eurobarometer **297** (2008). Available at: http://ec.europa.eu/public_opinion/archives/ebs/ebs_297_en.pdf

[148] BISCONTI, A.S., US Public Support for Nuclear Energy Soars to Record High, Perspective on Public Opinion Newsletter, NEI (2008). Available at: http://www.nei.org/filefolder/POPO_November2008.pdf

[149] GLOBAL WATER INTELLIGENCE, Global Water Market 2008: Opportunities in Scarcity and Environmental Regulation, Media Analytics Limited, Oxford (2007).

[150] DOLNICAR, S., SCHAFER, A.I., Desalination and Recycling: Australians raise health, environment and cost concerns, Desalination & Water Reuse, **16** 4 (2007) 10-15.

[151] BARAK, A., KOCHETKOV, L.A., CRIJNS, M.J., KHALID, M., Nuclear desalination: Experience, needs, and prospects, IAEA Bulletin **3** (1990) 43-48.

[152] WORLD NUCLEAR NEWS, Nuclear power plans for Kazakhstan firm up, WNN (22 Nov. 2007). Available at: http://www.world-nuclear-news.org/newsarticle.aspx?id=14444&LangType=2057&terms=aktau

[153] UNITED NATIONS ECONOMIC COMMISSION FOR EUROPE, Parties and signatories to the Convention, Aarhus Convention: Convention on Access to Information, Public Participation in Decision-making and Access to Justice in Environmental Matters (10 Feb. 2009). Available at: http://www.unece.org/env/pp/ratification.htm

[154] INTERNATIONAL ATOMIC ENERGY AGENCY, Nuclear Power and Sustainable Development, IAEA brochure, Vienna (2006)

[155] OECD/NUCLEAR ENERGY AGENCY, Society and nuclear energy: Towards a better understanding, OECD, Paris (2002). Available at: www.nea.fr/html/ndd/reports/2002/nea3677-society.pdf

[156] INTERNATIONAL ATOMIC ENERGY AGENCY, Milestones in the Development of a National Infrastructure for Nuclear Power, IAEA Nuclear Energy Series No. NG-G-3.1, IAEA, Vienna (2007).

[157] INTERNATIONAL ATOMIC ENERGY AGENCY, Status of innovative small and medium sized reactor designs 2005, reactors with conventional refuelling schemes, IAEA-TECDOC-1485, Vienna (2006).

[158] INTERNATIONAL ATOMIC ENERGY AGENCY, Status of small reactor designs without on-site refuelling, IAEA-TECDOC-1536, Vienna (2007).

[159] KUZNETSOV, V., Design and Deployment Strategies for SMRs to Overcome Loss of Economies of Scale and Incorporate Increased Proliferation Resistance and Security, presentation at COE INES International Symposium INES-2, Yokohama (2006).
[160] STEINBECK, J., HEDGEPETH, J., RAIMONDI, P., CAILLIET, G., MAYER, D., Assessing Power Plant Cooling Water Intake System Entrainment Impacts, Consultant Report (2007). Available at: http://www.energy.ca.gov/2007publications/CEC-700-2007-010/CEC-700-2007-010.PDF
[161] TENERA ENVIRONMENTAL, Appendix C Marin Municipal Water District Desalination Facility Intake Effects. TENERA Environmental, Lafayette CA (2007).
[162] CALIFORNIA ENERGY COMMISSION, Improving Assessment of Entrainment Impacts through Models of Coastal and Estuarine Withdrawal Zones, PIER Energy-Related Environmental Research Project Summary. Available at: http://www.energy.ca.gov/research/environmental/project_summaries/PS_500-04-025_LARGIER.PDF
[163] GOODYEAR, C.P., Entrainment impact estimates using the equivalent adult approach. Report No. FWS/OBS-78/65, United States Fish and Wildlife Service, Washington DC (1978).
[164] HENDERSON, P.A., SEABY, R.M.H., SOMES, J.R., A comparison of ecological impacts of power plant once-through, evaporative and dry cooling systems on fish impingement and entrainment, Pisces Conservation Ltd., Lymington (2003).
[165] HENDERSON, P.A., On the structure of the inshore fish community of England and Wales, Journal of the biological association of the United Kingdom **69** (1989) 145-163.
[166] BARKER, B., Running dry at the power plant, EPRI Journal, Summer (2007).
[167] OKADA, S., MOMOSHIMA, N., Overview of tritium: characteristics, sources, and problems, Health Physics **65** 6 (1993) 595-609.
[168] CALIFORNIA ENVIRONMENTAL PROTECTION AGENCY, Public Health Goal for Tritium in Drinking Water, CEPA Office of Environmental Health Hazard Assessment (2006). Available at: http://oehha.ca.gov/water/phg/pdf/phgtritium030306.pdf
[169] UNITED STATES DEPARTMENT OF ENERGY, DOE Handbook: Primer on Tritium Safe Handling Practices, US DOE, Washington DC (1994).
[170] VĂSARU, G., Tritium Isotope Separation, CRC Press, Boca Raton (1993).
[171] KAUFMAN, S., LIBBY, W.F., The Natural Distribution of Tritium, Physical Review **93** 6 (1954) 1337-1344.
[172] TAKASHIMA, Y., Environmental tritium. Its behaviour and application, Radioisotopes 40 (1991) 520-530.
[173] Swiss Federal Office of Public Health, Environmental radioactivity and radiation exposure in Switzerland in 2003, Division of Radiation Protection, Berne (2004).
[174] PAUNESCU, N., COTARLEA, M., GALERIU, D., MARGINEANU, R., MOCANU, N., Evaluation of environmental tritium level in preoperational period of Cernavoda CANDU Nuclear Power Plant, Journal of Radioanalytical and Nuclear Chemistry **239** 3 (1999) 465-470.
[175] UNITED STATES ENVIRONMENTAL PROTECTION AGENCY, RadNet. Available at: http://oaspub.epa.gov/enviro/erams_query.simple_query
[176] WEAVER, C.L., HARWARD, E.D., PETERSON, H.T., Tritium in the Environment From Nuclear Power Plants, Public Health Reports **84** 4 (1969) 363-372.

[177] UNITED STATES ENVIRONMENTAL PROTECTION AGENCY, Radionuclides Notice of Data Availability Technical Support Document, US EPA (2000). Available at: http://www.epa.gov/OGWDW/radionuclides/pdfs/regulation_radionuclides_rulemaking_techsupportdoc.pdf
[178] CENTRE FOR ENVIRONMENT, FISHERIES AND AQUACULTURE SCIENCE, Radioactivity in Food and the Environment, CEFAS, Lowestoft (2006).
[179] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, ICRP Publication 60: 1990 Recommendations of the ICRP, Pergamon Press, Oxford (1991).
[180] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, ICRP Publication 82: Protection of the Public in Situations of Prolonged Radiation Exposure, Pergamon Press, Oxford (2000).
[181] UNITED STATES ENVIRONMENTAL PROTECTION AGENCY, Water on Tap: What You Need to Know, Diane Publishing, Darby (2003).
[182] WORLD HEALTH ORGANIZATION, Guidelines for Drinking-water Quality. First Addendum to Third Edition. Volume 1: Recommendations, WHO Press, Geneva (2006).
[183] MELINTESCU, A., GALERIU, D., TAKEDA, H., Reassessment of Tritium Dose Coefficients for the General Public, Radiation Protection Dosimetry **127** 1-4 (2007) 153-157.
[184] UNITED STATES NUCLEAR REGULATORY COMMISSION, Regulatory Guide 1.109: Calculation of Annual Doses to Man from Routine Releases of Reactor Effluents for the Purpose of Evaluating Compliance with 10 CFR Part 50 Appendix I, NRC Office of Standards Development, US Govt. Printing Office (1977).
[185] OFFICE OF PUBLIC SECTOR INFORMATION, The Water Supply (Water Quality) Regulations (Northern Ireland) 2007 No.147, OPSI (2007). Available at: http://www.opsi.gov.uk/sr/sr2007/nisr_20070147_en_9#f01002
[186] ZAKRZEWSKA-TRZNADEL, G., Tritium removal from water solutions, Desalination 200 (2006) 737-738.
[187] ELECTRIC POWER RESEARCH INSTITUTE, EPRI Tritium Management Model. Project Summary Report, EPRI, Palo Alto (2005).
[188] INTERNATIONAL ATOMIC ENERGY AGENCY, Nuclear Power Reactors in the World, Reference Data Series 2, IAEA, Vienna (2006).
[189] OSTLUND, H.H., LUNDGREN, L.B., Stockholm natural tritium measurements, Tellus **16** 1 (1964) 118.
[190] INTERNATIONAL ATOMIC ENERGY AGENCY, Management of Waste Containing Tritium and Carbon-14, IAEA-TRS-421, IAEA, Vienna (2004).
[191] LUYKX, F., FRASER, G., Tritium releases from nuclear power plants and nuclear fuel reprocessing plants, Radiation Protection Dosimetry **16** 1-2 (1986) 31-36.
[192] TAKAHASHI, T., “Measurement of Tritium at Natural levels”, Nuclear Science of Japan 49, JAERI, Tokai-mura (1966).
[193] BOSS, C.R., ALLSOP, P.J., Radioactive Effluents from CANDU 6 Reactors During Normal Operation, Rep. AECL-11506, Atomic Energy of Canada Ltd, Chalk River (1995).
[194] McKAY, H.A.C., Tritium immobilization, Eur. Appl. Res. Rep., Nucl. Sci. **1** (1979) 599-711.
[195] YOOK, D., LEE, K.J., LEE, Y., HONG, D., Estimation of tritium behaviour in the pebble bed type gas cooled reactor for hydrogen production, Journal of Nuclear Science and Technology **43** 12 (2006) 1522-1529.
[196] INTERNATIONAL ATOMIC ENERGY AGENCY, Safe Handling of Tritium. Review of Data and Experience, IAEA-TRS-324, IAEA, Vienna (1991).

[197] STREHLOW, R.A., SAVAGE, H.C., The permeation of hydrogen isotopes through structural metals at low pressures and through metals with oxide film barriers, Nuclear Technology **22** (1974) 127-137.
[198] RÖHRIG, H.D., FISCHER, P.G., HECKER, R., Tritium Balance in High-Temperature Gas-Cooled Reactors, Journal of the American Ceramic Society **59** 7-8 (2006) 316-320.
[199] NATIONAL COUNCIL ON RADIATION PROTECTION AND MEASUREMENTS, Tritium in the environment, NCRP, Bethesda (1979).
[200] BALONOV, M.I., MUKSINOVA, K.N., MUSHKACHEVA, G.S., Tritium radiobiological effects in mammals: review of experiments of the last decade in Russia, Health Physics **65** 6 (1993) 713-726.
[201] STRAUME, T., Tritium Risk Assessment, Health Physics **65** 6 (1993): 673-682.
[202] DOBSON, R.L., KWAN, T.C., The RBE of Tritium Radiation Measured in Mouse Oocytes: Increase at Low Exposure Levels, Radiation Research 66 (1976) 615-625.
[203] PRESTWICH, W. V.; KWOK, C.S., A reanalysis of microdosimetric data pertaining to the quality factor of tritium, Health physics **65** 2 (1993) 190-192.
[204] CARSTEN, A.L., et al., "Summary update of the Brookhaven tritium toxicity program with emphasis on recent cytogenetic and life-shortening studies", Proceedings of the third Japan-US workshop: Tritium radiobiology and health physics (OKADA, S., Ed.), Institute of Plasma Physics. Nagoya University, Nagoya (1989) 239-250.
[205] JONES, D.C., KREBS, J.S., SASMORE, D.P., MITOMA, C., Evaluation of neonatal squirrel monkeys receiving tritiated water throughout gestation. Radiation Research 83 (1980) 592-606.
[206] RADFORD, E., Hearings on the Safety of Ontario's Nuclear Reactors, Testimony to the Select Committee on Ontario Hydro Affairs, cited in Health Dangers of Tritium Emissions Part 2, Canadian Coalition for Nuclear Responsibility. Available at: http://www.ccnr.org/tritium_2.html#radf
[207] UNITED NATIONS SCIENTIFIC COMMITTEE ON THE EFFECTS OF ATOMIC RADIATION, Sources and Effects of Ionizing Radiation, United Nations, New York (1994).
[208] UNITED STATES ENVIRONMENTAL PROTECTION AGENCY, Cancer Risk Coefficients for Environmental Exposure to Radionuclides. Federal Guidance Report No. 13, US EPA, Washington (1999).
[209] UNITED NATIONS SCIENTIFIC COMMITTEE ON THE EFFECTS OF ATOMIC RADIATION, Genetic and somatic effects of ionizing radiation, United Nations, New York (1986).
[210] UNITED NATIONS SCIENTIFIC COMMITTEE ON THE EFFECTS OF ATOMIC RADIATION, Sources, effects and risks of ionizing radiation, United Nations, New York (2000).
[211] MURALEV, E.D., et al, Experience gained in the operation and maintenance of the nuclear desalination plant in Aktau, Kazakhstan, Proceedings of an IAEA symposium, Taejon, Republic of Korea, 26 – 30 May 1997, Paper IAEA-SM-347/16, Vienna (1997).
[212] INTERNATIONAL ATOMIC ENERGY AGENCY, Options identification programme for demonstration of nuclear desalination, IAEA-TECDOC-898, Vienna (1996).
[213] GOTO, T., Operating experience gained with nuclear desalination plants by Japanese electric power companies, Proceedings of an IAEA symposium, Taejon, Republic of Korea, 26 – 30 May 1997, Paper IAEA-SM-347/15, Vienna (1997).

[214] MACIVER, A., et al, New trend in desalination for Japanese nuclear power plants, based on multiple effect distillation, with vertical titanium plate falling film heat transfer configuration, Desalination 182, pg 221 – 228 (2005).
[215] PANICKER, S.T., TEWARI, P.K., Safety and reliability aspects of seawater reverse osmosis desalination plant of nuclear desalination demonstration project, Int. J. Nuclear Desalination, Vol. 2, No. 3, (2007).
[216] PRATO, T., et al, Production of high purity water from seawater, Water Quality Products, Vol. 7 No. 3, March (2002).

CONTRIBUTORS TO DRAFTING AND REVIEW

Anastasov, V.	Private Consultant, The Former Yugoslav Republic of Macedonia
Betti, M.	International Atomic Energy Agency
Boisson, F.	International Atomic Energy Agency
Depisch, F.	Consultant, Austria
Houlbreque, F.	International Atomic Energy Agency
Jeffree, R.	International Atomic Energy Agency
Khamis, I.	International Atomic Energy Agency
Lattemann, S.	German Federal Environmental Agency, Germany
Miquel, J.C.	International Atomic Energy Agency
Nisan, S.	Nisan Desalination Services (NDS), France
Tewari, P.K.	Bhabha Atomic Research Centre (BARC), India

IAEA
International Atomic Energy Agency

Where to order IAEA publications

In the following countries IAEA publications may be purchased from the sources listed below, or from major local booksellers. Payment may be made in local currency or with UNESCO coupons.

Australia
DA Information Services, 648 Whitehorse Road, Mitcham Victoria 3132
Telephone: +61 3 9210 7777 • Fax: +61 3 9210 7788
Email: service@dadirect.com.au • Web site: http://www.dadirect.com.au

Belgium
Jean de Lannoy, avenue du Roi 202, B-1190 Brussels
Telephone: +32 2 538 43 08 • Fax: +32 2 538 08 41
Email: jean.de.lannoy@infoboard.be • Web site: http://www.jean-de-lannoy.be

Canada
Bernan Associates, 4611-F Assembly Drive, Lanham, MD 20706-4391, USA
Telephone: 1-800-865-3457 • Fax: 1-800-865-3450
Email: order@bernan.com • Web site: http://www.bernan.com

Renouf Publishing Company Ltd., 1-5369 Canotek Rd., Ottawa, Ontario, K1J 9J3
Telephone: +613 745 2665 • Fax: +613 745 7660
Email: order.dept@renoufbooks.com • Web site: http://www.renoufbooks.com

China
IAEA Publications in Chinese: China Nuclear Energy Industry Corporation, Translation Section, P.O. Box 2103, Beijing

Czech Republic
Suweco CZ, S.R.O. Klecakova 347, 180 21 Praha 9
Telephone: +420 26603 5364 • Fax: +420 28482 1646
Email: nakup@suweco.cz • Web site: http://www.suweco.cz

Finland
Akateeminen Kirjakauppa, PL 128 (Keskuskatu 1), FIN-00101 Helsinki
Telephone: +358 9 121 41 • Fax: +358 9 121 4450
Email: akatilaus@akateeminen.com • Web site: http://www.akateeminen.com

France
Form-Edit, 5, rue Janssen, P.O. Box 25, F-75921 Paris Cedex 19
Telephone: +33 1 42 01 49 49 • Fax: +33 1 42 01 90 90 • Email: formedit@formedit.fr

Lavoisier SAS, 14 rue de Provigny, 94236 Cachan Cedex
Telephone: + 33 1 47 40 67 00 • Fax +33 1 47 40 67 02
Email: livres@lavoisier.fr • Web site: http://www.lavoisier.fr

Germany
UNO-Verlag, Vertriebs- und Verlags GmbH, August-Bebel-Allee 6, D-53175 Bonn
Telephone: +49 02 28 949 02-0 • Fax: +49 02 28 949 02-22
Email: info@uno-verlag.de • Web site: http://www.uno-verlag.de

Hungary
Librotrade Ltd., Book Import, P.O. Box 126, H-1656 Budapest
Telephone: +36 1 257 7777 • Fax: +36 1 257 7472 • Email: books@librotrade.hu

India
Allied Publishers Group, 1st Floor, Dubash House, 15, J. N. Heredia Marg, Ballard Estate, Mumbai 400 001,
Telephone: +91 22 22617926/27 • Fax: +91 22 22617928
Email: alliedpl@vsnl.com • Web site: http://www.alliedpublishers.com

Bookwell, 24/4800, Ansari Road, Darya Ganj, New Delhi 110002
Telephone: +91 11 23268786, +91 11 23257264 • Fax: +91 11 23281315
Email: bookwell@vsnl.net • Web site: http://www.bookwellindia.com

Italy
Libreria Scientifica Dott. Lucio di Biasio “AEIOU”, Via Coronelli 6, I-20146 Milan
Telephone: +39 02 48 95 45 52 or 48 95 45 62 • Fax: +39 02 48 95 45 48

Japan
Maruzen Company, Ltd., 13-6 Nihonbashi, 3 chome, Chuo-ku, Tokyo 103-0027
Telephone: +81 3 3275 8582 • Fax: +81 3 3275 9072
Email: journal@maruzen.co.jp • Web site: http://www.maruzen.co.jp

Korea, Republic of
KINS Inc., Information Business Dept. Samho Bldg. 2nd Floor, 275-1 Yang Jae-dong SeoCho-G, Seoul 137-130
Telephone: +02 589 1740 • Fax: +02 589 1746
Email: sj8142@kins.co.kr • Web site: http://www.kins.co.kr

Netherlands
Martinus Nijhoff International, Koraalrood 50, P.O. Box 1853, 2700 CZ Zoetermeer
Telephone: +31 793 684 400 • Fax: +31 793 615 698 • Email: info@nijhoff.nl • Web site: http://www.nijhoff.nl

Swets and Zeitlinger b.v., P.O. Box 830, 2160 SZ Lisse
Telephone: +31 252 435 111 • Fax: +31 252 415 888 • Email: infoho@swets.nl • Web site: http://www.swets.nl

New Zealand
DA Information Services, 648 Whitehorse Road, MITCHAM 3132, Australia
Telephone: +61 3 9210 7777 • Fax: +61 3 9210 7788
Email: service@dadirect.com.au • Web site: http://www.dadirect.com.au

Slovenia
Cankarjeva Zalozba d.d., Kopitarjeva 2, SI-1512 Ljubljana
Telephone: +386 1 432 31 44 • Fax: +386 1 230 14 35
Email: import.books@cankarjeva-z.si • Web site: http://www.cankarjeva-z.si/uvoz

Spain
Díaz de Santos, S.A., c/ Juan Bravo, 3A, E-28006 Madrid
Telephone: +34 91 781 94 80 • Fax: +34 91 575 55 63 • Email: compras@diazdesantos.es
carmela@diazdesantos.es • barcelona@diazdesantos.es • julio@diazdesantos.es
Web site: http://www.diazdesantos.es

United Kingdom
The Stationery Office Ltd, International Sales Agency, PO Box 29, Norwich, NR3 1 GN
Telephone (orders): +44 870 600 5552 • (enquiries): +44 207 873 8372 • Fax: +44 207 873 8203
Email (orders): book.orders@tso.co.uk • (enquiries): book.enquiries@tso.co.uk • Web site: http://www.tso.co.uk

On-line orders:
DELTA Int. Book Wholesalers Ltd., 39 Alexandra Road, Addlestone, Surrey, KT15 2PQ
Email: info@profbooks.com • Web site: http://www.profbooks.com

Books on the Environment:
Earthprint Ltd., P.O. Box 119, Stevenage SG1 4TP
Telephone: +44 1438748111 • Fax: +44 1438748844
Email: orders@earthprint.com • Web site: http://www.earthprint.com

United Nations (UN)
Dept. I004, Room DC2-0853, First Avenue at 46th Street, New York, N.Y. 10017, USA
Telephone: +800 253-9646 or +212 963-8302 • Fax: +212 963-3489
Email: publications@un.org • Web site: http://www.un.org

United States of America
Bernan Associates, 4611-F Assembly Drive, Lanham, MD 20706-4391
Telephone: 1-800-865-3457 • Fax: 1-800-865-3450
Email: order@bernan.com • Web site: http://www.bernan.com

Renouf Publishing Company Ltd., 812 Proctor Ave., Ogdensburg, NY, 13669
Telephone: +888 551 7470 (toll-free) • Fax: +888 568 8546 (toll-free)
Email: order.dept@renoufbooks.com • Web site: http://www.renoufbooks.com

Orders and requests for information may also be addressed directly to:

Sales and Promotion Unit, International Atomic Energy Agency
Vienna International Centre, PO Box 100, 1400 Vienna, Austria
Telephone: +43 1 2600 22529 (or 22530) • Fax: +43 1 2600 29302
Email: sales.publications@iaea.org • Web site: http://www.iaea.org/books

10-02911