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Nuclear desalination: history and prospects

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Abstract

Both nuclear and desalination technologies are mature and proven by experience, and are commercially available from a variety of suppliers. From the early days of the two technologies, it was realized that the power of the atom could be utilized to overcome two of the challenges to the development of mankind, namely sustainable supply of electricity and water. As early as in the 1960s, the International Atomic Energy Agency (IAEA) and individual countries carried out several technical and economic feasibility studies to investigate the utilization of nuclear energy for seawater desalination. The assessments performed for these studies indicated that nuclear desalination would be technically feasible and economically competitive with fossil and renewable energy in a range of situations. However, coupling of nuclear reactor and desalination processes involves a number of issues that have to be addressed. These include safety of the nuclear plant and prevention of radioactive contamination of product water, assurance of potable water supply during reactor shutdown, as well as economic and financing issues. The objectives of this paper is to present the status of nuclear desalination and its prospects for implementation, through comprehensive review of historical development, recent studies and R&D activities, as well as the main issues confronting nuclear desalination and approaches to address them.

Keywords: Activities; Demonstration; Desalination; Development; Feasibility; History; Issues; Nuclear; Research; Seawater

1. Background

On December 2, 1942, a team headed by the Italian scientist Enrico Fermi started and stopped the first self-sustaining nuclear chain reaction and thereby initiated the controlled release of nuclear energy. Unfortunately, the first demonstration of its power was in military applications towards the end of World War II. However, in 1953 President Eisenhower launched his ‘Atom for Peace’ initiative which aimed at finding ways for harnessing the power of the atom for mankind’s benefit in peaceful applications while inhibiting simultaneously the spread of its military dimension [1].

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The first nuclear reactor designed to generate electricity was a 5 MWe power reactor. It was constructed in the town of Obninsk in Russia and was operated on June 27, 1954. The first commercial nuclear power plant in the United States was Shippingport, which was located near Pittsburgh. The plant was of the Pressurized Water Reactor (PWR) type, which was originally designed in 1954 by Westinghouse Bettis Atomic Power Laboratory for military ship applications, then by the Westinghouse Nuclear Power Division for commercial applications (90 MWe) at Shippingport, USA, in 1957. Other reactor types appeared in the following years.

The first Gas Cooled Reactor (GCR) was a 50 MWe reactor constructed in Calder Hall, UK in 1957. In 1960, the first Boiling Water Reactor (BWR) was constructed in Dresden, USA with a net electrical power of 200 MWe. The 22-MWe Nuclear Power Demonstration (NPD) was constructed in Canada in 1962 as a prototype for the Pressurized Heavy Water Reactor (PHWR).

Nuclear power has been used over the last four decades and has been one of the fastest growing energy options. By the end of 1998, there were 434 power reactors in operation worldwide, with a total installed capacity of 349 GWe [2]. There were also 36 reactors under construction, with a total capacity of 28 GWe. At present, about 16% of the world electricity are generated by nuclear power. The development of Nuclear power in the world is shown in Fig. 1. Although the rate at which nuclear power has penetrated the world energy market has declined, it has retained a substantial share, and is expected to continue as a viable option well into the future.

Seawater desalination by distillation is much older than nuclear technology. Prior to the early 1800s, it was practiced almost entirely in shipboard single stage stills, operated in the batch mode, fired directly from the cooking stove or furnace. These stills were bulky and inefficient. Distillation technology evolved slowly lacking major impetus for change. The developing sugar

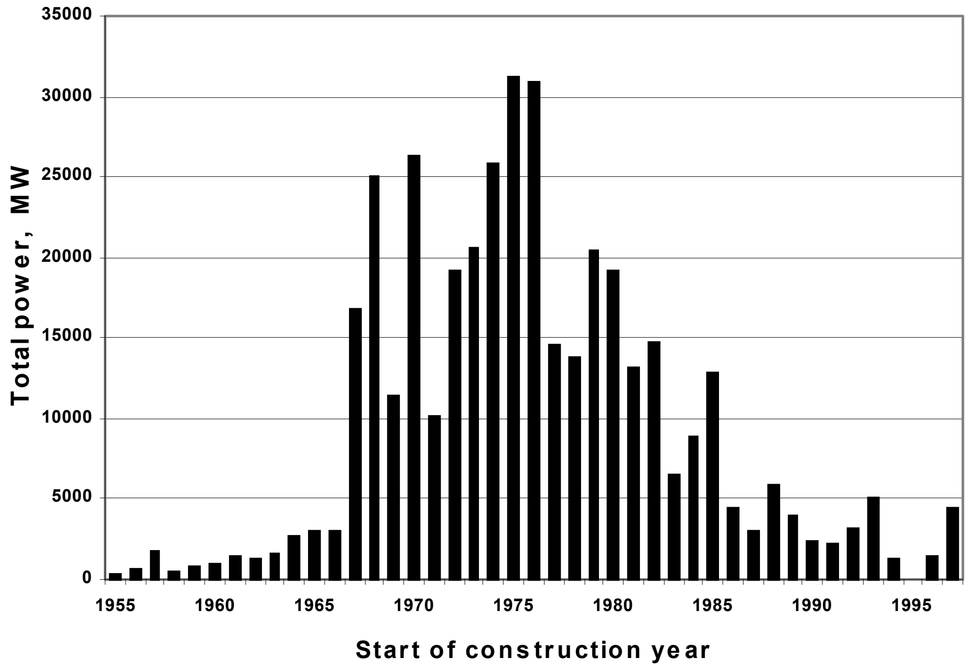

Fig. 1. Development of demand for nuclear power [2].

industry at the beginning of the 19th century was to be the driving force for more efficient systems. By the end of the century, Multi-effect systems were commonplace and several land-based desalination units were constructed [3].

However, the current desalination technology involving large-scale application, has a history comparable to nuclear power, i.e. it spans about four decades. Major milestones include:

1. Development in the late 1950s of MSF process by Prof. Silver that replaced the costly and uneconomic submerged tubes MED.

2. Manufacturing in the early 1960s of Cellulose Acetate membranes by Sourirajan and coworkers that made it possible to use RO desalination process.

3. Development of Hollow Fiber membranes by Dupont.

4. Development of vertical tube evaporators that made MED process more efficient and competitive with MSF.

The historical development of seawater desali-nation in terms of the total yearly contracted capacity is shown in Fig. 2. By the end of 1997, the total contracted capacity of all seawater desali-nation technologies exceeded 19 million m^3/d [4]. Comparison between Figs. 1 and 2 reveals general similarity in the trends of demand development for both nuclear and desalination technologies in the period 1955–1988. Peak demands for both technologies occurred after the 1973 Arab-Israeli War that increased oil prices and thus forced industrialized countries to rely on nuclear energy as a reliable alternative source.

High oil prices increased the financial resources of the oil exporting countries in the Middle East, and thus provided them with the means to acquire alternative source of potable water to augment their acute shortage of fresh water resources. With the falling oil prices, annual demand for nuclear power and seawater

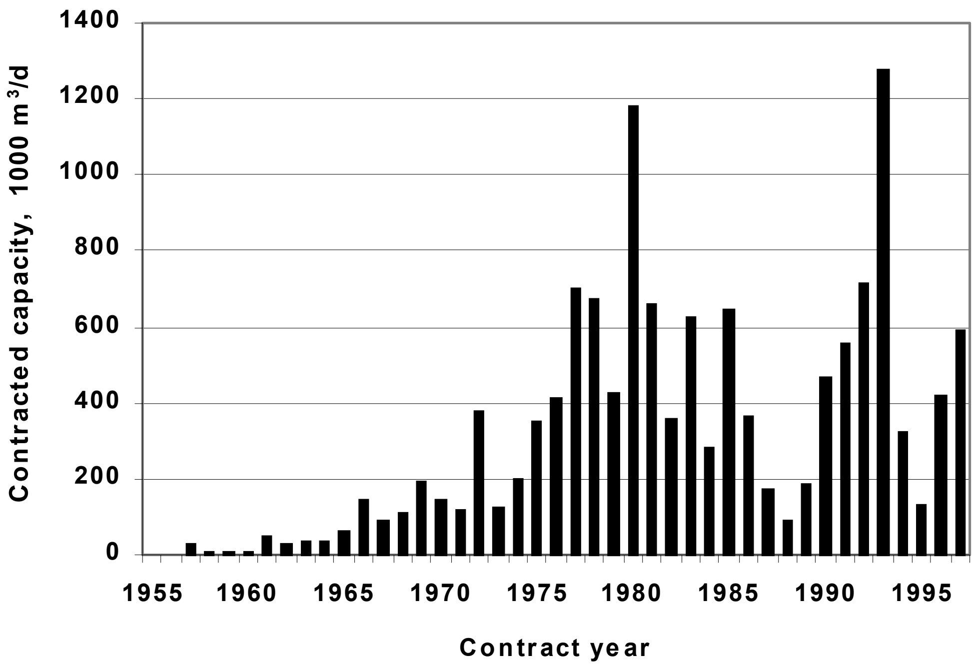

Fig. 2. Development of demand for seawater desalination [4].

desalination decreased. However, while this trend persisted for nuclear energy after 1988, it was reversed for seawater desalination. Nevertheless, both nuclear and desalination technologies are mature and proven by experience, and are commercially available from a variety of suppliers. Therefore, there are benefits in combining the two technologies together.

2. History of nuclear desalination

The term Nuclear Desalination was defined by the International Atomic Energy Agency (IAEA) [5] to be "the production of potable water from seawater in a facility in which a nuclear reactor is used as the source of energy for the desalination process. Electrical and/or thermal energy may be used in the desalination process. The facility may be dedicated solely to the production of potable water, or may be used for the generation of electricity and the production of potable water, in which case only a portion of the total energy output of the reactor is used for water production.

In either case, the notion of nuclear desalination is taken to mean an integrated facility in which both the reactor and the desalination system are located on a common site and energy is produced on-site for use in the desalination system. It also involves at least some degree of common or shared facilities, services, staff, operating strategies, outage planning, and possibly control facilities and seawater intake and outfall structures. Non nuclear desalination is understood to be the production of potable water from seawater in a facility in which a fossil-fuelled plant and/or the electrical grid is used as the source of energy for the desalination process." [5].

From the early days of the two technologies, it was realized that the power of the atom could be utilized to overcome two of the challenges to the development of mankind, namely sustainable supply of electricity and water. As early as in the 1960s, the IAEA surveyed the feasibility of using nuclear reactors for seawater desalination, and has since published a number of reports on the technical and economic aspects of the subject [6–10] and sponsored an international conference on nuclear desalination in 1968 [11]. These studies have drawn attention to the economical advantages of cogeneration (combining water and power production into a single system).

An extension of this concept was the integration of large food-producing centers and selected industries with nuclear power and desalting complex in nonproductive arid regions of the world to solve their socioeconomic problems. Increasing technological advances in several fields has accelerated development of this expanded agro-industrial concept, namely:

- Developments in nuclear energy and advanced reactors.
- Progress in developing the art of desalting seawater.
- Economical application of low-cost water in conducting new types of intensive agriculture.
- Developments in industrial processes which use large quantities of electricity as a basic raw material.

During the summer of 1967, a generalized study of the technological and economical feasibility of agro-industrial complexes was made at Oak Ridge National Laboratory (ORNL). The investigation indicated that seawater desalting on a large scale is expected to be accomplished most economically in dual-purpose plants, which also generate power on a large scale. The study report [12] suggested that agro-industrial complexes would be profitable for some developing countries even with near-term technology and indicated the desirability of carrying out studies in greater depth for specific regions, taking into account their local conditions. The ORNL study was followed by a number of regional and country studies [13–17].

The Middle East Study [13–15] was initiated in June 1968 to explore the technical and economic feasibility of using nuclear-powered dual-purpose plants to provide large amounts of fresh water and electricity in agro-industrial complexes (energy centers) for development of arid regions of the Middle East. The region studied included Egypt, Israel, Jordan, Lebanon, and Syria. It is worth mentioning that Egypt was interested in agro-industrial complexes as early as 1964, when it issued specifications for a dual purpose NPP to be built about 30 km west of Alexandria along the northern coast at Sidi Kreir.

The plant consisted of a 150 MW nuclear power station and a 20,000 m³/d-desalting unit to supply desalted water to an agricultural pilot area of about 10,000 acres. The primary objectives of this project were firstly to ascertain the economic feasibility of the method, and secondly to establish suitable farming techniques and cropping patterns, and ultimately to determine the conditions for the use of desalination as an economic and reliable means of water supply for future agricultural development in this area [17]. Al-though the nuclear power project has not been realized due to difficulties in securing financing after the 1967 War with Israel, studies of the pilot agricultural scheme were continued.

In accordance with the increasing demand for fresh water and power generation, a contract was signed in the late 1970's between Libya and ATOMENERGOEXPORT (USSR) to design and construct a dual purpose nuclear power plant for electric generation and seawater desalination. A Soviet design WWER-440, with thermal power of 1,375 MW, was proposed. The contract envisaged the construction of two units of 440 MW(e) with total power production of about 840 MW(e) and desalinated seawater production of about 80,000 m³/d. The plant was supposed to be constructed in the Gulf of Sirt, but realization was never materialized.

3. Experience with nuclear desalination

Nuclear desalination has been implemented only at locations in Kazakhstan and in Japan. While in Japan the desalination plants are mostly for on-site water supply, the Aktau desalination complex in Kazakhstan supplied water to a nearby population center. In Aktau (formerly Shevchenko), Kazakhstan, the liquid metal cooled fast reactor BN-350 has been operating as an energy source for a multi-purpose energy complex (Mangyshlak Complex) since 1973, supplying regional industry and population with electricity, potable water and heat. The complex consists of a nuclear reactor, a gas and/or oil fuelled thermal power station, and MED and MSF desalination units [18]. Seawater is taken from the Caspian Sea and the nuclear desalination capacity is about 80,000 m³/d. The nuclear reactor was shutdown at the beginning of 1999 after 26 years of successful operation. A simplified flow diagram of the complex is shown in Fig. 3.

In Japan, all of the nuclear power plants are located at the seaside. Several plants of the electric power companies of Kansai, Shikoku and Kyushu have seawater desalination systems using heat and/or electricity from the nuclear plant to produce feedwater for the steam generators and for on-site supply of potable water [19]. MED, MSF and RO desalination processes are used. Individual desalination capacity ranges from about 1000 to 3000 m³/d and the experience gained so far with nuclear desalination are encouraging. Table 1 shows the current status of the nuclear desalination plants in Japan [19].

In Ashdod, Israel, an integrated plant was built which was designed to simulate the coupling of a MED plant with a nuclear reactor. A low temperature horizontal tube multi-effect (LT-HTME) unit having a production rate of 17400 m³/d was coupled to an old 50 MW(e) oil-fired power plant. The steam to the desalination LT-HTMIE unit was supplied by modifying the steam conditions to simulate a nuclear power

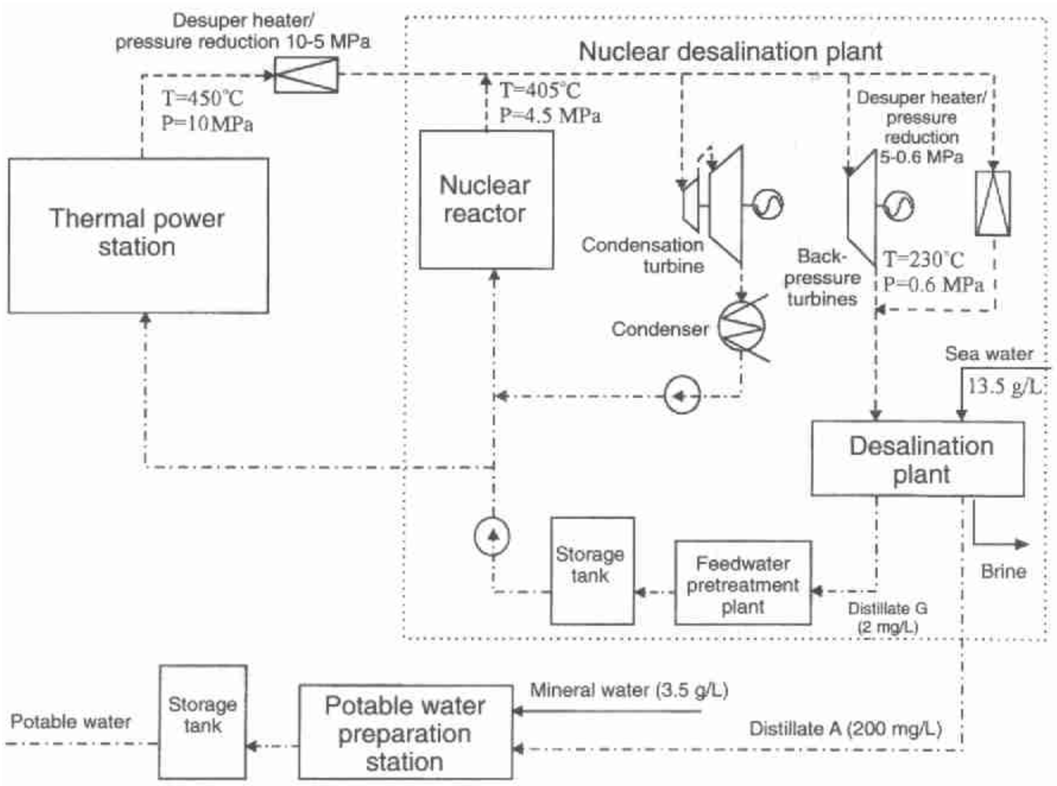

Fig. 3. Flow diagram of the Mangyshlak Atomic Energy Complex [18].

Table 1
Current status op nuclear desalination plants in Japan [19]

	Reactor				Desalination			
Name	Location	Type	Unit capacity, MW(e)	Grid connection	Process	Capacity, m^3/d	Year of startup	Remarks
Ohi-I, II	Fukui	PWR	1175	1979/1979	MSF MED	1300 2600	1974 1976	1300 m^3/d × 2 units
Ohi-Ill, IV	Fukui	PWR	1180	1991/1993	RO	2600	1990	1300 m^3/d × 2 units
Takahama	Fukui	PWR	870	1985	MED	2000	1983	1000 m^3/d × 2 units
Ikata-I, II	Ehime	PWR	566	1975/1975	MSF	2000	1975	1000 m^3/d × 2 units
Ikata-Ill	Ehime	PWR	566	1992	RO	2000	1992	1000 m^3/d × 2 units
Genkai-III, IV	Saga	PWR	1180	1992/1997	RO MED	1000 1000	1988 1992	
Kashiwazaki	Niigata	BWR	1100	1985	MSF	1000	1985	Not in operation

plant and flashing cooling water used in the back pressure turbine condenser. The Ashdod unit operated continuously for over a year as a demonstration plant and fulfilled the design requirements. It was stopped in 1983 because of the high oil price as it was too expensive to operate the low-efficiency 50 MW(e) unit [20].

In addition to the above applications, there are now about 60 reactors and over 500 reactor years of operational experience with nuclear heat applications: district heating, industrial processes and seawater desalination. There appear to be no major technical or safety concerns with nuclear heat application systems. Design precautions to prevent the carry-over of radioactivity into the heating network or into the desalted water have proven effective. These findings are important for future applications of nuclear heat for seawater desalination. The experience gained so far is encouraging. However, it does not cover all aspects of interest to future users and designers.

4. Recent developments

Despite of the above mentioned studies and applications, the main interest during the 1960s and 1970s was directed towards the use of nuclear energy for electricity generation, district heating, and industrial process heat. Therefore, as of 1977, IAEA nuclear desalination activities came to a halt [21]. Renewed interest in nuclear desalination has been growing worldwide since 1989, as indicated by the adoption of a number of resolutions on the subject in the IAEA General Conferences. This has been motivated by a variety of reasons. These include: economic competitiveness in areas lacking cheap hydropower or fossil fuel resources, energy supply diversification, conservation of fossil fuel resources, spin-off effects of nuclear technology for industrial development, and environmental protection by avoiding emissions of air pollutants and greenhouse gases.

Responding to this trend, the IAEA performed studies to assess the technical and economic potential of nuclear reactors for seawater desalination. In this regard, state-of-the-art desalination technologies were reviewed [21], and costs for different types of combinations of nuclear reactors and desalination processes were generically examined [22].

In 1991 five North African Countries (NACs): Algeria, Egypt, Libya, Morocco and Tunisia submitted a request to the IAEA for assistance in carrying out a feasibility study on seawater desalination by using nuclear energy at selected sites. The study was completed in 1995 [23]. It analyzed the electricity and potable water demands and the available energy and water resources in NACs.

The scope included the selection of representative sites, analysis of various combinations of energy sources and desalination processes appropriate for each site, economic factors, financial aspects, local participation, infrastructure requirements, and institutional and environmental aspects. The main conclusions of the study were [23]:

- Nuclear power could play an important role in meeting the expanding regional needs for energy that can be supplied to the grid in the form of electricity, or to desalination plants as heat and/or electricity. There are no technical impediments to the use of nuclear reactors for the supply of energy to the desalination plants.
- Based on the selected energy source/desalination process combination for the five representative sites, it was found that cost of desalted water for the most economic fossil and nuclear driven desalination processes (Table 2) were in the same range. Sensitivity analyses indicated that higher fuel price and/or lower interest rate will make the nuclear option more economic. The most economic desalination process seems to be RO plants with preheated feedwater (i.e. utilizing the

Table 2
Most economic cases of nuclear and fossil options [23]

Plant size (1000 m³/d)	Location	Economic couplings [(1)]				Average $/m³
		Nuclear	Water cost $/m³	Fossil	Water cost $/m³	
720	Tripoli	GT-MHR/RO[(2)]	0.73	GT/Hybrid	0.70	0.715
240	El-Dabaa	CANDU-6/RO	0.80	CC/RO	0.78	0.790
120	Oran	GT-MHR/RO[(2)]	0.79	CC/RO[(3)]	0.83	0.810
60	Zarzis	CAREM-25/RO[(2)]	0.87	CC/RO	0.89	0.880
24	Laayoune	— [(4)]	—	Diesel/RO	1.04	—

[(1)] Base case: 8% interest rate, 2% oil price escalation and US$15.5/bbl oil price including cost of transportation.
[(2)] Warm condenser cooling water is used as feedwater to the RO system.
[(3)] GT/MED will give a slightly lower cost of US$0.82/m³. However, this combination was chosen to facilitate comparison with other combinations in the Table.
[(4)] All selected reactors for this site were heat only reactors.

cooling water of the steam power plant's condenser as a feedwater to the RO system).

This was followed by a number of studies in different countries with and without technical assistance from the IAEA. In 1995 and 1997, Egypt carried out a feasibility study to investigate the prospects of constructing nuclear desalination plants of different capacities in three sites along its Mediterranean Coast [24]. The results of the economic evaluation confirmed those obtained during the IAEA generic study [22] and the NACs study [23].

Morocco performed a technical co-operation project in 1997 and 1998, jointly with China under the umbrella of the IAEA to carry out a pre-project study of a nuclear desalination demonstration plant with a 10 MW(th) Nuclear Heating Reactor (NHR-10) from China to be built in Tan-Tan, Morocco. The plant was designed to have a production capacity of 8,000 m³/d of potable water through an MED process. The production capacity of the demonstration plant was chosen so that it will reinforce the current supply in Tan-Tan and provide sufficient water for its growing population expected to reach 70,000 inhabitants by the year 2010 and to establish a database for reliable extrapolation of the water production costs for a commercial nuclear desalination plant for producing 140,000 m³/d of potable water using a 200 MW(th) NHR [25].

The project was suspended in 2000, pending the results of another project initiated with IAEA in 1998 on the introduction of small and medium reactors (SMR) for power production.

In Indonesia, a preliminary economic study is in progress to consider a nuclear desalination plant, as an alternative to fossil-fuelled desalination plants for the Madura Island. The purpose of the plant is to provide the Maduresses with sufficient power with less dependency on the Java-Bali interconnection grid and potable water for public and to support industrialisation and the development of tourism, with further utilization of waste brine for traditional salt production. The plant capacity is yet to be determined, but the projected values are around 100–200 MW of electricity and 100,000–200,000 m³/d of potable water [25].

Pakistan has been interested in nuclear technology and its application to seawater desalination in the coastal areas near Karachi. Pre-feasibility study and design studies were carried out for desalination projects involving solar, nuclear and diesel power. Since the arid zones are sparsely populated for places along the coast other than Karachi, the water and power requirements are essentially small, which can be adequately met by means of conventional power plants, or even a floating-ship borne plant, which was also considered in earlier studies. Recent work by the Pakistan Atomic Energy Commission (PAEC) on nuclear desalination has been undertaken in evaluating two approaches: connecting a desalination process to the existing 137 MW(e) nuclear power plant at Paradise Point, the Karachi Nuclear Power Plant (KANUPP); and design study of a large dual-purpose nuclear power/desalination plant [25].

Tunisia has already a deficit of 50,000 m^3/d potable water, covered by brackish water desalination using RO process powered by electrical energy. This deficit is expected to reach about 100,000 m^3/day in 2010, and can only be augmented by seawater desalination. Several studies are done to select the suitable desalination process including those using nuclear energy. Two sites, Skirat and Zarat located in the south-east area of the country, were identified for specific studies. Recently Tunisia organized a dedicated project team with participation of three relevant organizations (Nuclear Research and Technology, Electricity, and Water) and plans a feasibility study of a nuclear co-generation plant for electricity and water in the country [25].

To facilitate economic evaluations and screening analyses of various desalination and energy source options, IAEA has developed the PC-based computer program Desalination Economic Evaluation Program [DEEP], based on the spreadsheet methodology. The spreadsheet includes simplified models of several types of nuclear/fossil power plants, nuclear/fossil heat sources, and both distillation and membrane desalination processes. For the distribution of costs to the two products in a co-generation plant, i.e. power and water, DEEP uses the “power credit method”, i.e. the loss of electricity generation is charged to the water costs. Current cost and performance data have already been incorporated so that the spreadsheet can be quickly adapted to analyze a large variety of options with very little new input data required. The spreadsheet serves three important goals:

- side-by-side comparison of a large number of design alternatives;
- quick identification of the lowest cost options at a given location; and
- an approximate cost of desalinated water and power.

The software package of DEEP has been disseminated to many Member States and organizations for specific applications. It has been used in many of the above mentioned feasibility studies. The results generally show that nuclear seawater desalination yields water costs in the same range as fossil options hence both can be seen to be competitive with each other.

5. Demonstration and R&D activities

The results of these studies led to a general understanding that demonstration of Nuclear Desalination was necessary in order to build up technical and economic confidence in this application. There would be also a need to establish a programme for identifying a practical set of options from which one or more demonstration facilities might be chosen.

Therefore, the IAEA initiated in 1994 a two-year Options Identification Programme (OIP). The objective of the OIP was to identify candidate reactor and desalination technologies that could serve as practical demonstrations of nuclear desalination, supplementing the existing expertise and experience [26]. Demonstration desalination processes need not be implemented at the large-scale commercial production level. Two or three trains or units could provide design and operational characteristics fully representative of larger scale production facilities, as larger plants are simply multiple trains or units operated in parallel. The three options described below were identified as recommendable, practical candidates for demonstration. These options use well-proven water-cooled reactors and desalination technologies [26].

Option 1: RO desalination in combination with a nuclear power reactor being constructed or in an advanced design stage, with construction expected in the near term. The preferred capacity of the reactor is in the medium-size range. Two or three RO trains, up to 10,000 m^3/d each, would provide a suitable demonstration. A newly constructed reactor would offer the best opportunity to fully integrate the RO and reactor systems, including feedwater preheating and optimization of system design. Such demonstration could readily be extrapolated to larger scale commercial production facilities.

Option 2: RO desalination, as above, in combination with an operating reactor. Some minor design modifications may be required to the periphery of the existing nuclear system. Advantages include a short implementation period, a broad choice of reactor sizes, and the availability of nuclear infrastructures. A reactor in the medium-size range is preferred, as it provides a system close to that most likely to be used in commercial facilities.

Option 3: MED desalination in combination with a small reactor. This is suitable for the demonstration of nuclear desalination for capacities of up to 80,000 m^3/d.

The OIP also recommended intermediate steps before or in conjunction with recommended demonstration options, aiming at gradual, partial and progressive confidence building, to reduce unknowns and risks with relatively low cost [26]. Such intermediate steps might be for RO:

(a) Small scale preheated seawater desalination with reverse osmosis (RO);
(b) Small scale RO integrated with a NPP;
(c) Larger scale RO integrated with a fossil-fueled power plant.

Similarly, intermediate steps for demonstrating MED might be:

(d) Two or three parallel MED units with a heat source simulating NPP conditions;
(e) A small-scale MED unit connected to a NPP, which is operating, or under construction.

Following the steps taken by the IAEA, the European Community has approved the EURODESAL Project, which will be carried out during the period 2001–2002 by a consortium of eight partners from France, Italy, Spain, Portugal, Canada and IAEA [26]. The expected acute shortage of drinking water in Southern Europe motivated the project. The general objectives of the project include: demonstration of the technical feasibility of seawater desalination (MED and RO) with innovative reactors (GT-MHR, AP-600, IRIS); optimization of coupling schemes; and carrying out detailed economic analysis of various scenarios for nuclear, fossil and renewable energies [26]. The project is expected to evaluate the export potential to other countries/regions and to develop the specifications for a pilot plant project to be started in 2002 (EURODESAL Demo).

The research and development activities in several countries followed the recommendations of the OIP. A brief description of these R&D activities is presented below country-wise. Most of these activities are embraced in the IAEA coordinated research programme on *Optimization of the Coupling of Nuclear Reactors and Desalination Systems*. The emphasis is on the activities and what they are trying to achieve.

5.1. Canada

Although the proportional relationship between feedwater temperature and membrane permeability is well known, the idea of utilizing the condenser's cooling water as a source of feed for RO systems did not appear until early 1994 [28]. This concept was adopted and investigated by the IAEA in all subsequent studies [23,26]. These and other studies [24] have shown that there is a potentially significant economic and performance benefit through the combined effects of feedwater preheating and system design optimization.

These conclusions have been drawn from analyses and preliminary design studies without any experimental validation. Experimental validation is of extreme importance in the confidence building process. Indeed, Annex I.2 of the OIP report [26] has identified some concerns with the operation of RO membranes at elevated temperatures. These include the potential for higher product water salinity, more rapid membrane fouling, greater membrane compaction, reduction in membrane lifetime and that saving in total water cost by elevating temperature from 15~18°C to 30°C would be in the range of 3% only.

In view of the above, CANDESAL the developer of this concept reached an agreement with Atlantic Nuclear Services Ltd. and Babcock & Wilcox Canada to participate in an experimental program funded in part by the National Research Council of Canada. A conceptual design has been established for the experimental apparatus, and engineering design of the system has been initiated. Experiments are expected to go underway by the end of 2000.

5.2. China

Based on research work on the possible application of nuclear energy for low temperature heating initiated in the early 80s, a 5 MW(th) experimental Nuclear Heating Reactor (NHR-5) came into operation for space heating in 1989. A large-scale NHR with an output of 200 MW(th) (NHR-200) has been developed since 1990. The NHR can be used in district heating, seawater desalination, air conditioning and other industrial processes. In 1998, the research project Optimization of System of Seawater Desalination with Nuclear Heating Reactor was initiated by the Institute of Nuclear Energy Technology (INET).

The objective of the research project is to optimize coupling of NHR-200 with MED and Hybrid desalination processes. The investigation included HT-MED, LT-MED and MED/VC, and LT-MED/RO. The parametric analysis indicated that the most suitable desalination system for the characteristics of the heating reactor would be VTE-MED with multi-tower scheme. To obtain the necessary data for this coupling scheme, an experimental facility consisting of 4 effects has been designed. The facility will be used to simulate any successive 4 effects of the 28 effect VTE-MED through adjusting the operating parameters. The construction is expected to be completed by June 2001 and the experimental program will continue until the end of 2002.

5.3. Egypt

In view of the possible role of RO desalination technology in any future Egyptian nuclear desalination program and the need to validate the concept of RO feedwater preheating, the Nuclear Power Plants Authority (NPPA) has decided to carry out this research project, with the following objectives in mind:

A. Overall: to investigate experimentally whether the projected performance and economic improvements of preheated feedwater can be realized in actual operation.

B. Short-term (~3 years): to study the effect of feedwater temperature and pressure on RO membrane performance characteristics over a range of temperatures (20–45°C) and pressures (55–69 bar).

C. Long-term: to study the effect of feedwater temperature and pressure on RO membrane performance characteristics as a function of time.

A contract for the construction of a 1 million US dollars test facility has been awarded in July 2000. The test facility consists of two identical units: one unit operating at ambient seawater temperature and the other with preheated feedwater at 25, 30, 35, 40 and 45°C, as called for by the experimental sequence. This configuration is considered practical with 4" membranes, and has the benefit of giving direct comparison of performance characteristics for the preheated and no-preheated cases at all values of preheat temperature. The test facility will be commissioned in April 2001. The duration of the experimental program is expected to be 2 years after construction of the test facility divided into three Phases (I–III). Each Phase will be 8 months and will be based on a particular membrane make, with a matrix of fixed operational conditions such as:

- Feedwater temperature
- Feed pressure
- Chemical dosing and type
- Operating time, etc.

5.4. India

Based on the earlier experience in desalination pilot plants (MSF and RO), the Bhabha Atomic Research Center (BARC) is setting up a 6300 m³/d combined MSF-RO hybrid desalination plant to be coupled with 2 × 170 MW(e) PHWR units at the Madras Atomic Power Station at Kalpakkam, in the south east of India. The desalination plant has a 4500-m³/d MSF plant and a 1800 m³/d RO plant. Due to unavailability of raw seawater from MAPS, the seawater intake for the desalination plant is taken from the process seawater out fall. The temperature is normally 3–5°C higher than the ambient sea water temperature.

As no significant modifications are possible in an existing reactor, it has been planned that the steam at around 3.5 bar pressure will be tapped from the manholes in the cold reheat lines after HP turbine exhaust from both the nuclear reactors. The moisture content will be removed through a moisture separator and steam will be sent to intermediate isolation heat exchanger to produce process steam for the brine heater of the MSF plant. The condensate from the heat exchanger will be returned back to the power station. The feed to the RO plant is taken from the MSF plant cooling water reject and is mixed with ambient temperature feed sea water resulting in a RO plant feed water temperature of 36–38°C. The product water will be provided to the nuclear power station and the local inhabitants for drinking. The nuclear desalination demonstration plant has been licensed in 1999.

The tenders for the major equipment of this plant are released and are under various stages of procurement/fabrication. Tenders for seawater intake/outfall and steam supply are under preparation. The civil and electrical work has started in 1999 and scheduled to complete in 2001. Useful design data is expected from this plant on the coupling of SMR based on PHWR with a hybrid desalination plant. The plant is expected to be commissioned around March 2002.

5.5. Korea

Specific programmes on nuclear desalination started in 1996 with the projected plan for eight years till the initiation of construction, focusing mainly on the reactor and associated technology development. The scope of work includes [25]:

- Reactor and fuel design, associated technology development
- Design verification (experiments, tests)
- Power plant design including BOP design
- Component design, and manufacturing technology development
- Desalination process and plant design

The program is being carried out by the Korea Atomic Energy Research Institute (KAERI) as the leading organization with the Government support and participation of industries. Following the conceptual design completed in 1999, basic design started for the integrated nuclear desalination system. It will be completed by March 2002. The central part of the integrated system is a 330 MW(th) SMART (System-integrated Modular Advanced ReacTor). The SMART nuclear desalination plant aims at producing 40,000 m^3/d of potable water and 90 MW(e) of electricity. The program is open to involvement or co-operation from any interested countries and/or overseas organizations [25].

5.6. Russian Federation

Russia has a long history of developing and utilizing nuclear ice-breaker transport fleets for its northern regions. Using its experience, Russia has been developing a concept of floating nuclear power unit (FNPU) and its application for desalination. Following advantages are envisaged in the concept of floating nuclear desalination complexes:

- High quality of the entire floating power unit fabrication under shipbuilding work conditions followed by delivery to the customer possibly on a turn-key basis;
- Short construction period of the station to 4–5 years and reduced investments as compared with land-based NPPs;
- A potential of siting at any coastal regions;
- Simplification of anti-seismic design measures;
- Cost reduction by serially-produced reactor plants; and
- Simplified decommissioning of the station.

The design activities for a floating co-generation plant based on Nuclear Floating Power Unit (NFPU) with KLT-40C reactors started in the mid-1990s at the OKB Mechanical Engineering with participation of other relevant organizations. The final design and licensing activities are in progress now, with a construction permit expected in 2001. Application of NFPU as an energy source for seawater desalination is also under consideration.

Conceptual design of coupling of NFPU with MED facilities was prepared and further development is planning. Coupling of NFPU with a reverse osmosis process is also being investigated through a co-operation project on development of nuclear floating desalination plant using a Russian NFPU and a Canadian barge mounted RO desalination facility. Russian authority, Minatom has solidified their commitment to the joint development project with the Canadian CANDESAL to implement this program. This project is likely to be one of the earliest demonstrations of nuclear desalination, following only the Indian program that is currently under construction using the existing reactor at Kalpakkam. Various coupling schemes for several other Russian small reactors (RUTA, NIKA) are also being investigated.

6. Main issues

There are a number of nuclear reactors that have been or are being considered for nuclear desalination, as shown in Table 3. However, regardless of the reactor type, coupling of nuclear and desalination technologies involves a number of issues that have to be addressed. These include safety of the nuclear plant and prevention of radioactive contamination of product water, assurance of potable water supply during reactor shutdown, as well as economic, financing, safeguards and non-proliferation, and public acceptance issues.

6.1. Safety

The safety of a nuclear desalination plant depends mainly on the safety of the nuclear reactor and the interface between the nuclear plant and the desalination system. It must be ensured

Table 3
Summary of nuclear desalination projects

Reactor type	Where?	Desalination process	Status
LMFR	Kazakhstan (Aktau)	MED, MSF	In service till 1999
PWRs	Japan (Ohi, Takahama, Ikata, Genkai)	MED, MSF, RO	In service with operating experience of over 100 reactor-years.
	Rep. of Korea, Argentina, etc.	MED, RO	Under design
	Russia	MED, RO	Under design (floating unit)
BWR	Japan (Kashiwazaki)	MSF	Desalination unit decommissioned
PHWR	India (Kalpakkam)	MSF/RO	Being connected
	Canada	RO (preheat)	Under design
NHR	Morocco (Tan-Tan)	MED	In preparation
	China	MED	Under design
HTGR	South Africa, France, The Netherlands	MED, MSF	Interested in application

that any load variation of steam consumption in the desalination plant would not cause a hazardous situation in the nuclear plant. There should be suitable provision for monitoring the radioactivity level in the isolation loop and desalination system. In case of a pressurized heavy water reactor (PHWR), the tritium level in the heating steam and product water must be regularly checked. Adequate safety measures must be introduced to ensure that under any circumstances, no radioactive materials would be released to the product water.

The basic requirement to prevent radioactive contamination of the desalination plant and/or the atmosphere is of utmost importance in thermal coupling. At least two mechanical barriers and pressure reversal between the reactor primary coolant and brine must be incorporated. In the case of a pressurized water reactor (PWR), the steam generator is the first barrier. The second barrier could be the condenser of a backpressure turbine. In the case of heat generation reactors, careful attention must be given to providing sufficient barriers to prevent radioactive contamination.

The most suitable heat generation reactors for desalination coupling are those with a closed primary cooling circuit such as a low temperature PWR or PHWR. In this arrangement, heat is supplied through an interface with a steam generator or primary heat exchanger. This provides a barrier between the reactor coolant and the steam (or hot water) for desalination. Direct supply of steam from the reactor core to the desalination plant, such as in a boiling water reactor (BWR) is not suitable for desalination without an intermediate barrier.

6.2. Assurance of potable water supply

The fact that potable water is essential to sustain life, health and provide human comfort means that reliable supply for the population served must be assured under all conceivable conditions. Assurance of reliable supply also applies to industrial use because, without water, production would come to a standstill.

No industrial installation, whether it is a desalination plant or a power plant, can have 100% availability and reliability. There are always planned as well as unplanned outages and thus measures must be taken to provide for uninterrupted supply of the minimum requirements at all times. Provisions for sufficient water storage capacity and redundancy by having more than one, and possibly several, desalination units (trains) in parallel are measures included in the design of the desalination plant. Optimization of redundancy is performed on a case by case basis, taking into account expected availability, forced outage probability, cost of water storage and minimum supply requirements of the load served.

The desalination plant can only function if it is supplied with energy, so reliable energy supply must also be assured. Generating reserve capacity and redundancy are the only possible measures, because energy storage is not practical. Uninterrupted supply of electricity is relatively easy to assure when the desalination plant is connected to a reliable grid, which includes adequate reserve capacity and redundancy. Reliable supply of heat can only be achieved by having adequate on-site reserve capacity e.g. back-up boilers. In this respect, modular designs of the power plant are an asset. In general, increased reliability of supply always implies increased costs.

6.3. Economics

The economic competitiveness is one of most important factors for decision-making, even if not the first decisive criterion. A comprehensive economic investigation using the Agency's economic evaluation program DEEP generally shows that nuclear seawater desalination yields water costs in the same range as fossil options, hence both can viable options depending upon specific site conditions. The target cost of the product water of nuclear desalination plants is not easy to generalize, since it depends on energy cost (thermal and/or electricity) and many other local conditions. But good indication will be in the range of US$0.7–0.9/$m^3$.

6.4. Financing

The availability of financing at reasonable terms is a key factor for the feasibility of every large power/desalination project, in particular with nuclear power. There are four relevant characteristics of commercial nuclear desalination projects, which make the arrangement of adequate financing difficult. These are: high investment costs, longer construction times than for non-nuclear desalination plants, a high degree of uncertainty with respect to costs and scheduling, and potentially significant public opposition. These characteristics imply significant financial risks.

The primary difficulty in financing a nuclear desalination project is the magnitude of the investment. The initial investment cost for a 600 MW(e) size nuclear power plant would range between about US$ 1300—1800 million. The large capital requirement for a nuclear desalination plant may approach or even exceed the overall available credit limits identified by lenders for an individual developing country. Also, lenders may be reluctant to concentrate their financial risk in a single project of this magnitude. The implementation of a demonstration project could help to reduce cost and schedule uncertainties. As much as possible of the total project costs, but in any event the local portion of these costs, should be financed with domestic funds.

For successfully implementing a nuclear desalination project in a developing country, it is essential for the government/utility to [26]:

- Commit itself to the nuclear desalination project with necessary government support;
- Make a thorough financial analysis, together with an economic analysis for evaluating the feasibility of the project;
- Maintain generally acceptable credit ratings in order to obtain investments and debt financing;
- Finance as much as possible of the local cost component of the project in local currency from sources within the host country itself —

the importance and complexity of this are often underestimated;

- Utilize thoroughly a full range of expertise to deal with the technical, financial and legal complexities;
- Set electricity and water tariffs at a level necessary for sound financial strength, since one of the major sources of financial difficulties in utilities is often uneconomic pricing.

6.5. Safeguards and non-proliferation

International concerns regarding assurance of the use of nuclear energy for exclusively peaceful purposes are related only to the nuclear reactor and its fuel. The end use of the energy produced, i.e. desalination of seawater or any other use, is in itself irrelevant. For these reasons, a country will obtain nuclear technology, nuclear reactors, nuclear materials and equipment from a foreign supplier, only if it can provide adequate evidence of their exclusively peaceful uses, to the full satisfaction of the potential supplier and the international community. This situation prevails now and will also be the case for the foreseeable future.

6.6. Public acceptance

Experience shows that public and political acceptance of nuclear energy strongly depends on the perception of the risks incurred and of the benefits obtained from using this energy source. Opponents tend to exaggerate risks and ignore benefits, and the media often transmits this view to the public at large. The advanced reactor concepts currently being proposed by the nuclear industry share the common goal of achieving increased safety levels. This is expected to improve public acceptance of nuclear energy, as well as to alleviate to some extent growing public concerns regarding environmental pollution and climate change caused by emissions from the burning of fossil fuels. Obviously, to gain public acceptance of the combination of using nuclear energy for the production and supply of safe and clean drinking water, it will have to be demonstrated credibly that there is no risk whatsoever of radioactive contamination of the product water.

7. Conclusions

Both nuclear and desalination technologies are mature and proven by experience, and are commercially available from a variety of suppliers. There are economical advantages of combining the two technologies for the simultaneous water and power production. Interest in using nuclear energy for producing potable water has been growing worldwide in the past decade.

Technical and economic feasibility studies have been carried out in a number of interested countries. The results illustrate that application of nuclear energy to seawater desalination is a realistic option. R&D activities are going on worldwide to validate and demonstrate various aspects of nuclear desalination.

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