

Environmental Issues Related to Nuclear Desalination

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Abstract—The paper presents an overview of environmental issues that may be expected with nuclear desalination. The analysis of coupling nuclear power with desalination plants indicates that adverse marine impacts can be mitigated with alternative intake designs or cooling systems. The atmospheric impact of desalination may be greatly reduced through the coupling with nuclear power, while maximizing the socio-economic benefit for both processes. The potential for tritium contamination of the desalinated water was reviewed. Experience with the systems and practices related to the radiological quality of the product water, shows no examples of cross-contamination. Furthermore, the indicators for the public acceptance of nuclear desalination, as one of the most important sustainability aspects of any such large project, show a positive trend. From the data collected, a conclusion is made that nuclear desalination should be supported by decision-makers.

Keywords—Environmental impacts, nuclear desalination, public acceptance, tritium.

I. INTRODUCTION

NUCLEAR desalination as a process, involves coupling between the steam cycle of the nuclear power plant and the desalination water streams. This is the case for both reverse osmosis (RO) and distillation processes (MED and MSF). In the case of RO, the heat is used to preheat the seawater fed to the membranes, while in the second it is used as energy to drive the distillation process.

Two basic arguments draw attention to nuclear desalination. Firstly, nuclear energy is expanding once again. With 56 new plants currently under construction [1], one of the lowest carbon footprints [2], and economic competitiveness with fossil fuels, it presents a long-term sustainable solution. Secondly, water scarcity has become a development constraint even in countries that are not in the dry zone. This has propelled desalination (both seawater and brackish water) to a global online capacity of more than 48 million m³/d [3], making it an important part of water management practices today.

The energy-intensity of desalination (which is currently done by fossil fuel use, save a few minor exceptions), has already started a strong interest in considering alternative energy sources. Although their current market share is close to zero, these energy sources are being suggested due to their

lower carbon footprints, as the improvements in the efficiency of the desalination processes are reaching their limit. Thus for example, the US National Research Council has suggested that the use of wind, solar, hydro, geo-thermal and nuclear power be considered. This should avoid, or significantly reduce desalination's green-house gas emissions [4]. Another approach is co-location of power and desalination plants, recommended by US NRC, UNEP and desalination experts [4, 5, 6].

Nuclear power plants generate low carbon electricity, but also a lot of waste heat. That is what makes them particularly suitable for co-location with desalination plants. If this waste heat is used for co-generation, the overall efficiency of the power plant will increase, with lower cooling requirements. Again, as desalination is an energy-intensive process, with a climate change effect dependant on the energy source, co-location with nuclear power plants will lead to lower carbon footprints of the product water. From the perspective of co-location and green-house gas emissions, nuclear energy would be the preferred choice (see Figure 1.).

Due to growing energy demand, energy price volatility, environmental concerns and technological advances, nuclear power in the past few years is experiencing a revived interest. More than 60 Member States expressed interest in introducing nuclear power [7]. Countries look at nuclear as a serious option to lower their carbon footprints as well as ensure energy security and price stability. Additionally, nuclear power has the possibility to offer alleviation of regional water stress or scarcity.

Many of the interested countries are in water stressed regions: North Africa, Middle East and Central Asia. More importantly, countries with operating nuclear plants such as China and India, and even USA, are experiencing lack of water which is becoming an issue in the development of their economies. With the financial benefits of co-location, and the evermore stringent environmental regulations, nuclear desalination is increasingly attractive.

The nuclear desalination plants in operation today, in Japan, India and the United States, have small desalination capacities mainly for makeup and potable water at the site only. Together with the currently closed MAEC nuclear desalination plant, operating between 1973 and 1999 on the Caspian coast in Kazakhstan, they have provided over 200 reactor-years of gathered experience [8]. Based on Fig. 2, it can be presumed that nuclear desalination will likely be of interest in several regions around the world, such as Middle East, North Africa, India, South West US and North East China.

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This paper will present the important issues likely to arise should nuclear desalination be deployed on a larger scale. An emphasis will be put on the quality of the desalinated water, the environment, and the public acceptance regarding the co-location of nuclear power and desalination plants.

II. ISSUES IN NUCLEAR DESALINATION

In order to understand the potential of nuclear desalination, for the limited number of such applications, one must start from the information available. Because of the regulations at the time, or the small capacity, no specific nuclear desalination plant has presented a comprehensive and detailed assessment of its environmental impacts. However, enough data has been gathered both on nuclear power generation as well as desalination of seawater, to be able to determine the combined impacts. Additionally, the case of the operating nuclear desalination plants offers some very useful information which will be presented in the following sections. Compiled, these cases offer a positive environmental argument for nuclear desalination.

A. Radiological health impact

As with all nuclear projects, the main concern is radiation exposure of the public. The coupling between a nuclear plant's steam cycle and the desalination plant is therefore of extreme importance. The main radiological issue here is tritium, due to several reasons. The first is its ability to penetrate various materials, migrating through steam generator and condenser walls. Secondly, it shares its chemical affinity with hydrogen, forming tritiated water in the form of HTO or T₂O. Third reason for concern is the higher health impact of tritiated water compared to gaseous tritium: according to the US DoE this is 25 000 times more hazardous because of the body's ready adsorption of tritium in the form of water [9].

Most of the national health standards for tritium in drinking water are based on the WHO guideline, recommending the upper limit to be 10 000 Bq/L [8]. There are some exceptions (see Table 1), but apart from the USA, all of the values are based on the ICRP recommendations and the WHO calculation [10].

$$GL = \frac{RDL}{DCF \times q} = 7610 [Bq / L] \approx 10000 [Bq / L]$$

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).

As another illustrative reference which will be used to present the case of nuclear desalination, natural levels of tritium registered in the precipitation for Seattle and Pittsburgh have a maximum value of 11.1 and 18.5 Bq/L respectively [11].

However, it must be said that there have been no nuclear

desalination cases where the WHO or national standards have been breached in this regard, or health problems caused by tritium in the desalinated water [8].

Currently operating, the nuclear desalination plant in Kalpakkam produces desalinated water with tritium content below the detectable limit [12]. This facility uses a standard isolation loop, with higher pressure than the primary cooling circuit of the nuclear plant (Fig. 3). An isolation loop was used at MAEC as well. This ensures that leakage of contaminated fluid into the desalination loop is prevented. The Japanese nuclear desalination plants have tritium levels in the secondary loop of 0.5 Bq/L which is below the natural tritium levels in seawater. Moreover, the tritium levels in the steam used as a heat source for the Multiple Effect Distillation (MED) is near zero [13]. District heating applications of nuclear power have a similar coupling to desalination. Background tritium levels were also reported in the hot water or steam [14].

Particularly for MAEC, removal of tritium from the primary and intermediate (isolation) circuits was done with specially designed tritium traps, which resulted with tritium levels in the desalination plant streams not surpassing 6 Bq/L [14]. The 80 000 to 145 000 m³/d of MED produced potable water was supplied to the city of Aktau and the local industry. From the perspective of health standards, the water produced at MAEC can clearly be deemed safe for human use. The same conclusion can be reached even when it is compared to the precipitation in Pittsburgh. This nuclear desalination plant was closed in 1999, after 25 years of service [8].

The current procedures and technologies in nuclear desalination have obviously proven in practice that the radiological quality of the product water is more than satisfactory. With the material and technological development, it can be expected that the radiological quality will be enhanced further in the forthcoming years. This is a fundamental reason of great importance for nuclear desalination: the product water is safe for consumption.

B. Marine impacts

Nuclear desalination plants need water for two purposes: for cooling of the nuclear power plant and as a feedwater for the desalination facility. Since for co-located power-water generation it is quite common that the desalination's feedwater is taken from the power plants outfall, the water withdrawal rates are defined by the cooling needs of the power plant. Depending on the cooling system, with its intake and discharge technologies, nuclear desalination has a real potential for adverse impacts on the marine environment. In the case of the intake, the predominant environmental impacts are due to entrainment and impingement of marine organisms. The discharge impacts on the other hand, depend on the temperature and chemistry of the effluents.

The standard solution for seawater withdrawal in nuclear desalination, seen in the available experience, is the use of direct intakes and once-through cooling. Placing the intake in areas with low biological activity and out of the migration

paths of marine organisms is of high importance. Yet, although a site specific issue, these systems may inflict damage on the marine ecosystems through entrainment and impingement of aquatic organisms [15]. As a result of the generally lower efficiency of nuclear compared to fossil fuel plants, the current once-through cooling requirements for nuclear power are the highest average in power generation. A much quoted report by EPRI suggests an average of 25 percent higher water withdrawal rates for nuclear compared to coal, or 95 to 230 m³/MWh(e) [16]. On a generic level, it is therefore very likely that the entrainment and impingement rates for nuclear desalination are also higher when compared to fossil fuel co-located desalination.

The entrainment and impingement rates are largely attributed to the intake velocity, which has been identified by the US EPA as a key factor affecting the impingement of marine organisms, and the volume of water withdrawal, which was confirmed by studies that found a correlation between intake volume and impingement rates [17, 18, 19, 20]. Additional measures are thus necessary if the marine environment is to be unaffected.

To mitigate for the adverse impacts, alternative designs have been applied with significant success. Direct intakes with travelling screens, barrier nets, or even reduction of intake stream velocity, may reduce entrainment by up to 80 percent from the baseline [21]. Low velocity intakes, imitating the effect of natural currents and therefore allowing for the organisms to swim away from the intake, have also been developed (using what is known as Aquatic Net Barriers or Aquatic Filter Barriers). New technologies such as horizontally-drilled drains that collect seawater from under the sea bed, and synthetic infiltration galleries that can be placed in a variety of sites regardless of their geology and biological activity, could potentially allow sufficient water supply for co-located desalination in combination with recirculating cooling. The choice taken from these water intake solutions for a nuclear desalination plant will be very much case- or site-specific.

The coupling of nuclear and desalination will likely mitigate the outfall environmental issues. For instance, the desalination facility can play the role of a heat sink for the nuclear plant, lowering the discharge temperature. Calculations have shown that 20 to 25 percent of the nuclear plant's waste heat may be used by the desalination process [22]. If this amount of heat is removed from the same quantity of discharge effluents, their temperature will also be 20 to 25 percent lower. Compared to a stand-alone nuclear power plant, this heat removal would result with an accordingly lower thermal impact on the marine environment from the nuclear desalination plant.

On the other hand, the adverse impacts from the high concentrations of toxic substances in the desalination discharges, are mitigated when diluted with the cooling water. For instance, a typical RO desalination discharges coagulants, biocides, chlorine inhibitors like sodium bisulfite, alkaline and acidic solutions, and high salinity brine. MED and MSF

(Multi-Stage Flash distillation) in addition to biocides, require antifoaming agents and antioxidants, with corrosion which may result in copper concentrations 200 times higher than the background [5], raising the brine's toxicity.

The most common discharge method, cheap and simple, is the surface discharge. It was also applied in the MAEC nuclear desalination plant, which discharged in a nearby artificial lake. There, the discharged waters were cooled, aerated and cleared of solids which settled at the bottom before released back into the Caspian Sea (Table 2) [23]. The radioecological surveys performed around MAEC found that measured values of radionuclides (including tritium) were not higher than background radioactivity level, concluding that the reactor had minimal additional environmental impact [24].

A different solution was applied at the nuclear desalination plant in Kalpakkam, India. Out of the monsoon season, is feeding its 1500 m³/d of brine to the local salt production facility, enhancing their production [12].

Overall, the higher cooling water quantity allows two things: (i) brine dilution from the desalination facility and, (ii) nuclear plant's waste heat has a lower thermal impact due to its higher utilization. Thus, although the most suitable cooling and feedwater solution will be very much a site specific issue, increased efficiency of nuclear power generation is coupled with a solution for the increased brine salinity and toxicity.

In conclusion, the design of the cooling water intake for any power plant can be engineered for a low adverse marine impact. But the coupling of nuclear and desalination allows for higher dilution rates of the brine, presenting lower adverse marine impacts from the outfall.

C. Atmospheric Impact

The main adverse impacts of desalination on the atmosphere are indirect, originating from the power source driving the energy intensive desalination process. Although the energy intensity of desalination has been significantly lowered in the past decades, it is approaching the thermodynamic minimum energy value, leaving only a small energy reduction potential [4]. In the same time, the seawater desalination capacity is growing exponentially (Fig. 4) [3]. It is clear that cleaner energy sources are needed if water is to be provided without the climate change penalty.

Having in mind the emissions from nuclear power (Fig. 1), nuclear desalination is the right step towards solving one of desalination's greatest impediments – its atmospheric impact. Indeed, nuclear power greenhouse emissions per kWh are much lower than coal, oil and natural gas; even lower than solar power's emissions; and at the same level or lower than wind power. For 1 m³ of desalinated water with a very efficient SWRO (2,5 kWh/m³), the atmospheric pollution contribution is: 1000 to 2000 g of CO₂eq with natural gas and 1950 to 3250 g of CO₂eq when coal is used as energy source. The respective case for nuclear and wind may result in GHG emissions of 10 to 65 g of CO₂eq to the atmosphere for a cubic meter of desalinated water [8].

Even radioactive emissions to the atmosphere are lower

from a nuclear power plant. Coal, among thorium, radon and other radioactive materials, contains 1 to 4 ppm of uranium. Since large quantities of coal are used in power plants, the overall quantity of uranium in the plant's air emissions is 100 times higher compared to a nuclear power plant of comparable size (1000 MW) [25]. Furthermore, the cost of externalities (in large due to atmospheric impacts) associated with nuclear are among the lowest costs [2]. As already mentioned, the US National Research Council also suggests the use of nuclear and different types of renewable energies for desalination to avoid green-house emissions [4].

Hence, nuclear desalination can be considered as environmentally benign from the aspect of air pollution and a suitable energy source for large desalination capacities, allowing for mitigation of atmospheric pollution. That is one very important reason for adopting nuclear desalination - the low climate change impact in providing energy and water.

D. Other impacts

The construction impacts of a nuclear desalination plant may be significantly smaller, due to the smaller size of the construction site and the lower specific use of materials for the power plant [26]. On the other hand, it may happen due to various indirect reasons that the nuclear plant's construction time can be prolonged, so special attention will have to be paid to this issue.

Land use impacts depend mainly on the needs for water and power. Desalination capacity of 100 000 m³/d with its auxiliary systems may require only 12 MW installed power [8]. Land use requirements for various energy sources are presented in Table 3 [27]. In this case small size reactors coupled with desalination plants might prove to be the better choice. The Korean reactor design SMART, with 330 MW(t) is planned for a MED desalination capacity of 40 000 m³/d, providing water and 90 MW(e) for the needs of approximately 100 000 population [28]. Nuclear desalination coupling might prove to be very much the choice for minimal land use.

The reason for this is that renewable energy coupled desalination has to account for the stochastic power supply. If water supply is to be constant, additional water storage has to be available as well as additional power for it. Essentially, this may increase land use to several times the nominal value. The effect on land use will therefore very much depend on the solar or wind availability factor, provided that water conveyance to the distribution network is not an issue.

Noise from the plant itself may be considered as an impact which is easily mitigated with appropriate acoustical planning and barriers. For the cooling system however, in this case as well as for visual impacts, once-through cooling systems have an advantage over cooling towers.

For reasons of minimal impact on its surroundings, the coupling of nuclear and desalination plants is an attractive option.

III. SOCIO-ECONOMIC IMPACTS

Socio-economic impacts of nuclear desalination are likely

to be positive, as it may increase the quality of drinking water, alleviate water scarcity and even be environmentally less damaging. Water availability can create wealth through development, as seen in the case of Aktau in Kazakhstan. Using IAEA's DEEP software, the water costs are estimated at 0.5 and 0.96 \$/m³ [29], which is a competitive cost value for desalinated water. Additional factor for economic competitiveness is the high energy availability from a nuclear plant, allowing for a continuous energy supply to the desalination plant.

Though documented and proven as reliable, the coupling of nuclear and desalination plants cause many concerns in the public. As a matter of high importance for sustainability, attention must be given to public acceptance. According to the small experience so far, this was not a problematic issue. Two cases confirm this.

The first one refers to the nuclear desalination plant in Kalpakkam where the nuclear desalination plant, based in a water-scarce region, is experiencing growth of demand for desalinated water [12].

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 (around 80%) [30].

The large number of desalination facilities in the world (more than 15 000 [3]), suggests that desalination does not share the same level of controversy with nuclear power. Yet, in the last few years, there is a trend of higher acceptance rate for nuclear power. Not only that the number of countries that are interested in introducing nuclear power has increased, but the public has also turned towards a more favorable opinion. In that regard, the EU countries have witnessed a significant change (Fig. 5) [31].

Although by no means a fact, it is plausible that coupling nuclear with desalination, might increase the support from the general public for nuclear power - particularly in this age of combating climate change. Fulfilling a variety of needs, as did the MAEC for Aktau, might prove as a valuable factor in the public debates on nuclear power.

IV. CONCLUSION

The gathered knowledge, experience and facts, strongly suggest that the next step in augmenting the benefits of nuclear power is nuclear desalination. It presents itself as a sound option that enhances water management practices as well as development policies. In offering energy, high reliability of supply and economic competitiveness, the application of nuclear desalination is also capable of mitigating environmental impacts.

Thus, it qualifies as a serious option for decision-makers' consideration. Its potential should be used more in the short-term future, for the benefit of societies which seek to ensure not only energy, but also adequate water supply.

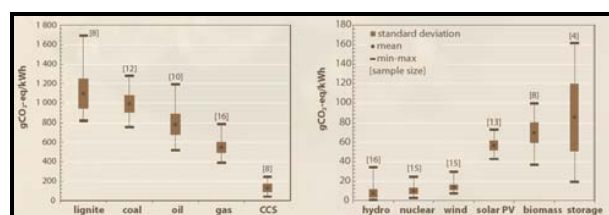


Fig. 1 Greenhouse Gas Emissions (g Ceq per kWh)

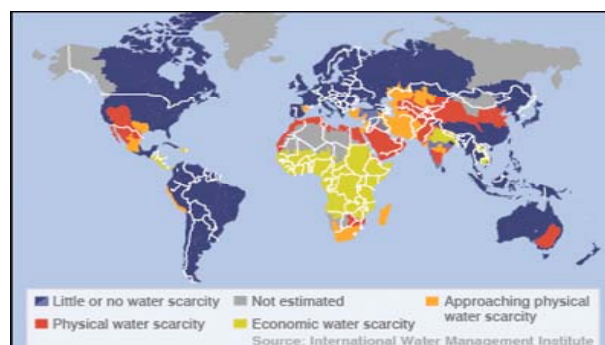


Fig. 2 Global water scarcity

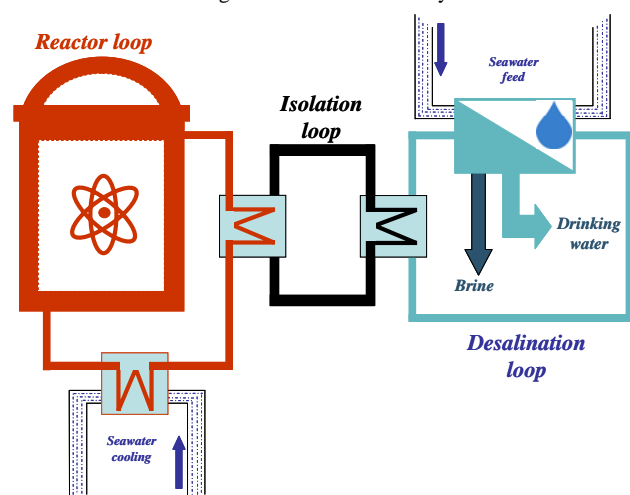


Fig. 3 Schematic of nuclear and desalination plants coupling with an isolation loop

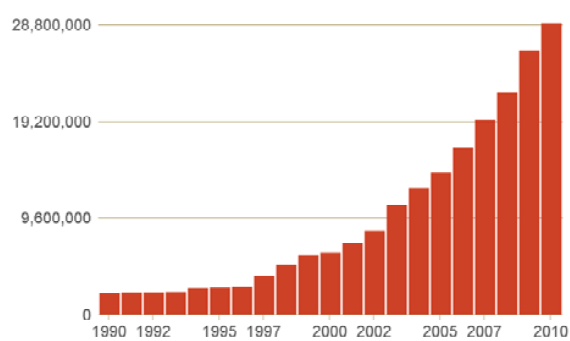


Fig. 4 Global on-line seawater desalination capacity [m³/d]

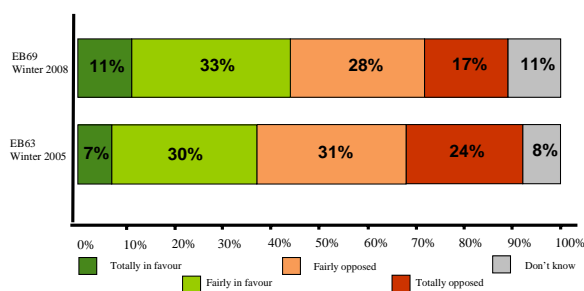


Fig. 5 Growth of support for energy production from nuclear power stations in the EU

TABLE I
REGULATORY TRITIUM LEVELS IN DRINKING WATER

Country	Tritium limit [Bq/L]
European Union	100*
USA	740
Canada	7000
Kazakhstan	7700
Switzerland	10000
WHO	10000
Finland	30000
Australia	76103

* This is an alarm level, not a regulatory limit.

TABLE II
MAEC DISCHARGE CHARACTERISTICS

Parameter	Brine from the desalination plant	Flow into the Caspian Sea*	Quality of water in the Caspian Sea
Volume [1000 m³/a]	100 000	844 220	/
TDS [mg/L]	40-45000	/	13500
Temperature [°C]	/	2-24	2-24
pH	8.1-8.3	8.1-8.3	8.2-8.3
Iron [mg/L]	0.12-0.2	0.04-0.07	0.02-0.04
Copper [mg/L]	0.012-0.02	0.004-0.006	0.003-0.005
Oil products [mg/L]	0.02-0.07	0.03-0.05	0.02-0.05
Suspended substances [mg/L]	13-20	11-16	10-20
Cesium-138 [Bq/L]	/	$< 4.96 \times 10^{-2}$	$< 4.96 \times 10^{-2}$

*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.

TABLE III
LAND USE FOR POWER PLANTS

Power source	Solar PV	Wind	Nuclear	Gas-fired	Geothermal
Area needed for 1 GW(e) [km²]	10-50	22	3	6.5	7

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