European Water 58: 345-350, 2017.

Water management in nuclear power plant using advanced low-temperature systems

G. Zakrzewska - Kołtuniewicz
Institute of Nuclear Chemistry and Technology (INCT), ul. Dorodna 16, 03-158 Warsaw, Poland
e-mail: g.zakrzewska@ichtj.waw.pl

Abstract: Nuclear power plants (NPPs) consume large quantity of water, more than coal-burning plants. Water is used for every-day plant operation, for dissipation of large amount of heat produced in nuclear reactors. Big volumes of clean water are needed in emergency situations for decontamination of contaminated buildings, equipment and apparatus. On the other hand, the need for cleaning large amounts of contaminated water in such cases requires appropriate purification systems. Moreover, during regular operation the NPPs produce also some amounts of contaminated liquid effluents that need treatment. Appropriate water management in nuclear power plants reduces water consumption and decreases emission of radioactive pollutants to the environment. In the paper the possibility of using membrane methods for water desalination, which could be coupled with nuclear reactor supplying heat and electricity for operation of membrane installations, is reported. Such processes like reverse osmosis and membrane distillation are low-temperature desalination methods that could be driven using heat from the condenser or from the vapour generator. The main aims to construct the membrane installation in the NPP will be production of large amount of clean water for power plant purposes, as well as wastewater decontamination. The use of nuclear energy for desalination provides number of benefits; such an approach is economic and environment-friendly. Shared facilities, low operational costs and the possibility of optimisation make nuclear desalination competitive and profitable method for production of pure water, as well as rational for low-level waste management in the future NPPs.

Key words: nuclear desalination, reverse osmosis, membrane distillation, water management

1. INTRODUCTION

Desalination is high-energy consuming process; it uses much of electricity, most often drawn from conventional power plants burning fossil fuels which emit gaseous pollutants. However, it was proved that desalination can also utilize low-temperature heat sources like solar, geothermal energy or waste heat.

Last years, growing interest in using nuclear reactors to supply heat for production of fresh water has arisen. The twin production system which combines generation of energy by nuclear reactors and turning the seawater into potable water known in the literature as "nuclear desalination" seems economically viable in many water shortage regions (IAEA 2000). It has been revealed that small and medium-size nuclear reactors are convenient for that purpose; they can be used for desalination, often with cogeneration of electricity using low-pressure steam from the turbine or hot seawater feed from the final cooling system. Desalination can be the next to district heating low temperature, non-electric application of nuclear energy.

The methods used for desalination typically run with phase change; they are energy intensive and costly. Searching for new technologies that could replace the distillation methods, and their more economical varieties, such as multi-stage flash, multiple effect distillation or distillation with vapour compression, is necessary. Great expectations are associated with membrane techniques, such as reverse osmosis, electrodialysis, or hybrid systems combining two or more processes acting in synergy.

The common technologies applied for desalination are the multi-stage flash (MSF), an evaporation process using steam, and reverse osmosis (RO), which is driven by high-pressure electric pumps. Less often in desalination plants multi-effect distillation (MED) or vapour compression (VC) are used. The hybrid plants coupling two different processes were also considered for industrial applications. The hybrid processes like combination of MSF-RO allow obtaining products of different quality, depending on actual, local needs.

Many activities are undertaken concerning application of nuclear reactors in technologies of water desalination in many countries around the world (Khamis, 2016). Most systems developed use thermal processes, which usually require the use of high temperatures and large amount of energy.

In the present paper application of such processes like membrane distillation (MD) and reverse osmosis, separately or in combined systems, is proposed for nuclear desalination. Membrane distillation (MD), thermally driven process, advantageous beacuse of use of low-temperature heat sources seems reasonable for water desalination (Hogan *et al.* 1997, Quist-Jensen *et al*. 2016, Drioli *et al.* 2015). RO, pressure-driven process, however it is intensified when works at elevated temperatures. Both processes can be considered as components of low-temperature desalination systems employed in nuclear desalination.

The objective of the work currently undertaken in the INCT is to develop a desalination system that consumes heat from low-temperature sources and is useful within a nuclear power plant in the management of water and wastewater. These works are connected with the plans to build the first nuclear power plant in Poland.

2. MEMBRANE PROECESSES FOR WATER DESALINATION

2.1 Reverse osmosis

Reverse osmosis (RO) became a common method for water desalination (Bindra *et al.* 2001, Wade 2001, and Avlontis *et al.* 2003). There are examples of researches on use of reverse osmosis in nuclear desalination (Uchiyama *et al.* 2003, Hanra 2000, Nuclear desalination of sea water 1997, Epimakhov *et al.* 2004, Nisan 2003) using heat from PWRs. The concept to use fusion reactors for this purpose was also evaluated (Borisov *et al.* 2001). The first commercial nuclear desalination plant based on MED and MSF was built in Kazakhstan, at Aktau (IAEA 2000, I. Khamis 2016). The BN-350 fast breeder reactor produced up to 135 MWe of electricity and 120 000 m^3/day of potable water over some 27 years. Ten MED units produced drinking quality water (TDS up to 200 mg/L) and high quality water for boiler feed water (TDS 2-10 mg/L). Several installations were operated in Japan for production of drinking water. Initially MSF process was applied there, however more effective appeared MED and RO.

The idea of coupling the RO plant with nuclear reactor is based on the possibility of use hot water from the main condensers of the PWR type of plants. The viscosity of water is inversely proportional to its temperature. Therefore, as temperature increases, water viscosity decreases and RO membrane becomes more permeable, with a consequent increase in productivity. It was revealed that reverse osmosis with pre-heating (ROph) can lead to a desalination cost reduction of about 14% as compared to the desalination cost of a conventional RO system. The ROph process was initially applied to the economic assessment of nuclear desalination systems in the EURODESAL project carried out under the aegis of the European Commission’s 5th Framework Programme (Nisan et al. 2003, 2005). Later, the CEA studied a new method for the mathematical description of the process, extending its application to all power producing plants. The mathematical tool developed took into account performance parameters like the recovery ratio, the total production, and the product salinity of the system as functions of operating variables such as temperature, feed salinity and feed flow. The method was then applied to the specific site study for la Skhira, Tunisia (IAEA 2007).

2.2 Membrane distillation

Membrane distillation is a reltively novel separation process proposed for water desalination and wastewater treatment. It can be also applied for concentration of acids, bases or salt solutions.

The driving force of MD is temperature gradient across the membrane that generates vapour pressure difference. The temperature of the feed solution is below its boiling point. Because of that MD can use low-enthalpy sources of heat, e.g. waste heat or solar energy (Hogan *et al.* 1997, Alkhudhiri *et al.* 2012). Moreover, it does not involve high pressures at all. The process seems to be a cost effective method anywhere, where sources of waste heat are available, e.g. in convential or nuclear power plants.

Membrane distillation for water desalination and waste water treatment was studied at the Institute of Nuclear Chemistry and Technology (Zakrzewska-Trznadel *et al.* 1999, 2001) with the laboratory plant, 0.05 m^3/h of capacity, equipped with the PTFE membrane module, working surface area of 4 m^2. The experiments conducted with NaCl solutions at initial feed concentration up to ca. 50 g/L confirmed the feasibility of the process. During 120 hours of the experiments carried out with recycling of the excess of the distillate to the vessel with the concentrate, there was no change of the salt concentration in both streams. At the same time purification of the distillate occurred and the obtained product had the parameters of distilled water. However, longer expriments at the concentration higher than 50 g/L resulted in decrease of membrane hydrophobicity and in some cases membrane breakthrough took place. Moreover, distillate flow rate significanly declined and the process efficiency decreased, especially at low inlet temperatures applied.

Wetting the hydrophobic membrane due to crystallization of salts inside the pores is a serious drawback of membrane distillation process. Operation at higher temperatures may reduce the risk of crystallization and may avoid hydrophilization of the membranes; it can also be economic, as previous experience showed. At elevated temperatures energy consumption per unit of the product was lower, especially when part of the heat supplied to the system was recovered by appropriate installation design (Zakrzewska-Trznadel et al. 1999).

Membrane distillation is promising technology; however it still needs more attention and studies on influence of high salt concentration, membrane hydrophobic character and process economy. Most of conducted MD investigations are based on laboratory-scale experiments; large-scale studies and industrial applications are still scarce. Although some pilot plant and full-scale testes are reported in literature (Jansen *et al.* 2013, Guillen-Buriezza *et al.* 2012, Raluy *et al.* 2012).

The combination of MD with nuclear reactor supplying heat or working in cogeneration seems to be reasonable solution (Zakrzewska-Koltuniewicz, 2016). MD plant can be used for production of pure water for NPP and cleaning radioactive effluents; it could be essential element of water management system across the whole nuclear power plant helpful also in emerging situations. MD installation can operate alone or in combination with other techniques. It can replace other distillation processes in hybrid desalination plants.

2.3 Hybrid processes

The hybrid MD-RO system combines the advantages of the desalting performance of membrane distillation and lower energy requirements of RO process. It allows a better match between power and water requirements. Hypothetic hybrid MD/RO system was shown in Figure 1.

The coupling enables better utilization of the heat from MD plant to RO unit. RO plant can be fed by the sea water heated up by the brine from the MD unit. Higher feed temperature is advantageous because it results in higher productivity of RO modules (reduction of the water viscosity, higher diffusion rate of water through the membrane). However, lower salt rejection takes place in case of RO.

The hybrid system aims in reducing operational costs. Both plants have common seawater intake facilities and post-treatment facilities. Blending the product water is possible. Other advantages are higher overall availability and flexibility, lower power demand, and improved water quality. RO can use the electricity from the power plant and can operate during periods of reduced power demand (off-peak), thus optimizing the overall efficiency of the entire operation. RO plant can be designed to produce water with higher level of total dissolved salts and thus it lowers its production costs. In hybrid systems, it is also possible to use the cooling seawater return stream from the thermal desalination component as feed to the RO component.

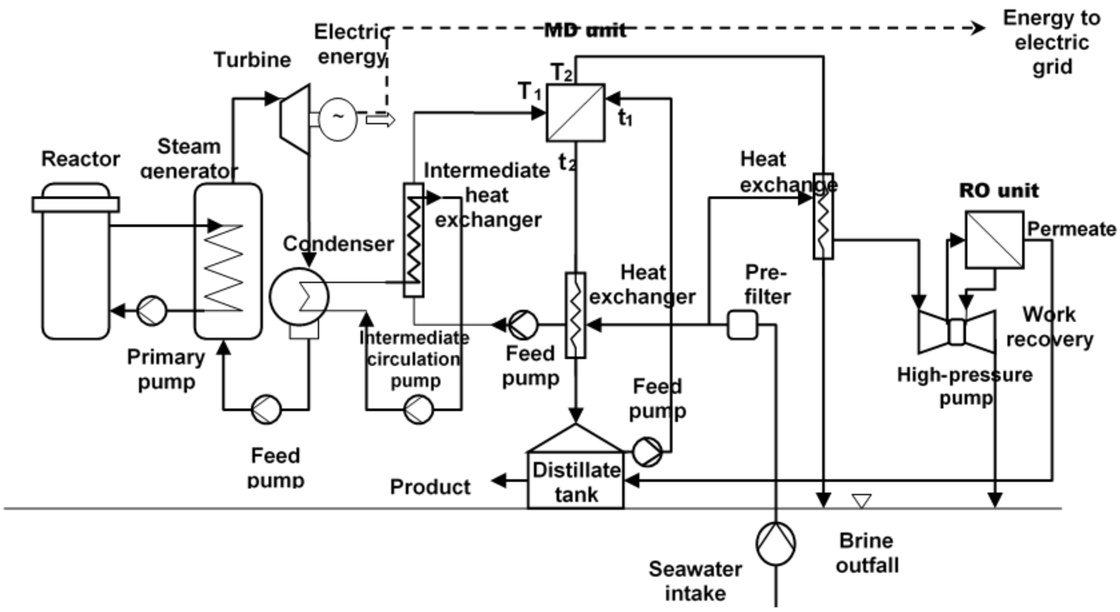

Figure 1. The concept of hybrid MD/RO system with energy recovery device (ERD).

To optimize the hybrid system with minimization of energy consumed it is possible to use energy recovery devices, e.g. energy recovery turbine and motor on the same drive shaft. Booster pump with e.g. HPB^{TM} provides brine energy recovery in reverse osmosis. The HPB^{TM} uses the high pressure brine to energize the turbine which drives the single-stage feed booster pump. The feed pressure boost generated by HPB^{TM} reduces the required feed pump discharge pressure resulting in significant energy savings and a reduction in size of the feed pump and motor (Fluid Equipment Development Company, LLC 2013).

Speaking about nuclear desalination one should mention the safety aspects which are very important for the society. The safety of coupled nuclear desalination plants depends mainly on the safety of nuclear reactor itself, and the interface between desalination plant and nuclear system. Potential for release of radioactive materials into the product water is avoided by multiple barriers and pressure differentials to block the transport of radioactive materials to the desalination plant (Khamis and Kavvadias 2013).

The use of two different forms of energy; electricity for the RO plant and heat for the MD plant provides much flexibility and independence of particular desalination technology. Moreover, the thermal efficiency of the power plant improves as a greater part of the installed power capacity can be beneficially utilized.

3. MEMBRANE PROECESSES FOR RADIOACTIVE WASTEWATER TREATMENT

In addition to desalination of sea water for household and industry purposes, membrane systems driven by heat from nuclear power plants could perform numerous other functions. They might be used for:

- Production of water for NPP's purposes, cleaning the coolant, recycling of water with recovery of boric acid, preparation of water for decontamination actions;

- Treatment of low-level radioactivity effluents during regular, every-day operation (waste from laboratories, floor drains, boron recycling water, wastes contaminated with transuranic elements, waste from decontamination);
- Decontamination of wastewater in case of accident.

The work performed in INCT proved that such processes like RO and MD are effective methods for treatment of liquid radioactive waste. On the basis of research and development works done the reverse osmosis plant for the treatment of radioactive waste generated from application of radioisotopes was designed by INCT and built in Radioactive Waste Management Plant in Swierk, the organization responsible for processing the radioactive waste from all of Poland (Chmielewski *et al*. 2001).

The experiments performed in the laboratory confirmed applicability of membrane distillation for removal of radioactive compounds from wastewater (Zakrzewska-Trznadel *et al*. 1999, Khayet *et al*. 2006). Hydrophobic membrane used in MD process is enable to reject all dissolved species as well as macromolecular compounds. The experimental results of MD filtration of water solution with radioactive cesium ^{137}Cs was shown in Figure 2. 8-fold volume reduction of the waste caused almost 3-fold reduction of radioactivity in the retentate, while distillate remained pure and did not contain radioactive cesium.

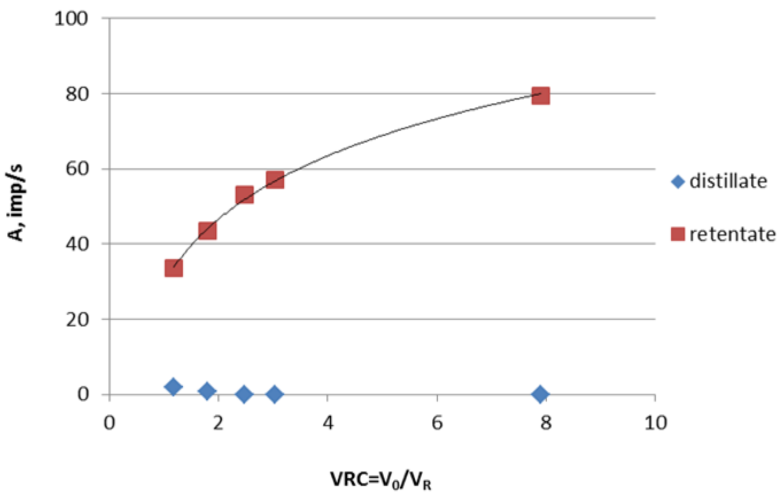

Figure 2. Concentration of ^{137}Cs water solution by membrane distillation

Membrane instllations based on RO and MD built in the NPPs are reasonable soultion for proper management of water and for decontamination of radioactive streams. The presence of adequatly designed systems that can produce large amount of water, and in case of emergency can treat great amounts of contamined streams, would increase the safety of nuclear power plants.

4. CONCLUSIONS

Nuclear desalination is an attractive technology since desalination is energy intensive process that can utilize the waste heat from the nuclear reactor and/or the electricity produced by the plant. Membrane processes are effective desalination methods operating alone, as well as a part of hybrid distillation-membrane systems. The use of membrane desalination is advantageous because of the lowest ratio of energy input to the amount of produced water, a high salt retention, and easiness of the process and equipment servicing. RO is a mature technology; it needs only process intensification by development of more advanced membranes and membrane systems, as well as energy recovery devices. The operation at elevated temperatures brings many benefits, therefore coupling RO plant with nuclear reactor seems to be economically justified.

MD uses low-temperature heat sources and is reasonable for non-electric applications of nuclear energy. The combination with other membrane techniques like RO is very advantageous creating very efficient and flexible system for water treatment. The process needs more studies concerning feasibility of long operation, membrane wettability and economy.

ACKNOWLEDGMENTS

The research described in this paper was financially supported by the IAEA Coordinated Research Project No 18539/R2 “Application of Advanced Low Temperature Desalination Systems to Support NPPs and Non-electric Applications” and MNiSW research project “Application of advanced membrane systems for nuclear desalination”.

REFERENCES

Alkhudhiri A., Darwish N., Hilal N., 2012. Membrane distillation: A comprehensive review. Desalination; 287: 2-18.

Avlonitis S.A., Kouroumbas K., Vlachakis N., 2003. Energy consumption and membrane replacement cost for seawater RO desalination plants. Desalination; 157: 151-158.

Bindra S.P., Abosh W., 2001. Recent developments in water desalination. Desalination; 136: 49-56.

Borisov A.A., Desjatov A.V., Izvolsky I.M., Serikov A.G., Smirnov V.P., Smirnov Yu.N., Shatalov G.E., Sheludjakov S.V., Vasiliev N.N., Velikhov E.P., 2001. Fusion power plant for water desalination and reuse. Fusion Eng. Des.; 58-59: 1109-115.

Chmielewski, A. G., Harasimowicz, M., Tymiński, B., Zakrzewska Trznadel, G., 2001. Concentration of Low- and Medium-Level Radioactive Wastes with 3-stage Reverse Osmosis Pilot Plant. Sep. Sci. Technol.; 36(5&6): 1117-1129.

Drioli E., Ali A., Macedonio F., 2015. Membrane distillation: recent developments and perspectives. Desalination; 356: 56-84.

Epimakhov V. N., Oleinik M. S., Moskvin L. N., 2004. Reverse Osmosis Filtration Based Water Treatment and Special Water Purification for Nuclear Power Systems. Atomic Energy; 96(4): 234-240.

Guillen-Buriezza E., Zaragoza G., Miralles-Cuevas S., Blanco J., 2012. Experimental evaluation of two pilot-scale membrane distillation modules used for solar desalination. J. Membr. Sci. 409-410: 264-275.

Hanra M.S., 2000. Desalination of sea water using nuclear heat. Desalination; 132(1-3): 263-268.

Hogan P.A., Sudjito, Fane A.G., Morrison G.L., 1997. Desalination by solar heated membrane distillation. Desalination; 81: 81-90.

IAEA (International Atomic Energy Agency), 2000. Introduction of nuclear desalination. A guidebook. IAEA Technical Reports Series No. 400. Vienna

IAEA (International Atomic Energy Agency), 2007. Status of Nuclear Desalination in IAEA Member States. IAEA-TECDOC-1524, Vienna.

Jansen A.E., Assink, J.W. Hanemaaijer J.H., van Medevoort J., van Sonsbeek E., 2013. Development and pilot testing of full-scale membrane distillation modules for deployment of waste heat. Desalination; 323: 55–65.

Khamis I., 2016. Non-Electric Applications of Nuclear Energy. Technical Meeting on Operating Experience with, and Project Feasibility of, Process Heat Applications, 23-25 May 2016, Budapest, Hungary.

Khamis I., Kavvadias K.C., 2013. Nuclear desalination: Practical measures to prevent pathways of decontamination. Desalination; 321: 55-59.

Khayet M., Mengual J.I, Zakrzewska-Trznadel G., 2006. Direct contact membrane distillation for nuclear desalination:, Part II-Experiments with radioactive solutions. J. Nucl. Desalination; 2(1): 56-73.

Nisan S., Caruso G., Humphries J.-R., Mini G., Navigilio A., Bielak B., Asuar Alonso O., Martins N., Volpi L., 2003. Seawater desalination with nuclear and other energy sources, Nuclear Engineering & Design; 221: 251–275.

Nisan S., Commercon B., Dardour S., 2005. A new method for the treatment of a reverse osmosis process with preheating of the feed water. Desalination; 182: 485–495.

Quist-Jensen C.A., Macedonio F., Drioli E., 2016. Integrated Membrane Desalination Systems with Membrane Crystallization Units for Resource Recovery: A New Approach for Mining from the Sea. Crystals; 6: 36.

Raluy R.G., Schwantes R., Subiela V.J., Peñate B., Melián G., Betancort J.R., 2012. Operational experience of a solar membrane distillation demonstration plant in Pozo Izquierdo-Gran Canaria Island (Spain). Desalination; 290: 1-13.

Uchiyama Y., Minato A., Shimamura K., 2003. Seawater desalination using reusable type small PWR. Int. J. Nucl. Desalination; 1(1): 81-94.

Wade N.M., 2001. Distillation plant development and cost update. Desalination; 136: 3-12.

Zakrzewska-Koltuniewicz G., 2016. The possibility of nuclear cogeneration in the future NPPs in Poland. Technical Meeting on Operating Experience with, and Project Feasibility of, Process Heat Applications, Budapest, Hungary, 23-25 May 2016.

Zakrzewska-Trznadel G., Harasimowicz M., Chmielewski A.G., 1999. Concentration of radioactive components in liquid low-level radioactive waste by membrane distillation. J. Membr. Sci.; 163: 257-264.

Zakrzewska-Trznadel G., Harasimowicz M., Chmielewski A.G., 2001. Membrane processes in nuclear technology – application for liquid radioactive waste treatment. Sep. Purif. Technol.; 22-23: 617-625.