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Nuclear desalination: A review on past and present

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ABSTRACT

Dual nuclear electricity-thermal desalination plants were the subject of investigation for almost 5 decades, starting around 1960 and on. Desalination plants use the steam released from the reactors to drive the evaporation process, just as in conventional dual-purpose plants. They are installations of very large capacities, suitable for construction in places where shortage of water and conventional fuels prevails, or where the transport of both is extremely expensive. From the beginning, many studies on these combinations have been made and today several such installations, of a rather small capacity, are in operation. In this paper, an attempt is made to present the most important studies on dual nuclear electricity-desalination plants, from the earlier ones up to the present date.

Keywords: Nuclear reactors; Thermal desalination; Agro-industrial complexes; Feasibility studies

1. Introduction

A nuclear desalination plant is practically a dual-purpose power and thermal desalination plant, in which the turbine is driven by steam from a nuclear reactor. Coupling of nuclear reactors with desalting plants does involves some technical problems, however steam supplied to the water plant is largely affected by the cost of power and steam supplied to the water, as is also the case in any conventional dual-purpose, power-water plants. These factors that influence the integration of nuclear power and water desalination plants are discussed [1]. The substantial difference in coupling a nuclear reactor to a desalination plant is mainly the grade between the steam produced in a reactor and nuclear reactor to a desalination plant is mainly the grade between the steam produced in a reactor and that required for heating the feed water for the desalination. Steam from reactors is delivered at higher temperatures than those needed for the feeding water for desalination. Heating up the feed water to higher temperature may cause heavy scale deposits. Thus, as reactor steam can not be directly fed, there exist various coupling configurations to lower the steam temperature, which are presented by D' Orival [2]. Interest in nuclear desalting became prominent when the increased size of nuclear plants and advancing nuclear technology became promising at reducing energy costs. One of the main problems in using nuclear energy for desalting, as steam cost decreases considerably with increasing power level, is that only large size nuclear reactors were expected to be sufficiently economic for coupling with desalination plants. Parallel advances in desalting technology gave hope for scale up of desalting plants to sizes suitable for reactor use.

Nuclear power plants used to be more capital-intensive than conventional power plants. Accordingly over-

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head costs were higher for nuclear power plants, but fuel costs may be lower. Nuclear-plant economics do not vary to any great extent with geographic location. This factor is of importance for those regions or countries, which have low availability of fossil fuels. Thus, nuclear power offers an additional degree of freedom in securing local energy requirements. These characteristics of nuclear energy are of particular advantage to developing countries, which lack of abundant natural energy resources. Other advantages of nuclear desalination may include the fact that nuclear power units are operated at higher load factors than most fossil fuel power plants and provide a more compatible load pattern for combined water production. Furthermore, the cheap electrical power and the large amounts of desalinated water may benefit the construction of large industrial and especially agro-industrial complexes. Large nuclear desalination plants can be used, especially in arid regions to provide water and electricity to large industrial and agro-industrial complexes [3,4]. Many countries, in early years, especially the developing ones expressed an interest mainly in agro-industrial nuclear powered complexes. For this reason IAEA [5] organized a Panel on "Value to agriculture of high-quality water from nuclear desalination" in Vienna in 1967.

Both nuclear and desalination technologies are well proven due to the experience gained over the past 5 decades. Today, for nuclear electricity production, there exist more than ten thousand reactor-years of operating experience whereas more than 16% of electricity produced, world wide, is provided by nuclear power stations [6]. On the other hand, desalination industry provides today more than 50×10^6 m^3/d desalinated water all over the world and these figures are increasing rapidly. 40% of this desalinated water is produced by thermal energy and the rest by electrical driven methods, mainly reverse osmosis and less by electrodialysis [7].

2. The early years

The interest in the possibility of using energy from nuclear plants for large scale desalination plants arose in the early 1960s. It has been recognized that by combining electric power and water desalination in single, large dual-purpose plants, inherent economics can be achieved in relation to single production of either water or electricity. Until about 1975 intensive activities took place in the form of design studies for dual water-nuclear power plants. Hence, a large number of studies were made, either of regional interest or engineering background.

- **Egypt**: Studies have been conducted on a dual-purpose plant of 50 MWth natural uranium, heavy water moderated reactor to be coupled with a thermal desalination plant [9].
- **France**: Design features of a 25,000 m^3/d fresh water unit were reported by Balligant and Balligant et.al. [10,11], the multiplication of which can form several hundred thousands m3/d in dual-purpose plant, supplied with both water and power from a nuclear reactor.
- **Germany**: Badische Anilin und Soda Fabrik (BASF) in Ludwigshafen was the first industrial company to consider a nuclear station. Steam requirements of up to 2000–2500 t/h and requirements of 700 MW formed the necessary potential for a full-load nuclear reactor of 2000 MWth over a year [12]. The erection of a seawater desalination plant in conjunction with heat supply from various nuclear reactors built or planned in West Germany have been investigated by Lenz [13]. The economics of a dual-purpose electricity-desalination plant using a high temperature reactor as heat source, along with a gas turbine and a multi-stage-flash distillation unit was analyzed by Schwegmann and Bonnenberg [14] at the Nuclear Research Center, Juelich.
- **Greece**: A study was made with the assistance of the Office of Saline Water (OSW), US Department of the Interior and the US Atomic Energy Commission, [15] for a nuclear fuelled, dual-purpose power-desalination plant of about 190,000 m^3/d and 300 MW capacity.
- **Israel**: The country is very poor in natural energy resources and most of the oil is imported. All power stations are interconnected by a countrywide grid. A joint US–Israel technical team was nominated, with the task to review and analyze the possibility to meet electricity and water needs with a large, dual-purpose desalting-power plant. The feasibility study showed a capacity of 200 MWe and 380,000 m^3/d of desalted water. A light water reactor was considered by Kaiser Engineers [16,17]. In extended Reports of Technion by Aschner et al. [18,19] the feasibility of nuclear reactors for seawater desalination from 1964 to 1967 is presented, with an analysis of eight reactor types. Adar [20] makes an analysis of coupling nuclear power with horizontal multi-effect desalination units and in a later paper [21] he discusses the possibility of applying nuclear desalination to large agro-industrial complexes in Israel.
- **Pakistan**: Kamal [22] illustrated the theoretical use of an extraction cycle for combining a one Mgd multi-stage-flash desalination plant with the 456 MWth heavy-water nuclear reactor installed near Karachi. In a follow-up paper Kamal [23] analyses the results of a feasibility study on nuclear desalination with particular reference to the Karachi-Sonmiami area.
- **United Kingdom**: Although Britain has never faced any particular water problems, a few studies have been made on a 200 MWe steam-generating, heavy-water reactor where 377,000 m^3/d of fresh water were produced by eight multi-stage flash units, as described by Clelland [24]. In another study, it was estimated that in the range 667–1500 MWth, nuclear heat must be competitive to that generated by fossil fuels [25].

- **USA**: Early studies include the evaluation of desalting plants with a capacity of 15–150 Mgd (57,000–570,000 m^3/d) and nuclear reactors of 200–1500 MWthby by Catalytic Construction [26]. Five small-capacity desalting plants have been constructed, and were supplied with heat from nuclear reactors: one in San Onofre, California, with a capacity of 658 m^3/d, two at Indian Point, New York, of 545 m^3/d capacity and two at the Surry, Virginia, nuclear power plant with a capacity of 655 m3/d. The plants were of local importance only.
  The most important feasibility study was the one carried out for the Metropolitan Water District of Southern California [27]. The proposal was for approximately 1900 MW of gross electrical power from two reactors and three multi-stage flash (MSF) trains producing 190,000 m^3/d per train. The cost of desalinated water was estimated at ¢9.64/m^3 [28]. Another study was performed concerning a large-scale installation for the New York City Metropolitan area. Details of the study are given by Clyde and Blood [29] and by Shiozawa [30]. It was concluded that generation of off-peak power and steam are the most economical alternatives to make this project feasible. In another study Brice and Shiozawa [31] analyse a large-scale prototype desalting plant to evaluate the technical and economic feasibility of a 151,000 m^3/d (40 Mgd) to be located adjacent to nuclear units under construction in South California .
- **USSR**: In the Ex-USSR studies on nuclear-desalination plants were also presented, such as those described by Alksnis and Kruflikov [32] and Sinev et al. [33]. Here it has to be emphasized that despite the optimism and the expectations associated with nuclear desalting and despite the large number of engineering studies in many countries, the only large capacity plant ever built was that at the Mangyshlak Peninsula, in the Caspian Sea (ex-USSR), the Shevchenko, later renamed Aktau plant (now in Kazakhastan). The nominal power of the BN-350 reactor was 1000 MWth, producing 150 MW of electric power and 120,000 m^3/d of desalinated water. Its operation has ceased since 1999. Papers on this plant are given by Novikov et al. [34] describing the plant, Egorov et al. [35] on the improvements of the plant, Trofimov et al. [36] and Baranov et al. [37] on the operating experience gained during operation of the Shevchenko nuclear desalination plant.

There were also some other countries that presented studies on nuclear desalination, such as: India, Japan, Kuwait, Saudi Arabia, and Sweden. Details on the relevant activities and studies along with detailed bibliographic references can be found in Water Desalting, main volume and supplement I by A. Delyannis and E. Delyannis [38]. The types of reactors suitable for coupling with thermal desalination plants are presented by Giambusso [39] in a book on *Water Production Using Nuclear Energy* published by the University of Arizona .

3. Recent years

The interest on nuclear desalination was revived in the early 1990s by promotions of the IAEA, in light of the experience gained over the previous years. The promotion of nuclear energy in the past was focussed on generating electricity, intended for district heating and for coupling with desalination plants especially for providing water and electricity to agro-industrial complexes. The present interest is focussed instead on small nuclear reactors for desalination, concerned also with environmental effects and safety.

On the other hand, thermal desalination technology has considerably improved, especially as far as performance and cost reduction of produced desalinated water. Around the mid-1970s, reverse osmosis (RO) was introduced commercially as part of the proven desalination technologies, and reactors became competitive to fossil fuels plants. A report by IAEA [40] discussed the economic viability of dual nuclear seawater desalination plants compared with desalination using fossil fuel. More reports of IAEA on this subject can be traced in w.w.w.iaea@.org.

With the relevant interest growing, IAEA [41] adopted a number of resolutions on this subject and performed studies to assess the technical and economical use of nuclear reactors for desalination. Three options were identified and are recommended for nuclear desalination demonstration plants:

(a) Reverse osmosis in combination with existing and operating reactors.
(b) Reverse osmosis in combination with nuclear power.
(c) Small reactors in combination with multiple-effect distillation plants.

Misra and Kupitz [42] summarize past experience, current developments and dual plants for nuclear-powered desalination. The authors' present designs, under construction and/or operating plants coupled to thermal and reverse osmosis units. The following activities are commissioned in nuclear desalination:

- **North Africa**: An early study by IAEA [43] on the potential of nuclear desalination for five North African Countries, Algeria, Egypt, Libyan Jamahiriya, Morocco and Tunisia was completed in 1996. It was concluded that the cost of desalted water for the most economic fossil fuel and nuclear driven desalination plants was in the same range, as reported by Kupitz [44]. Crijns [45] describes the potential of nuclear power for desalination, for Nnorthern African regions.
- **China**: Many designs have been studied for coastal Chinese cities using Nuclear Heating Reactors (NHR).

Among those, a pre-feasibility study for coupling a 200 MWth, deep-pool reactor (DPR) with a multi-effect desalination plant (MED) of 80,000 m^3/d capacity in the Tianjin coastal area was performed and presented by Tian and Cheng [46]. In another study by Jia and Zang, [47] a nuclear heating reactor type NHR-200 is coupled to a multi-effect desalination (MED) plant.

- **Egypt**: A feasibility study for dual nuclear RO-desalination plant was performed. The pre-heat RO plant has already been constructed in El-Dabaa [48]. Karameldin et al. [49] developed a mathematical model on the dynamics of RO in a stand-alone, co-generative nuclear reactor considering the effect of primary side transient on the system reactivity change.
- **France**: In collaboration with Libyan Jamahiriya, France undertook a techno-economic feasibility, as well as main study to adapt a hybrid desalination MED/RO system to the experimental reactor at Tajoura. A feasibility techno-economic study was also performed for Agadir and Laayoun, Morocco [50]. In a joint effort France provided Tunisia with a techno-economic feasibility study for Skhira, at the south-eastern part of the country [42].
- **Japan**: This was among the first countries that erected and operated small nuclear desalination plants. of 538 MWel-net/, and 2000 m^3/d MSF. From 1982 up to 1997 various other small-capacity nuclear desalination plants have been erected, ranging from 538 to 1127 MWel-net/ and desalination capacity from 1000 up to 5600 m^3/d. The detail characteristics of the Japanese plants are presented in the paper of Misra and Kupitz [42] and in IAEA TECDOC-1326 [51].
- **India**: Misra [52] describes the design of the nuclear desalination demonstration project (NDDP) at Kalpakkam near the Madras Atomic Power Station. The desalination plant is a MSF/RO hybrid system consisting of a 1800 m^3/d reverse osmosis plant and a 4500 m^3/d MSF unit. Reverse osmosis has been in operation since 2000 and the study refers to an increase of desalinated water capacity to be installed. Dangore et al. [53] present the experience gained in constructing and operating the above nuclear desalination plant at Kalpakkam and in a final paper by Nagaraj et al. [54] the problems encountered during erection, commissioning and operation of the Kalpakkam plant are analysed. Another study by Balasubramanian et al. [55] describes the seawater reverse osmosis plant to be erected at the Kudankulan nuclear power station. It is expected that 2400 m^3/d fresh water will be produced.
- **Kuwait**: In a country depending almost entirely on desalinated water, Darwish et al. [56] outlined the prospects, the expected problems and merits of using co-generation nuclear power desalting plants in Kuwait and other Gulf Countries, by using light-water reactors. They concluded that nuclear power plants are more competitive compared with the most efficient gas/steam, combined-cycle plants.
- **Morocco**: A preliminary study using a 10 MWth heating reactor from China, to be coupled with a MED desalination plant, was the objective of a governmental agreement between Morocco and China [50]. A further study was undertaken on coupling nuclear reactors to different combinations of desalination plants [57].
- **Pakistan**: An engineering feasibility study was presented by the Pakistan Atomic Energy Commission, aimed at integrating a 1 Mgd thermal desalination plant into the for almost 30 years in operation Karachi nuclear power plant. A RO desalination plant is already coupled to the nuclear operating plant [52].
- **Russia**: The Russian Federation faces, for the time being, no particular water shortage problems. Nevertheless, it participates in relevant studies and R&D activities, e.g. the special Russian Project on the "Use of Small Size Russian Nuclear Reactors as Power Source for Nuclear Desalination Complexes" by using reactor types KLT-40C, Nika and Ruta. Another study, the RF MINATOM is a Russian–Canadian project on a floating nuclear desalination complex based on a Russian floating power unit and Canadian preheating RO units [51]. A co-generation nuclear-desalination plant was also constructed in the shipyard in the Arkhangelsk region, equipped with two KLT-40s reactors [48]. Only technically and economically proven reactors may be used for coupling to desalination plants. The first generation of proven reactors proposed in the early studies were [2]: Boiling-water, enriched-uranium reactors (BWR), Gas-graphite reactors, natural-uranium (GGR), Pressurized-water reactors, enriched-uranium (PWR), Heavy-water reactors (HWR), natural-uranium and advanced, gas-cooled reactors, with enriched uranium. The types of reactors used in presently operating or under study plants are: BWRs coupled to MSF, MED and RO desalination plants. These plants are in operation or under consideration in Japan and other countries. In India and Pakistan, HWRs are proposed coupled with MSF/RO hybrid plants and MED. In China heat reactors (HHR) are being used, coupled to MED desalination plants. Finally other countries, such as France, USA etc. adopted high temperature reactors (HTR) coupled to MED or RO desalination units [48].

The authors may also note that the new promising desalination method of Membrane Distillation, being a low-energy, small capacity procedure may be an alternative for coupling to nuclear reactors. Khayet et al. [58] studied three membrane distillation processes, i.e., direct contact, sweeping gas and vacuum membrane distillation, giving a theoretical analysis for mass and heat transfer. They conclude that membrane distillation can be an alternative for liquid nuclear waste treatment. Another promising desalination method is Humidification/ dehumidification. Both new methods are of small capacities and, for the time being, not yet commercialized. They can be powered either by conventional energy sources or by solar energy

In very recent years, the solar energy source and the associated new technologies, suitable for remote regions were introduced into the already established technical applications of desalination: The concentrating solar collectors that can be coupled to conventional desalination plants. They are dual purpose power–desalination plants. It is a new, already mature technology. Large concentrating collector fields producing medium or high temperature steam for electrical power-thermal desalination and/or reverse osmosis units, though not yet totally commercialized, may be competitive to dual nuclear desalination plants of small capacities, but not for large capacities better suited to nuclear coupling. Trieb and Mueller-Steinhagen [59] presented a study on concentrating power seawater desalination for Middle Eastern and North African (MENA) countries, concluding that seawater desalination based on concentrating solar power offers affordable, sustainable and secure fresh water potentials. As MENA countries are faced with a severe water crisis, nuclear-coupled desalination may offer a solution to problem. Most large conventional desalination plants are dual purpose, electricity–desalinated-water producing installations. El-Nashar [60] presents a state-of-the-art review on cogeneration power-desalination concluding that the optimum cogeneration option depends strongly on the load variation throughout the year and that: the power-to-water ratio of different combinations of cogeneration plants spans the range from 4 to 18 MW per imperial million gallons per day.

From the numerous studies and the applications already available it has been proven that cogeneration of electricity and desalinated water offers a technically and economically feasible option although some farther deployment is needed, mainly in the coupling of the large amounts of reactor waste heat to desalination units. Khamis [61] reports that when coupling nuclear systems the following considerations must be taken into account:

- Avoiding activity cross contamination
- Providing back-up heating energy sources, in case the nuclear system is not in operation
- Incorporating certain design features so that the thermal desalination option may also be used

Barak [62] reports that in order for nuclear desalination to be preferred over alternative solutions the system must overcome three competing factors:

- Single-purpose desalination processes which operate with reliable electricity from the grid
- Dual-or single-purpose plants where low cost energy is available, and
- Absence of other economical water resources

Barak also analysed the advantages and disadvantages of nuclear desalination vs. other conventional energy sources.

3. Conclusions

From this very brief review on nuclear desalination and from the numerous studies from the early years up to the present day as well as the few low-capacity applications already available, one may conclude that coupling conventional desalination plants to nuclear installations is a feasible and already mature technology which can be beneficial for many regions world wide. This might be the time for agro-industrial/nuclear desalination complexes to be re-examined under new perspectives with regard to the exploitation of natural resources.

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