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IAEA coordinated research activity on nuclear desalination: the quest for new technologies and techno-economic assessment

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HIGHLIGHTS

- The IAEA CRP identified some promising technologies to support nuclear desalination.
- Using heat pipes in nuclear desalination enhances overall safety and economics.
- Hybrid desalination technologies seem to be the most suitable option.
- Low temperature nuclear desalination is economically competitive.

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ABSTRACT

A coordinated research project (CRP) on new technologies for seawater desalination using nuclear energy was conducted by the International Atomic Energy Agency (IAEA). The CRP goal was to quest for innovative seawater desalination technologies which can be integrated with the existing nuclear power plants, could make seawater desalination using nuclear energy more viable, and promote the exchange of technical information on national programs in the field of seawater desalination using nuclear energy. Other activities carried out within this CRP include conducting preliminary feasibility analysis for nuclear seawater desalination based on national site specifics, economic and life cycle assessment of nuclear seawater desalination projects, and scoping of new ideas to improve the IAEA Desalination Economic Evaluation Program (DEEP). Among other outcomes, the CRP identified several potential technologies which can make nuclear desalination a more viable option such as: heat pipe, the low temperature Multi-Effect Desalination (MED), enhanced Reverse Osmosis (RO) at elevated temperature, and hybrid low temperature desalination processes. This paper summarises the activities carried out by participating Member States and the results achieved. Elaboration on different nuclear desalination technologies is provided. It also presents an overview of the financial model suggested for further improvement of the IAEA DEEP tool.

1. Introduction

Shifting from fossil fuel driven desalination plant to a more environmentally benign option became of great interest due to increasing environmental concerns and global warming. Renewable and nuclear based energy sources are eyed as the most appropriate candidates to be utilized to power large desalination plants. There are several renewable driven desalination plants operating around the world. However, the cost of product water is still relatively high and very much affected by the instability and fluctuation of the energy source. Nuclear power technology is well established. Currently, there are over 200 reactor-years of operating experience in nuclear desalination [1–3]. Energy may be provided from the nuclear reactor to the desalination plant in form of thermal, electrical or both energies. This depends on the selected desalination technology and the reactor type. Water cooled reactors like pressurized light and heavy water cooled reactors (PWR, PHWR) are the most utilized reactors for desalination as in Japan, India, USA, Pakistan and China. In Aktau, Kazakhstan, the fast reactor BN-350 was operating until 1999 for the production of power and fresh water.

Currently, a worldwide renewed interest has been witnessed in nuclear desalination, such as in Saudi Arabia, UAE, Egypt, and Algeria. For the last 25 years, the International Atomic Energy Agency (IAEA) have been recognizing seawater desalination using nuclear energy for fresh water production as one of the most promising alternatives for nuclear cogeneration. This paper covers the recent activity of the IAEA on nuclear desalination. Elaboration of the results and outcomes of the R&D activities conducted by Member States on novel technologies related to nuclear desalination are presented.

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2. IAEA coordinated research activity

The IAEA coordinated research projects (CRPs) have been conducted with the aim of enhancing the capability of interested Member States for building up innovative and advanced nuclear technologies. This target is being achieved through promoting the exchange of information and expertise and conducting collaborative R&D to resolve issues associated with specific problems or concerns. The IAEA conducted a coordinated research activity (CRA) on the innovative technologies that would help making nuclear desalination safer and more economical. This comes as the third coordinated research project (CRP) following the earlier two CRPs that were concerned with the optimization of coupling nuclear reactors with desalination plants and the economic, thermodynamics and safety assessments of the current technologies. The third project title is 'new technologies for seawater desalination using nuclear energy'. The aim of this project is to further investigate the novel and innovative technologies among the participating Member States for a sustainable and feasible nuclear desalination scheme. This CRP was launched in 2009 with the participation of research proposals from 9 Member States: Algeria, Egypt, France, India, Indonesia, Pakistan, the Syrian Arab Republic, the United Kingdom and the United States of America.

3. Results of the CRP domains

3.1. Promising technologies for nuclear desalination

Several R&D activities were conducted through the IAEA CRPs to demonstrate more viable, reliable, cost effective and safe nuclear desalination cogeneration plants. Novel ideas are pursued to alleviate environmental impact and prevent radioactive cross contamination to the product water, especially reducing tritium concentration in the product water [4]. Utilizing the harnessed nuclear waste heat is the most convenient approach to integrate desalination for fresh water production with nuclear power plant operating for electric power production [5]. This brings the systems to more environmentally benign multi-generation system, reduces the operation losses and results in an increased overall operating efficiency. An example of such systems is the one proposed by Gabaraev et al. [6] for multi-purpose integrated nuclear based system. This system is based on the VK-300 boiling type reactor in Russia. Their developed system produces fresh water and thermal energy along with electric power. In the following, most promising novel ideas introduced by the participating Member States are presented.

3.1.1. Experimental investigation

3.1.1.1. Heat pipe technology. The utilization of heat pipe technology for desalination purposes have been reported in the literature, mainly for solar desalination systems [7,8]. For nuclear desalination sector, heat pipes technology poses a good alternative for the shell and tube heat exchangers commonly used in desalination systems. Due to irradiation corrosion among other risks [9–12], there are concerns regarding the mixing of streams in the evaporator, between the steam in the tubes and the seawater side, or in the condenser, between the produced fresh water and the contaminated seawater. This gives a risk of contamination that requires system shut down for maintenance and decontamination. The utilization of heat pipes eliminates the risks of contamination as the nuclear reactor steam and seawater stream are physically separated from the product water. The ultrahigh thermal conductivity of the heat pipes has two effective advantages to the system: first is the elimination of the pumping power requirements as the heat transfer process is passive, the second advantage is the utilization of temperature difference recording between the hot and cold sides of the heat pipe as indicator of any issues with the operation through the heat pipes. In addition, less fouling problems would be experienced as fouling only affect the external surfaces of the heat pipes. Another merit of using heat pipes is that if the heat pipes partially stopped functioning, the system remains operational, but at a reduced capacity, until the next scheduled maintenance. Fig. 1 shows heat pipe proposed system. The heat carried by the nuclear steam is used to evaporate the physically separated seawater stream. It is also utilized to recover the waste heat from the rejected brine [13,14]. In general, the use of heat pipes is economically competitive [14] and provides efficient heat transfer with radiation safety of the product water due to lower tritium diffusion [10,11,14]. Using heat pipes instead of the standard nuclear-desalination intermediate loop leads to reduction in capital, operating and maintenance cost elements. Experimental investigation is conducted for more understanding of the process. Heat pipe of 1 m long and 22 mm outer diameter is tested using water as working fluid and copper shell. The results concluded that a temperature difference of 0.1 °C is required to transfer 1 W of heat between the two ends of the heat pipe. This thermal resistance is almost 300 times that of solid copper tube. The thermal resistance of the heat pipe can be reduced to values as low as 0.05 °C using heat transfer enhancing mechanisms [15–18].

This technology can be also effectively used as an auxiliary intermediate loop for the prevention of contamination in nuclear desalination plants, especially tritium contamination. Tritium is a highly penetrating radioactive hydrogen isotope. It is considered as the primary radiation concern as it is capable of oxidization forming tritiated at hazardous levels for drinking water. The high thermal heat transfer effectiveness of heat pipes results in smaller heat transfer surface, compared with conventional heat exchangers, for the same energy transfer. Hence, a reduction of the diffusive surface for tritium is achieved.

3.1.1.2. Low temperature evaporation plants (LTE). LTE plants are actually MEDs operating at very low temperature levels. This gives a great potential to utilize the nuclear waste heat effectively for water desalination. It also leads to a higher overall operating efficiency, more economic competitiveness and sustainability. The Bhabha Atomic Research Centre (BARC) developed a demonstration nuclear desalination plant using a 40 MW_{th} nuclear research reactor, using LTE technology. The plant is designed to produce 1.25 m^3/h of water with high purity (<2 μS/cm) using portion of the thermal heat rejected from the reactor primary cooling cycle. The produced water is utilized as reactor makeup water. The reactor uses metallic natural uranium, heavy water moderator, demineralized light water coolant and seawater as secondary coolant. The waste heat is captured through the Primary Cooling Water (PCW) and transferred to the desalination unit through the intermediate isolated cycle. A schematic for the modified system employing double effect LTE desalination unit can be seen in Fig. 2.

The waste heat harvested through the isolation loop is in the form of hot water at 65 °C. This heat is transferred from this hot water flowing at rate of 78 m^3/h in the shell side of a shell and tube heat exchanger heater of the first effect of the evaporation plant. In the tube side of the heat exchanger flows the seawater at rate of 4 m^3/h and is heated from 37 °C to 55 °C. Seawater in the tube side of the first effect is under vacuum created by water jet ejector. Vapor and concentrated seawater from the first effect are directed to the second effect. The second effect generated vapor flow through the demisters to the horizontal overhead condenser and condenses producing fresh water. Seawater from cooling tower basin is directed to the condenser tubes as a coolant before it flows to feed the first effect. The condensate from the second effect heater and condenser resemble the plant produced water.

3.1.1.3. Enhanced reverse osmosis (RO) at elevated temperature. The salt separation process in RO systems operates with high pressure pumps. Several studies recommend using energy recovery devices to save pumping power [19], and preheat the seawater feed to increase the plant productivity. The latter option needs more long term investigation to study the effect of the feed temperature on the membrane lifespan. Based on the system described in Fig. 2, a modified pilot plant with the utilization of UF-RO system, coupled with LTE was developed as