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Heat pipes as an extra measure to eliminate radioactive contamination in nuclear seawater desalination

Ibrahim Khamis[a]*, Hussam Jouhara[b], Vladimir Anastasov[a]

[a]*International Atomic Energy Agency, Wagramer Strasse 5, P. O. Box 100, A-1400, Vienna, Austria*
Tel. +43 (1) 260022822; Fax +43 (1) 260029598; email: i.khamis@iaea.org
[b]*School of Engineering and Design, Brunel University, Uxbridge, Middlesex, UB8 3PH, UK, Tel. +44 1895 267656; Fax +44 1895 256392; email: hussam.jouhara@brunel.ac.uk*

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ABSTRACT

Reduction in tritium contamination levels in the product water is a top priority for gaining public confidence in nuclear seawater desalination. Hence, the search for new technologies, to enable such reduction is an ongoing process. Heat pipes are seen as a promising technology to achieve such goal. In fact, concern over possible contamination of the product water could well be eliminated using this technology. Utilising new designs for desalination heat exchangers based on the heat pipe technology will add an extra loop, which will prevent direct contact between the nuclear and the product water loops under normal and anticipated operational failure occurrences. As a result, heat pipes can play a decisive role in enhancing public perception of nuclear desalination in particular and seawater desalination in general.

When coupled to the Low-Temperature Multi-Effect Distillation process, heat pipes based heat exchangers could harness waste-heat generated in nuclear power reactors and effectively improve the overall economics of desalination using nuclear power. Furthermore, the use of heat pipes-based systems in desalination plants may improve the overall thermodynamics of the desalination process.

Keywords: Heat pipe; Tritium-related safety; Nuclear seawater desalination

1. Introduction

Water scarcity is a global issue, affecting many countries every year. Apart from water conservation, pollution control and water reclamation, solutions aiming for new sources of fresh water including desalination are also being considered to meet the water shortages. The rising concern over fossil fuel cost and its uncertain availability as well as other associated environmental concern has prompted a search for alternative energy sources for the future desalination needs including nuclear energy.

The coupling of desalination systems with a nuclear plant is technically feasible [1,2] taking into account the need to (a) avoid cross-contamination by radioactive materials, (b) incorporate certain design features which minimise the impact of the thermal desalination systems' coupling to the nuclear reactors and, (c) provide backup heat or power sources in the case where the nuclear system is not in operation (e.g. during refuelling and/or maintenance of the nuclear power plant).

In case of nuclear desalination, concerns over a possible contamination of the product water require a

*Corresponding author

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special attention [3,4]. In specific, tritium is the major concern as it is able to penetrate various materials and possibly end up into the product water. With the application of appropriate safety measures (discussed later), the experience from Kazakhstan, India, Japan and the United States, shows that nuclear desalination complies with various health standards. Indeed, public health problems have never occurred due to the tritium levels in the desalinated water. Moreover, the Multi-Stage Flash - Reverse Osmosis (MSF-RO) facility in Kalpakkam has delivered desalinated water outside the facility with tritium content below the detectable limit [5]. Similarly, a number of non-electrical applications of nuclear power have reported background tritium levels in the product water or steam [6].

Tritium is produced in nuclear reactors either as a direct product of nuclear fission or as a result of reactions of neutrons with elements, which are present in the reactor such as lithium and boron. It is a soft beta emitter and presents no dangerous hazard for external exposure. However, it is considered a health hazard if inhaled, digested via food, or entered the body as tritiated water.

In general, the quality assurance of desalinated water against any radioactive contamination is usually guaranteed through two types of measures: regulatory and technical ones. This paper focuses primarily on the advantages/benefits of using heat pipes as a technical measure to eliminate any possible radioactive contamination in nuclear seawater desalination.

2. Regulatory measures for water quality

As a potential hazard to public health, tritium in drinking water is regulated by various national and international standards and guidelines. Most of them differ in the limits set, but they all follow the calculation pattern used in the WHO guideline.

The WHO limit for tritium in drinking water is based on the ICRP recommendation for an effective dose limit of 1 mSv per year for any combination of internal and external radiation doses [7], as well as the dose coefficient of $1{,}8 \times 10^{-11}$ Sv/Bq for ingestion of tritium by an adult member of the public [8]. The WHO regulatory recommendation starts with 10% of the ICRP's effective dose limit of 1 mSv. Given the fact that other radiation sources will contribute to the committed effective dose, 0.1 mSv per year through drinking water is a reasonable value. The guideline level for tritium activity GL, is calculated as:

$$GL = \frac{RDL}{DCF \times q}$$

Table 1
Allowed tritium levels in drinking water

Country	Tritium limit (Bq/l)
Australia	76,103
Finland	30,000
Canada	7,000
EU*	100
Kazakhstan	7,700
Switzerland	10,000
United States	740
WHO	10,000

* This value is not a limit, but rather an alarm level.

Where: RDL is the reference dose level (= 0.1 mSv).

DCF is the dose conversion factor for ingestion by adults ($= 1.8 \times 10^{-11}$ Sv/Bq).

q is the annual ingested volume of drinking-water (= 730 l/yr).

The subsequent guideline level of 7,610 Bq/l is rounded up to 10,000 Bq/l, referring to the total beta activity in a water sample and not just tritium. It is used by many of the WHO member states as a basis for regulation as well as other UN agencies [9], some of which are presented in Table 1. The limit though, does not exclude the ALARA principle in efforts to further reduce the level of radionuclides in drinking water [10].

For comparison, the reported levels of tritium in the drinking water from the nuclear desalination plants were below the detectable limit in Kalpakkam [5] and 6 Bq/l in Aktau [10]. Nevertheless, monitoring of tritium levels is recommended for the nuclear plant as well as the intermediate safety loop between the nuclear and desalination plants, but it is absolutely necessary for the desalination plant. The drinking water quality can be monitored in the reservoirs which hold the water prior to its release into the drinking water network. This is common for all desalination plants, allowing for a chemical and bacteriological analysis. In the case of nuclear desalination, tritium activity measurement must be included in this analysis.

3. Heat pipes as a technical measure for product water quality

Safety is the most important aspect of nuclear power. In that sense, nuclear desalination applies all measures feasible to guarantee potable water free of radioactive contamination, as seen in the existing facilities. The use of heat pipes as a technical measure in nuclear seawater desalination would increase not only

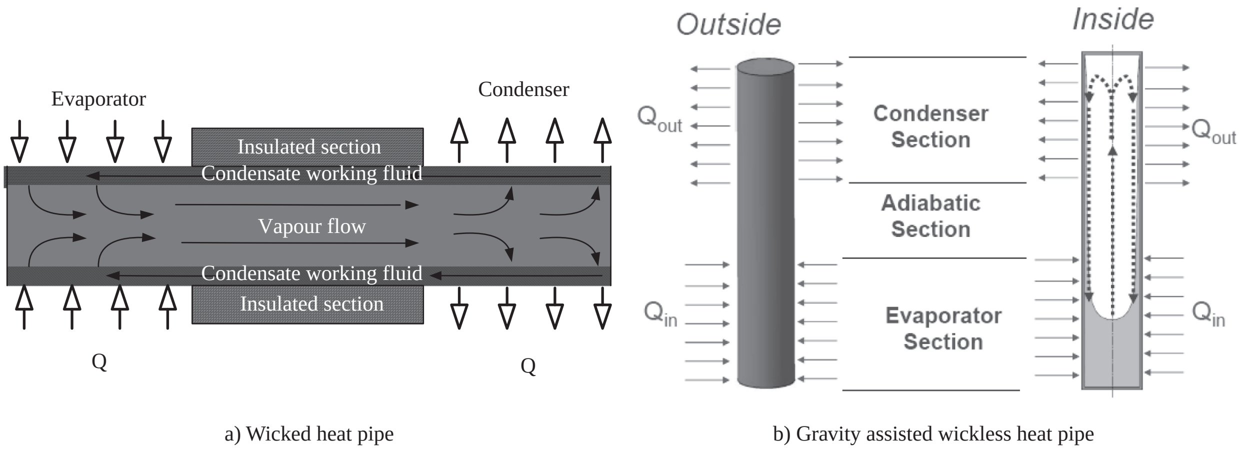

Fig. 1. Basics and types of heat pipe.

tritium-related safety but also improve the economic performance of the nuclear desalination facility.

3.1. Principles and applications of heat pipes

Heat pipes are hermetically sealed tubes containing a small amount of working fluid (see Fig. 1). They utilise the highly efficient thermal transport process of evaporation and condensation to transport heat from one end to the other where the heat can be dissipated through a heat sink. Inside the heat pipe, the working fluid is present in two phases: vapour and liquid. The thermal transport process of evaporation–condensation within the heat pipe is illustrated in Fig. 1. When the evaporator section of the heat pipe is placed in a hot medium, the heat will be transferred to the working fluid through the pipe wall. The working fluid absorbs heat energy which is sufficient to convert the fluid from the liquid phase to vapour phase. The increased pressure in the hot end of the pipe forces the vapour to flow to the cooled end of the pipe. Here the vapour condenses releasing the heat that was absorbed in the evaporator section. This region is termed in Fig. 1 as the condenser section. The heat then flows across the tube wall of the heat pipe and dissipates to the ambient surroundings by various forms of convection, depending on the application. In many applications, fins are attached to the outer surface of the heat transfer surface to minimise the thermal resistance in order to improve the heat transfer capability of the heat pipe system. Within the pipe, the condensate liquid returns to the evaporator section of the heat pipe where it is again evaporated. Since the latent heat of evaporation is large, considerable quantities of thermal energy can be transported very efficiently with a very small temperature differences from end to end.

Heat pipes are categorised based on the way the condensate working fluid in the heat pipe returns from the condenser to the evaporator section to wicked heat pipes and wickless heat pipes (or thermosyphons). Capillary driven or wicked heat pipes utilise a wick structure to return the condensate to the evaporator by means of capillary forces so they can operate in any orientation (Fig. 1a). Gravity assisted or wickless heat pipes rely on gravity to return the condensate working fluid from the condenser to the evaporator. Therefore, the wickless heat pipe must have an inclination of at least 5° from the horizontal with the condenser above the evaporator.

Heat pipes can be used in bundles to create heat exchangers which are passive (no external power requirement) and contain no moving parts (see Fig. 2).

Heat pipes have a wide manufacturing range, come in a variety of sizes, which allow for a compact equipment design, and can be tailored for various thermal applications and ranges. These advantages make them a suitable choice for the nuclear desalination option regardless of the reactor type and steam temperature. Along with their high efficiency, such advantages of heat-pipe-based heat exchangers resulted in their use in wide range of applications. Many of these applications are related to space technology [11,12], thermal storage [13,14], harnessing of renewable energy [15,16], in air conditioning systems, space heating and waste heat recovery of various processes [17–23]. Heat pipes have also been tested for the hydrogen production in a HTTR reactor in Japan [24]. The control of the tritium permeation through heat transfer tubes was done by adjusting the coolant chemistry and thus the formation of oxidized film layer on the heat pipes.

3.2. Rationale for heat pipes in nuclear desalination

The advantages of using the heat pipe technology in nuclear seawater desalination include:

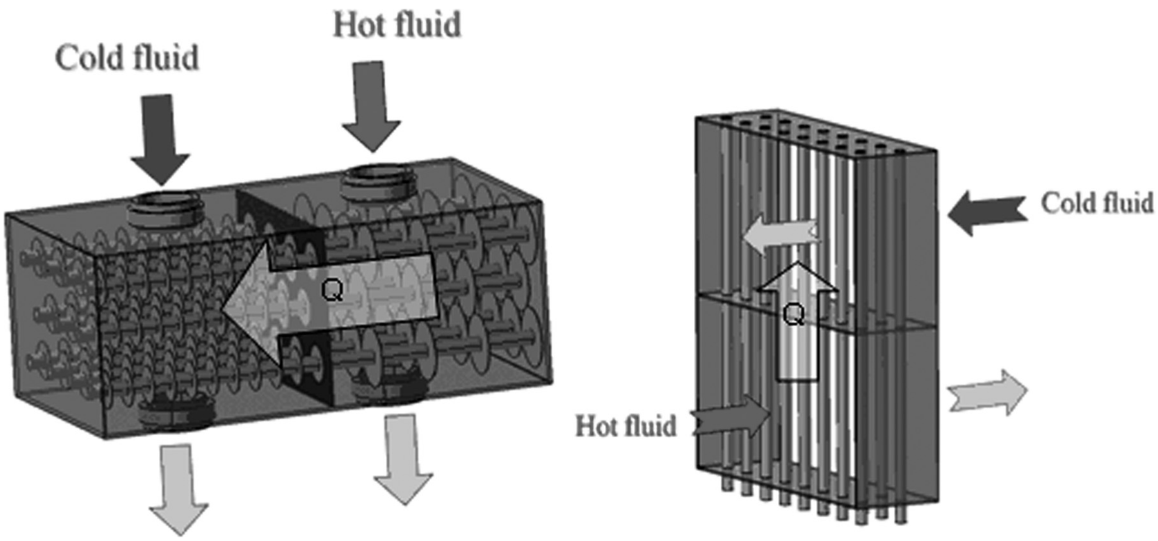

Fig. 2. Heat pipe based heat exchangers.

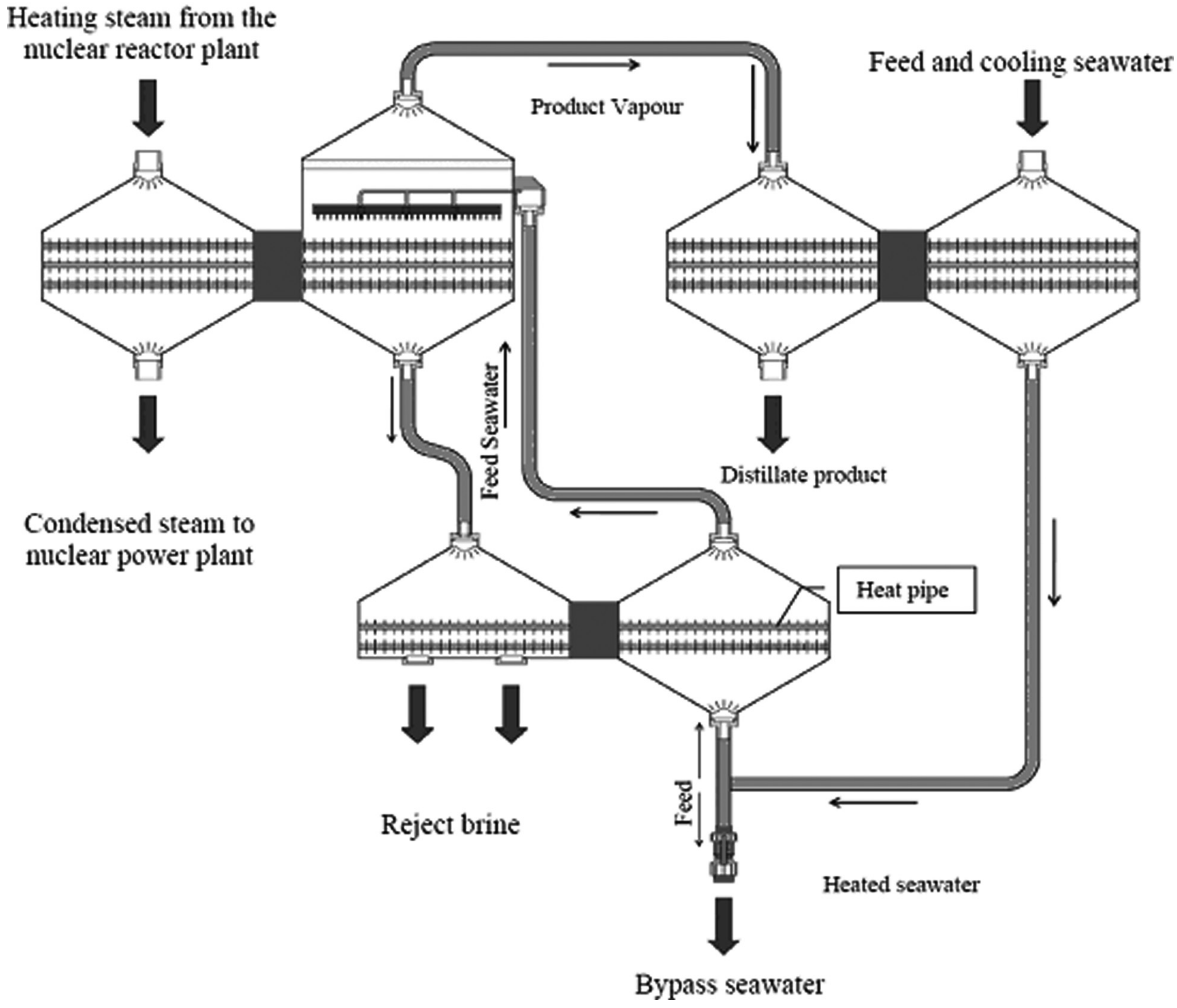

Fig. 3. Heat pipe-based single effect nuclear desalination plant.

High efficiency heat transfer between two systems while they are *physically* separated with an insulating section. That may practically eliminate the risk of mixing between the steam from the nuclear reactor and the seawater in the evaporator section and from the condensed fresh water and the brine in the condenser section of the desalination system.

As the heat pipe has an extremely high effective thermal conductivity, by placing two temperature sensors on the hot and the cold side of the heat pipe, the temperature difference will be an indication of the heat pipe operational status. That will lead to an easy detection of any faulty heat pipe.

It provides a much needed contingency plan. In the heat pipe – based heat exchanger, the system will stay operational safely even if a number of heat pipes stop functioning.

Because of the high efficiency of the heat pipe systems, they will have much smaller size when compared to equivalent conventional heat exchangers and lower tritium permeation rate.

Major reduction in the fouling problem (the fouling will be only on the external surfaces of the heat pipes).

Significant reduction in pumping power as the heat pipe is a passive heat transfer device.

A typical layout of a single-effect nuclear desalination plant using heat pipes is presented at Fig. 3.

Due to gaseous tritium diffusion through physical barriers, a certain amount of tritium in the desalination loop is inevitable. The diffusion rate differs according to the barrier material and surface conditions, as well as the difference in pressures and temperatures on both of its sides.

Tritium usually stays in the reactor fuel [25]. Only a fraction of tritium escapes from the core diffusing into the primary coolant. Part of this fraction then diffuses to the secondary cooling circuit through the surface of the heat-exchanger. From there, again through the surface of the intermediate heat-exchanger, it diffuses to the water-steam circuit. Diffusing and penetrating through reactor vessel walls, heat-exchanger and steam-generator surfaces, machinery and pipelines, a small portion of tritium is transferred into the desalination loop [26].

Large part of the tritium in the nuclear coolant oxidizes into tritiated water, which is similar to natural water and cannot permeate through metallic barriers. Thus, the use of the added intermediate loop (Fig. 4) with higher pressure is considered a sufficient radiation protection, minimizing the tritium contamination potential [5,27]. It should be noted that pressure barriers are likely to be a regulatory requirement as part of the established ''defence in depth'' principle for nuclear power plants.

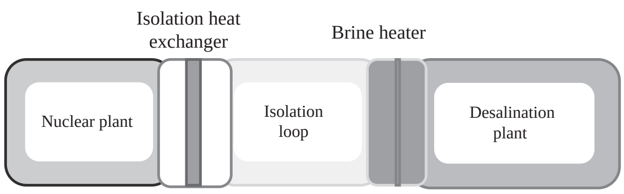

Fig. 4. Nuclear desalination coupling with an intermediate isolation loop.

In principle though, heat pipes should provide even lower tritium permeation rates. If we assume the same material, surface, temperature and pressure conditions for the heat exchanging area in a given nuclear desalination facility, the difference in reducing tritium permeation would be defined by the surface size. Heat pipes, with their higher thermal transfer efficiency, need a smaller surface for the same energy transfer; which in he same time reduces the diffusive surface for tritium. Having in mind that most of the tritium in the desalinated water follows the path described previously; this could bring a substantial increase in tritium-related safety for the desalinated water.

4. Conclusion

The use of heat pipes is likely to allow for greater radiation safety of the product water since tritium diffusion will be appropriately lower. For the same reason of a smaller heat-exchange surface, the probability of tritiated fluid leaks in the desalination loop will be reduced. At the same time, application of heat pipes instead of the standard intermediate loop can decrease the capital, operating and maintenance costs. Heat pipes are expected to play an important role in making nuclear seawater desalination more economical as they are expected to recover a great percentage of waste heat. In addition to that, lower thermal discharges will improve the environmental performance of the nuclear desalination plant.

Finally, the reliability of water supply from the plant should increase due to the robustness of the heat-pipe system. For example, possible leaks can be detected and located immediately, while a physical barrier to the desalination loop is still provided. Uninterrupted supply has not only the benefit of higher revenue, but also higher safety of the product water and enhanced public support for the nuclear desalination plant. These points present a very good case for the use heat pipe-based heat exchangers in the nuclear desalination systems.

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