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Nuclear desalination: A viable option of the future based on existing experience

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ABSTRACT

Seawater desalination using nuclear energy is a viable option to meet the growing demand of potable water. This paper summarizes experience on nuclear desalination in member states and recent activities conducted by the IAEA. Over 200 reactor-years of operating experience of nuclear desalination have been accumulated worldwide. Experience also has been accumulated through current nuclear demonstrated projects such as the Indian Kalpakkam plant (6,300 m^3/d hybrid RO-MSF plant coupled to a pressurized heavy water reactor (PHWR)), and Pakistani plant (4,800 m^3/d MED coupled to a PHWR and has been commissioned early in 2010). These demonstration projects aimed to confirm the technical and economic viability of nuclear desalination under country specific conditions. All projects have demonstrated excellent operational performance, high reliability and safety producing high quality water at competitive costs. An overview of the economic benefits of nuclear desalination is highlighted. Recent case studies conducted under an IAEA coordinated research programme have revealed that nuclear desalination should be considered as a real option to meet the water needs and shortages in the water scarce areas. Yet, the main challenge for the large-scale deployment of nuclear seawater desalination is the lack of infrastructure and resources in the countries affected by water scarcity problems which are however, interested in adoption of nuclear desalination for the sustainable water resource. A summary of the IAEA activities on seawater desalination using nuclear energy is presented.

Keywords: Nuclear desalination; Existing experience; Economics; Nuclear energy; IAEA activities

1. Introduction

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 1000–1600 MW electrical outputs. A large number of smaller nuclear units are currently under consideration. It is expected that within the next decade also smaller nuclear reactors will become commercially available. In comparison to alternative energy sources nuclear power has several main advantages [1]:

- It is economically competitive;
- It is environmentally benign;
- Its production costs are much less dependent on changes of fuel costs; and
- It provides a high level of security of energy supply.

Nuclear power is a well suited source of energy for all types of desalination plants. When applied for desalination, nuclear power offers significant economic incentives

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and improvements in the area of environmental impacts, removing some of the impediments for the use of fossil fuel or renewable energy sources.

Nuclear desalination as a concept has been around for almost 50 years as an economically reasonable option, though it never achieved wider application. Still, sufficient amount of 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 [2,3]. Indeed, any reactor capable of providing electrical and/or thermal energy can be coupled to an appropriate desalination process. Small and medium sized nuclear reactors currently under development will further increase the economic and environmental attractiveness of nuclear power to be used as energy source for desalination plants, due to their easier applicability to cover smaller energy loads. Nuclear reactors suitable for desalination can operate as dedicated systems (producing only the desalted water), or as co-generation systems producing both water and electricity. Dedicated nuclear systems are considered more suitable for remote and isolated regions. Adopting co-generation concept along with hybridization of desalination systems would help in cost effective production of desalinated water. By sizing the power plant to supply both electricity to the grid and energy in form of heat and/or electricity to a co-located desalination plant, better thermal utilization is achieved which is reflected to the overall economy of the plant. [4]

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. Nuclear desalination faces the same challenges as a nuclear power plant such as 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.[5] 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.

2. Experience with nuclear desalination in member states

Nuclear desalination is gaining interest in 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. Considerable experience has been made in several Member States on the development and operation of nuclear desalination plants which is summarized in Table 1. In addition, there are two demonstration plants of nuclear desalination in India and Pakistan.

2.1. Experience with the nuclear desalination plant Aktau

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 freshwater of 70 up to 120 m^3/d. 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 (Fig. 1)

The next step was to construct a fossil (gas/oil) power station (750 MWth) , a nuclear reactor, three MED plants of five effects, each with a capacity of 12,000 m^3/d, coupled

Table 1
Existing experience of nuclear desalination

Project	Country	Water capacity (m^3/d)	Type	Commercial/ shutdown date	Water use
Aktau	Kazakhstan	145,000	MED	1973–1999	Distillate for industrial use and potable water
Ohi	Japan	6500	RO+MED+MSF	1974	Make-up and household
Takahama	Japan	2000	MED	2003	Make-up and potable
Ikata	Japan	2000	MSF	1994	Make-up and household
Genkai	Japan	2000	RO+MED	1988	Make-up and household
Trombay	India	30	LTE	2004	High quality demineralised make-up
Kalpakkam	India	1800 + 4500	RO + MSF	2003	Make-up
Diablo Canyon	USA	4500	RO	1992	Potable water – make up for steam
Karachi	Pakistan	4800	MED	2010	Potable

Fig. 1. Distillation units at Aktau, Kazakhstan.

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 8000–14,500 m^3/d leading to a total design capacity of the desalination plant of 145,000 m^3/d.

The nuclear reactor used in this nuclear desalination plant was the BN350 which was 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 reactor had been in operation since 1973 and achieved more than 160,000 h of operation. It was shut down in 1999 mainly due to political reasons and is currently under decommissioning.

Two different types of product water were prepared at the MAEC nuclear desalination plant: distillate with very low solids content which was suitable for industrial purposes, and distillate which was used in the preparation of potable water. 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 2 [6]. The nuclear desalination plant at MAEC was scaled gradually to a large scale desalination plant showing flexibility and high reliability 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 2
Technical data of desalination plant (one unit)

Technical characteristics	
No. of effects	10
Heat exchange area	
Evaporator	1760 m^2
Regenerative pre-heater	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	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 kW/t

2.2. 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 freshwater 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 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 m3/d (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 [7,8].

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 are used [9]. 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 op-

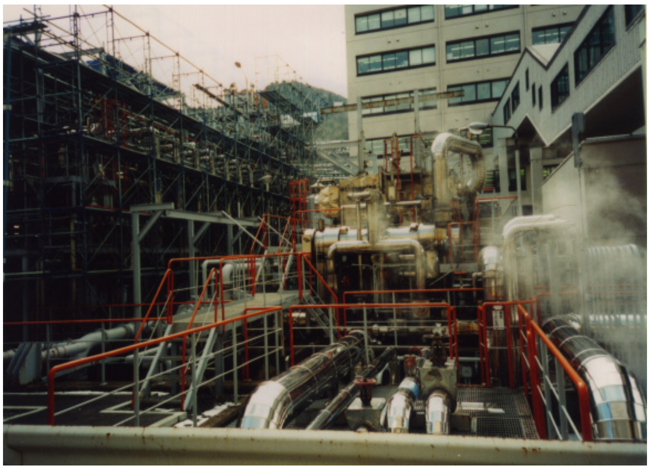

Fig. 2. Desalination plant at the nuclear power plant Ohi, Japan.

erational performance for more than 30 years. They have been free of any serious problems related to migration of radioactive material into the desalted water.

2.3. 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.

2.3.1. 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 (Fig. 3). It is a 6300 m^3/d hybrid MSF-RO desalination plant comprising of 4500 m^3/d multi-stage flash (MSF) and 1800 m^3/d 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.

Fig. 3. 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/d water was commissioned in 2003 and the MSF plant with a capacity of 4500 m^3/d water was commissioned in 2008. The salinity of seawater is normally around 33,000–38,000 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. 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. As presented above the MSF plant is designed for production of water with a quality of <20 ppm TDS and the RO plant with 350–500 ppm TDS; blending of both types of product water will produce a quality of 125–175 ppm TDS.

The production costs of the desalinated water were estimated 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.

2.3.2. Experience with nuclear desalination at Trombay

CIRUS, located at BARC, Trombay, is a heavy water moderated reactor of 40 MW(th) 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 (Fig. 4) for utilizing a part of its waste heat for producing desalinated water from seawater to meet the make-up water requirement of the reactor.

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

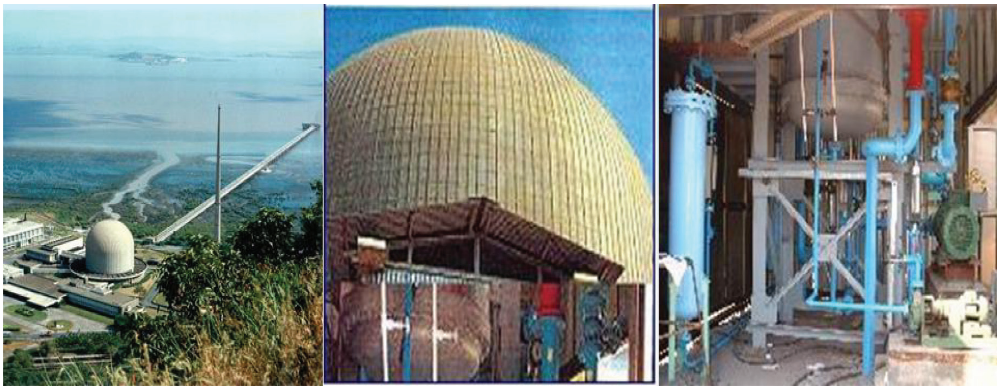

Fig. 4. Desalination plant at CIRUS research reactor, Trombay, India.

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 [10–12].

2.4. 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/d in two parallel units. The product water of the desalination plant is pumped to a set of twin reservoirs with a combined capacity of about 20 million litres. 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 (Fig. 5) has a pre-treatment system with chemical additions (e.g., ferric sulphate and polyelectrolyte as anti scaling), several types of filters (including UF — ultrafiltration) 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.

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.

Fig. 5. Desalination plant at nuclear power plant Diablo Canyon, USA.

2.5. Experience with nuclear desalination in Pakistan

The demonstration on nuclear desalination has just been completed. Early of year 2010, the plant was commissioned and consists of a 4800 m^3/d MED thermal desalination plant which is coupled to the Karachi Nuclear Power Plant (KANUPP). The demonstration plant at KANUPP will help PAEC to evaluate the most feasible options for developing future nuclear desalination facilities along the coastal areas of Pakistan thus contributing to the socio-economic development of these areas.

3. Economic benefits of desalination

The competitive advantage of nuclear desalination has been analyzed extensively in the literature. As mentioned before water costs are dependent on capital costs, energy costs and other O&M costs. An important benefit is that nuclear power can provide the desalination plant for its entire lifetime with cheap and stable energy. Economic comparisons indicate that water costs (and associated

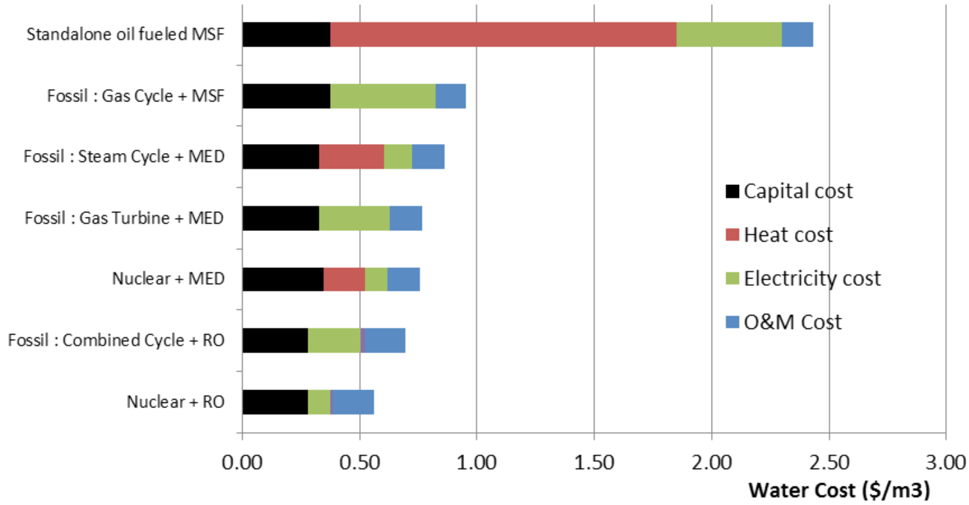

Fig. 6. Characteristic water costs for various power and desalination technologies.

electricity generation costs) from nuclear seawater desalination are generally in the same range as costs associated with fossil-fuelled desalination. Given the conclusion that nuclear and fossil-fuelled desalination are broadly competitive with each other, any particular future investment decision will depend on site-specific cost factors and on the values of key parameters (fuel price, interest rate, construction time, etc.) at the time of investment. Higher fossil fuel prices would of course favor nuclear desalination; higher interest rates would favor less capital-intensive fossil-fuelled options [13]. Fig. 6 summarizes some characteristic cases of various combinations of power and desalination plant technologies.

One implicit benefit of nuclear desalination is that fuel costs share of nuclear power is generally low in comparison with other energy producers. Moreover, the nuclear fuel cost is not affected by price uncertainties and of course is more sustainable comparing to fossil fuels. As a result, water costs are less volatile; i.e a doubling in the price of uranium would cause only 5% increase in the total cost of generation; while a similar increase in the price of Oil/NG would lead to 70% increase.

Moreover, nuclear desalination offers a solution for one of desalination's greatest impediments – its atmospheric impact. This effect is estimated by the use of 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. 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. Nuclear generates the lowest external costs after the wind power, even when the low probability accidents with high consequences are integrated into the calculation [14].

During an IAEA coordinated research project (CRP) it has been concluded that results of cost estimation are very site-specific. Within this CRP the following countries participated and presented their own cases: Argentina, China, Egypt, France, India, Republic of Korea, Pakistan, Russian Federation, Syrian Arab Republic, and USA [15]. Several types of desalination systems and power plants were evaluated and each country presented each own site-specific study. It was concluded that desalination plants coupled to combined cycle gas turbine (CCGT) plants as power source showed systematically higher water costs of about 20% compared to desalination plants coupled to nuclear power plants. In addition, water costs of thermal nuclear desalination plants showed high sensitivity to the discount rate, but also to the availability of the plant. 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%.

4. IAEA activities on nuclear desalination

Since the 1980s the IAEA has continuously promoted the use of nuclear power for desalination and provided its Member States with guidebooks, technical documents, and computer programs on this subject as well as the provision of technical assistance through the framework of technical cooperation programs. Several technical cooperation projects and international collaboration activities under the IAEA inter-regional technical cooperation (TC) framework have been successfully completed. IAEA organizes coordinated research programmes (CRPs) that bring together research institutes in both developing and developed Member States to collaborate on the research topic of interest.

To assist Member States facing both power or/and water shortages, the IAEA has conducted several studies to address the key issues that might arise in nuclear desalination and has made available a toolkit on nuclear desalination which provides information on how to utilize and perform an assessment on the economics of such options. The IAEA studies have shown that for some site specific conditions the small and medium sized reactors (SMRs), when operating in the cogeneration mode, could be most appropriate as nuclear desalination systems. Moreover, dedicated nuclear desalination systems are considered more suitable for remote and isolated regions. Yet if the grid size is large enough to accommodate larger sized reactor, the cogeneration option would even present a more viable and economic option of using nuclear power for nuclear desalination.

In order to support Member States for water cost estimation based on site-specific characteristics IAEA is providing the recently updated Desalination Economic Evaluation Program (DEEP) [16] that can be also used for comparison of various cases of standalone, fossil-fuel or nuclear desalination plants. Moreover, IAEA has recently released the Desalination Thermodynamic Optimization Program (DE-TOP) that compliments DEEP with thermodynamic analysis of coupling between the power and desalination plant. Both applications can be downloaded freely from the IAEA website.

5. Conclusion

Nuclear desalination is an attractive option due to its potential to use environmentally clean energy source from nuclear reactors, to be economically competitive energy source, to provide driving force for developing relevant infrastructures and to provide two essential elements for sustainability, i.e., electricity and water. Currently, several Member States have shown interest in the utilization of the nuclear energy for seawater desalination not only because recent studies have demonstrated that nuclear desalination is feasible, but also economical and has been already demonstrated in several countries. The accumulated experience in Asia and other regions around the world will undoubtedly contribute to what many consider as the world-wide central issue of the 21st century: the crucial need for new sources of freshwater for sustainable development. One is sure, the future for nuclear desalination is entirely dependent on the activities in the member countries which are focused on the development, design and deployment of different reactor designs.

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