Nuclear Desalination: A Viable Option for Producing Fresh Water- Feasibility and Techno-Economic Studies

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Abstract: A comprehensive overview of the activities in the area of nuclear desalination (i.e., the production of freshwater via seawater desalination using nuclear energy as the thermal and/or electrical energy source) is provided in this paper.Present and future market of desalination is discussed in detail. Of particular interest is a nuclear desalination demonstration NDDP/MED plant (1600 m^3/d LT-MED coupled to a PHWR). Technologies that are used mainly in the seawater desalination industry are reviewed and evaluated in this paper. Other related activities are also presented, including a technical and economic overview of desalination processes as well as assessment of economic competitiveness of nuclear desalination with conventional desalination options. The overall intent is to demonstrate that production of potable water to supplement the increasingly scarce water resources is an option that should be considered by coastal areas of Saudi Arabia, which will soon have greater water demands that cannot only be fulfilled by conventional desalination technologies. Multi- Effect Distillation technology is considered in detail, and the Desalination Economic Evaluation Programme (DEEP), provided by IAEA, is used for general feasibility study. A special feature of commercialization of fresh water and brine products from NDDP/MED plant is also included in the paper. The product water cost from different desalination processes like MSF, MED, RO and Hybrid systems is incorporated in this paper.

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Keywords: Nuclear desalination; Techno- Economic studies; NDDP/MED system; Desalination Economic Evaluation Program (DEEP)

1. INTRODUCTION

Freshwater is a fundamental necessity for life and sustainable development; yet it is a limited resource. Only about 2.5% of the world's water is freshwater, of which two-thirds are locked up in icecaps and glaciers. Of the remaining amount, some 20% is in remote and not easily accessible areas, while the balance of about three-quarters includes mainly rainwater, which falls at the wrong place and time (i.e., during monsoons and floods) and is not useable. The accessible freshwater for human use is therefore less than 0.08% of the total water on the planet.

The increasing population, together with increasing industrial and agricultural activities, has led to excessive exploitation of available water resources and pollution of fresh water resources. The paper points out that the amount of shortage of fresh water resource in mega cities [1]. Hence, water resource shortage and pollution have become a serious problem. Currently about 2.3 billion people live in water-stressed areas and among them 1.7 billion live in water-scarce areas, where the water availability per person is less than 1000 m^3/year. Statistics show that by 2025 the number of people suffering from water stress or scarcity could swell to 3.5 billion, with 2.4 billion expected to live in water-scarce regions. Water scarcity is a global issue, and every year new countries are affected by growing water problems. Many countries are facing unprecedented shortage of clean drinking water and electricity due to the lowest recorded levels of water in the dams [2]. According to a 2006 World Bank report, the developing countries are fast moving from being a “water stressed country to a water scarce country”, mainly due to its high population growth, and water is becoming the key development issue. The groundwater is over-exploited and polluted in many areas; most of the water infrastructure (even some of the major barrages) is in poor repair; the entire system of water management is not financially sustainable. Among the 25 most populous countries in 2009, South Africa, Egypt and Pakistan are the most water-limited nations [3,4]. There are many ways to solve the water shortage problem depending on location, such as transportation of water between different areas, reusing of wastewater in industry and agriculture, and improving management of water resource. Desalination of sea water has become one of the most important ‘nonconventional’ growing sources of drinking water in coastal cities[5,6], and plays an important role in solving fresh water scarcity in areas where other water supply alternatives are not available or feasible, especially within coastal regions ofKSA. Sometimes seawater desalination maybe the best choice in many situations [7, 8].

As with the depletion of fossil energy sources and a progressive degradation of its environment due to pollution and gas emissions, we look for the answer to the water scarcity problem in the use of Nuclear Energy as an alternative energy source as a cleaner and safer way for providing fresh water by desalination. The prospects of using nuclear energy for seawater desalination [i.e., nuclear desalination] on a large scale remain very attractive since desalination is an energy intensive process that can utilize the heat from a nuclear reactor and/or the electricity produced by such plants.

Nuclear desalination is defined to be the production of potable water from sea water in a facility in which a nuclear reactor is used as the source of energy for the desalination process. Electrical and/or thermal energy may be used in the desalination process. The facility may be dedicated solely to the production of potable water, or may be used for the generation of electricity and the production of potable water, in which case only a portion of the total energy output of the reactor is used for water production. In either case, the notion of nuclear desalination is taken to mean an integrated facility in which both the reactor and the desalination systems are located on a common site and energy is produced onsite for use in the desalination system. It also involves at least some degree of common or shared facilities, services, staff, operating strategies, outage planning, and possibly controls facilities and seawater intake and outfall structures. KANUPP has a 1600 m^3/day Nuclear Desalination (NDDP/MED) facility supported by IAEA.

In this paper, the main topic areas for the nuclear desalination are as follows:

- Thermal desalination
- Membrane desalination
- Techno-Economic studies
- Feasibility studies of desalination best option for Pakistan

2. DESALINATION TECHNOLOGIES

Seawater desalination technologies and processes are mainly categorized into two groups: thermal and membrane desalination. Besides, there is ion exchange method, evaporation and so on, as shown in Fig. 1.

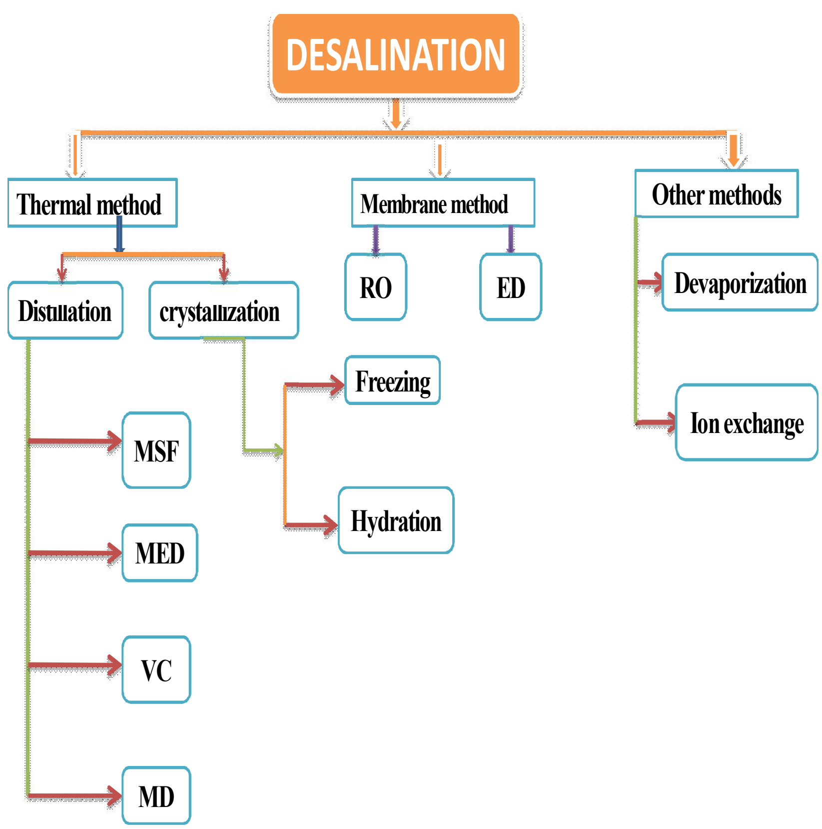

Figure 1Schematic diagram of the main desalination processes.

Thermal desalination includes multi-stage flash (MSF), multi-effect distillation (MED), vapor compression (VC) and membrane distillation (MD), and so on. In the membrane desalination, the reverse osmosis (RO) and electro-dialysis (ED) are technologies used frequently. The dominant processes are MSF and RO, the MSF process represents more than 93% of the thermal process production, while RO process represents more than 88% of membrane processes production [9, 10].

2.1 Thermal desalination

The basic principle of thermal process is simple, and it depends on phase transition by energy addition or removal to separate fresh water from saline water. The most important thermal processes are MED and MSF.

2.1.1 MSF

MSF had been the main process for the desalination industry, which has a market share close to 60% of the total world production capacity until the late 20th century; MSF remains to have a sizeable market share during the first half of 21st century [11].Fig.2 shows a schematic diagram of the MSF system. This system contains flashing stages, a brine heater, pumping units, venting system, and a cooling water control loop. Incoming seawater is passed through heat exchanger. Then the water flashes into steam when the water is heated to 100°C or above and held under pressure until it is released into a vacuum chamber. The water vapor is condensed to fresh water product by the cooling water control loop. Finally, it is passed to the brine heater where steam from an external source supplies the energy for the process and heats the seawater to the maximum process temperature.

Low temperature heat source can be utilized and construction of equipment is simple in the MSF process. These are the special features of the MSF process, which distinguish it from other desalination con-figurations. A small number of connection tubes were used in the MSF process construction. It limits leakage problems and simplifies maintenance work. Evaporation and condensation is done in many stages, thereby increasing efficiency. However, the development and progress in the MSF process, the performance ratio has remained at a value of eight for more than two decades [12,13]. The results show that the gain ratio could be increased by 74.1% and annual capital cost of fresh water production will decrease by 10.7% in comparison with conventional MSF. Consequently, the MSF distillation process has received widespread acceptance, especially in the Middle East. This is due to the following:

1) Low temperature heat source can be utilized;
2) Simple construction of equipment;
3) Extensive experience in operation;
4) Process reliability;
5) Simple maintenance work.

2.1.2 MED

Multi-effect distillation means that the column pressures are adjusted such that the cooling (energy removal) in one column can be used as heating (energy input) in another column. To achieve this, each column must be operated at different pressures. In the conventional MED plant [14], which is shown in Fig. 3, the seawater enters the first effect and is raised to the boiling point. Both water feed and heating vapor to the evaporators flow in the same direction. The remaining water is pumped to the second effect, where it is again applied to a tube bundle. This continues for several effects, with 8 or 16 effects in a typical large plant.

The conventional MED process is the oldest method used to desalt seawater in large quantities. Modern MED units use horizontal or vertical falling film evaporators in seawater desalination [15]. The low temperature horizontal tube multi-effect desalination (MED) process is thermodynamically the most efficient of all thermal distillation processes in use [16].

Development of MED has brought this process to the point of competing technically and economically with the MSF process. Competing with the MSF process, major features of the MED process are as follows:

1) The simultaneous transfer of latent heat onboth sides of the heat transfer surface of a film type horizontal tube evaporator occurs at a constant temperature;
2) The utilization of inexpensive aluminum tubes permits a large heat transfer area, thus reducing thermal loads as well as vapor velocities hence contributing to higher distillate purity;
3)Flexibility is achieved since MED's plants have short start-up periods with little time loss for heating up.

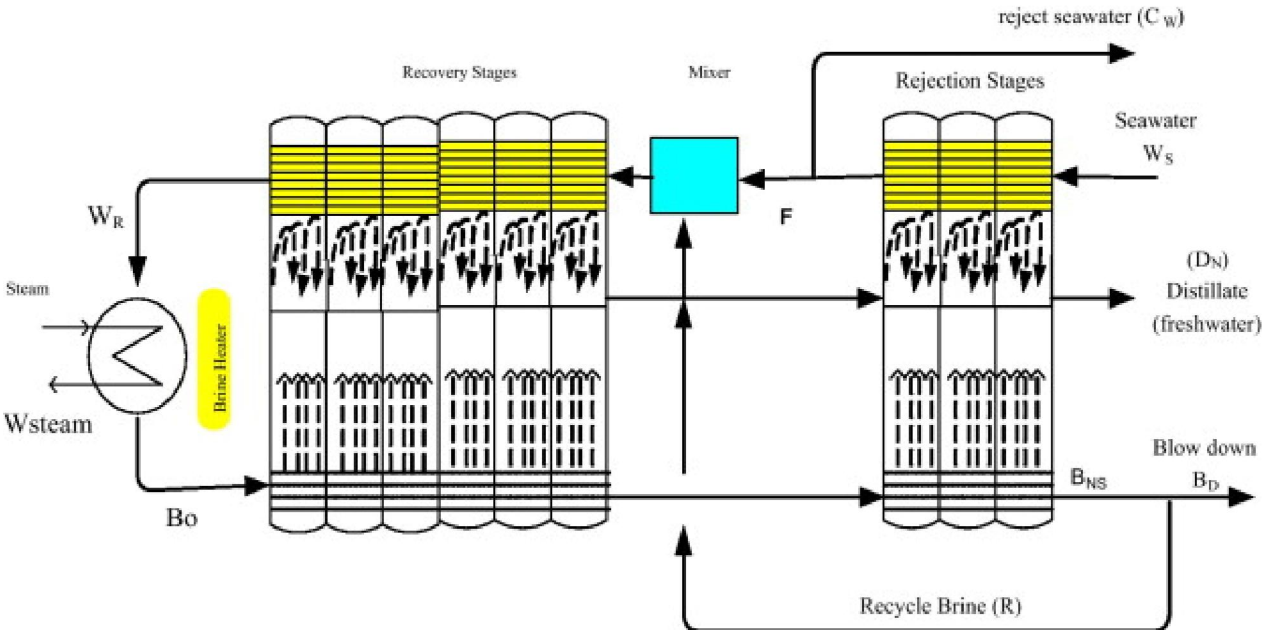

Figure 2.MSF process flow diagram

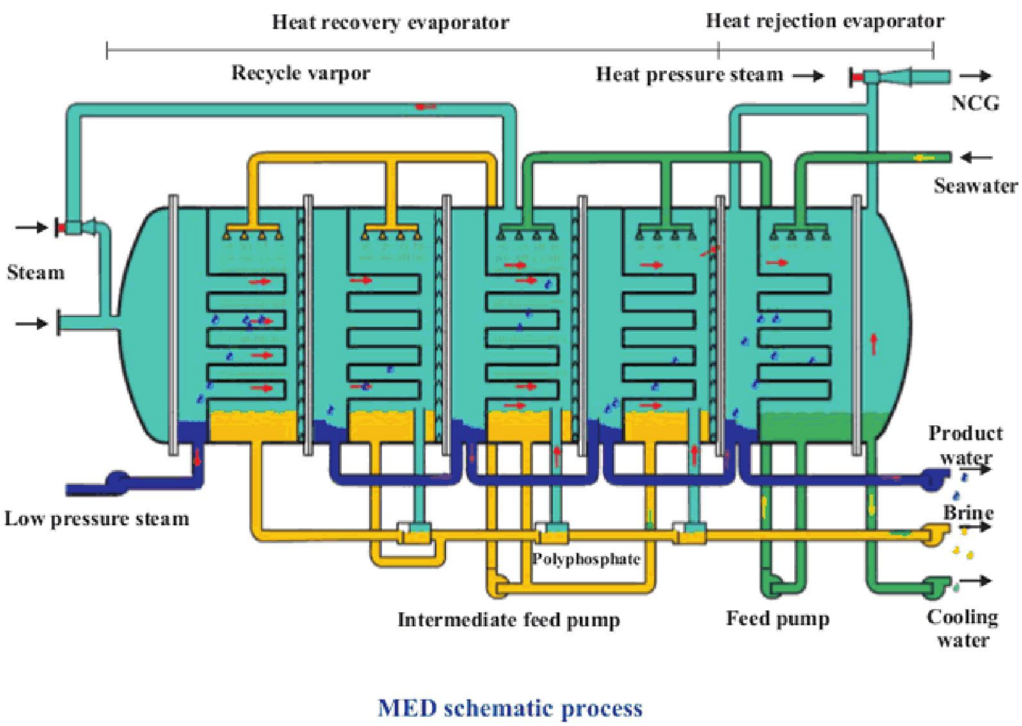

Figure3.MED process flow diagram

2.2. Membrane desalination

As depicted in Fig. 1, the reverse osmosis (RO) and electro-dialysis (ED) are the main technologies in membrane desalination. RO process is based on separation rather than distillation although membrane distillation can also be performed. A typical RO plant is shown in Fig. 4.

The seawater passing through the modules is not completely desalted, part is rejected as brine. Before being returned to sea, the mechanical energy of brine is used in energy recovery systems [17], which achieved a significant energy saving.

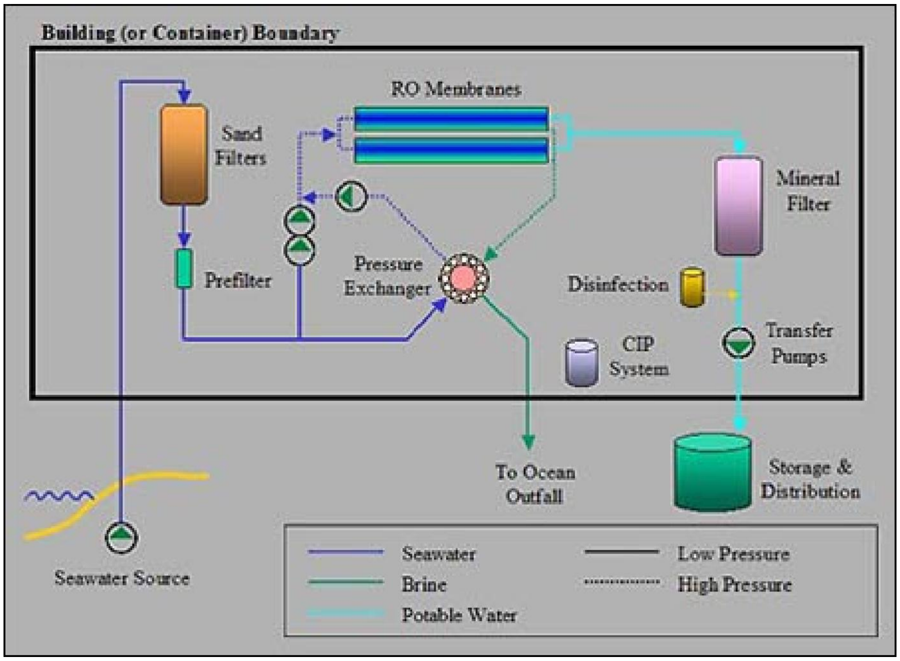

Figure 1.RO process flow diagram

RO has gotten more and more extensive application in the desalination process of water treatment. Advanced RO facilities recently developed for energy recovery or minimizing RO energy consumption using the pressure exchange and system design of operate condition optimization technology. The new high rejection and high flow membranes made conversions to 55–60% economically feasible. This can be ascribed to the permitted operating at high pressures (up to 80–90bars). Hydraulic efficiency of this type of equipment ranged from 90–94%. All of these technologies have resulted in minimizing RO system capital and operating costs [18].

3. TECHNO-ECONOMIC ASPECTS OF NUCLEAR DESALINATION

The IAEA has developed a software package known as "Desalination Economic Evaluation Program" (DEEP) [19]. Past studies with DEEP have demonstrated that nuclear desalination can be, in general, economically competitive with conventional desalination options [20]. In this paper we have provided a detailed economic calculations using DEEP for a range of fossil and nuclear energy sources (e.g., Nuclear power plant, oil fired plants etc.), which were coupled to selected desalination technologies (i.e., MSF, MED, and RO). The study employed specific seawater and economic conditions, which are prevalent in Karachi and Gawadar.

3.1. DEEP calculations for the case of NDDP/MED

In this chapter the results from the Desalination Economic Evaluation Program (DEEP) are presented in detail. Different cases of DEEP are run for specific plants of available data specially the NDDP/MED plant Kanupp, and these results are compared to actual results i.e. the product water cost and electricity production or lost electricity.

3.1.1. DEEP Input Data and Output Description

DEEP includes both generally applicable default data (e.g. for economic parameters and electric motor efficiency) and default data which are specific for certain energy sources and desalination technologies. In these calculations we have used some ofthe default data of DEEP, especially for energy plant

3.1.2. GENERAL INPUT PARAMETERS OF DEEP

Relevant input data include:

- Required water plant capacity (m3/d),
- Distillation plant type (MED,MSF,RO ,etc)
- Average cooling water temperature (ºC),
- Seawater total dissolved solids (TDS) ppm.

It also uses some other data, like the capital cost, fuel cost, O&M cost, etc. of energy plant as well of the water plant.

3.1.3. RESULTS OF SPECIFIC CASES FROM DEEP

CASE-1: 1600m^3/d distillation plant coupled to nuclear plant (KANUPP)

The distillation plant data is the actual data available from supplier of NDDP/MED. Results provided by DEEP are as below.

Table **Error! No text of specified style in document.** Cost results by DEEP 3.2

Cost Results

Specific Power Costs		
Fixed charge	0.015	$ / kWh
Fuel cost	0.006	$ / kWh
O&M cost	0.009	$ / kWh
Decommissioning cost	0.005	$ / kWh
Total carbon cost	N/A	$/kWh
Levelized Electricity Cost	**0.035**	$ / kWh

Specific Water Costs		
Fixed charge	0.386	$ / m^3
Heat cost	0.358	$ / m^3
Plant electricity cost	0.090	$ / m^3
Purchased electricity	0.000	$ / m^3
O&M cost	0.640	$ / m^3
Water production cost	1.474	$/m^3
Water transport cost	0.000	$/m^3
Total Specific Water Cost	**1.474**	$ / m^3

From the above cost results we have the specific cost of water as of 1.474 $/m^{3}i.e. Rs 88.44/m^3 (@Rs 60 =1 US $) and the actual cost of water (Based on Cost of Steam from Method on PC-1) is Rs 90/m^3. The present cost of water is Rs 122.342/m^3 (Rs 83 =1US $) and the cost calculated by the plant management is Rs 126/m^{3}so from the results provided by DEEP which looks to be good estimations one can go for the project.

4. CONCLUSION

Interest in nuclear desalination has been growing in many countries of the world over the past decades as one of the feasible means to contribute to the solution of freshwater shortages in arid and semiarid regions. Energy required for desalination could be provided by nuclear reactors in the form of electricity and/or low-grade heat. A number of factors contribute to the recent growing interest in nuclear desalination technology and application; these include: growing concerns about the environmental effects of burning fossil fuels, which are not experienced in NPPoperation; recognition of the benefits of diversification of energy sources; expected spin-off effects in industrial development; the development of new, safer than ever advanced reactor concepts in the small- and medium-power range; and, perhaps the most appealing factor of them all - demonstrated economic competitiveness of nuclear desalination facilities with conventional power/desalination cogeneration plants. Indeed, it was found that the cost of desalting 1 m^3 of seawater via nuclear desalination can be as low as $0.40. This figure is quite comparable to the present-day cost of producing freshwater using some of the most efficient desalination processes available. Several nuclear desalination projects are ongoing around the world, mostly in developing countries as end-users. Indeed, expanded nuclear desalination operations will soon be a reality in Pakistan. New and promising design concepts for future nuclear desalination options have in fact materialized over recent years and their technical and economic feasibility demonstrated.

5. FUTURE RECOMMENDATIONS

Low Temperature Vacuum Evaporation (LTVE)

The waste heat from a nuclear reactor and from the heavy water (D2O) moderator in a PHWR system can be effectively utilized in a low temperature vacuum evaporation (LTE) plant for seawater desalination.

We have made calculations for the heat provided by the Moderator cooling system of Kanupp. The calculations shows that the two HX, S provide a heat of approximately 13 MW.This much of heat is wasted by the moderator to process water, so we can use this heat in LTE desalination process.

Extraction of uranium

Valuable minerals like uranium can be extracted from the discharged brine.

Abbreviations

DEEP--Desalination Economic Evaluation Program
HR --Heating reactor
HTR -- High temperature reactor
IAEA-- International Atomic Energy Agency
MED -- Multi-effect distillation
MSF **-- -** Multi-stage flashing
NPP --Nuclear power plant
O&M- - Operation and maintenance

RO --Reverse Osmosis
NSC--Nuclear Steam Condensing
TDS -- - Total dissolved solid
NDDP--Nuclear Desalination Demonstration Project

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REFERENCES

[1] INTERNATIONAL ATOMIC ENERGY AGENCY, Introduction of Small and Medium Reactors in Developing Countries, IAEA-TECDOC-999, Vienna (1998).
[2] Operating Manuals, section1, *Description of the Desalination Package, (Document No.13459-OM-001),* KANUPP (2009).
[3] RAST, W., Water scarcity, sustainable development and integrated water management, Desalination. (2005).
[4] INTERNATIONAL DESALINATION ASSOCIATION (IDA), World-Wide Desalting Plants Inventory Report No. 16, Wangnick Consulting GmbH, Germany (1997).
[5] "Use of Nuclear reactors for seawater desalination*,"* IAEA-TECDOC-57, (1990).
[6] INTERNATIONAL ATOMIC ENERGY AGENCY, Use of Nuclear Reactors for Seawater Desalination, IAEA-TECDOC-574, Vienna (1990).
[7] Seawater desalination, August (2009), URL: http//www.iestech.com/.
[8] INTERNATIONAL ATOMIC ENERGY AGENCY, Technical and Economic Evaluation of Potable Water Production through Desalination of Seawater by Using Nuclear Energy and Other Means, IAEA-TECDOC-666, Vienna (1992).
[9] INTERNATIONAL ATOMIC ENERGY AGENCY, Technical and Economic Evaluation of Potable Water Production through Desalination of Sea Water by Using Nuclear Energy and Other Means, IAEA-TECDOC-666, Vienna (1992).
[10] INTERNATIONAL ATOMIC ENERGY AGENCY, Potential for Nuclear Desalination as a Source of Low Cost Potable Water in south Asia, IAEA-TECDOC-574, Vienna (2000).
[11] "Water analysis for Reject brine from plant at KNPC," document, KANUPP-STR-03-12".
[12] INTERNATIONAL ATOMIC ENERGY AGENCY, Methodology for the Economic Evaluation of Co-generation/Desalination Options, IAEA Computer Manual Series No. 12, Vienna (1997).
[13] INTERNATIONAL ATOMIC ENERGY AGENCY, Options Identification Programme for Demonstration of Nuclear Desalination, IAEA-TECDOC-898, Vienna (1996).
[14] KHAN, A.H., Desalination Process and Multistage Flash Distillation Practice, Elsevier Science Publishers, (1986).
[15] INTERNATIONAL ATOMIC ENERGY AGENCY, Thermodynamic and Economic Evaluation of Co-production Plants for Electricity and Potable Water, IAEA-TECDOC-942, Vienna (1997).
[16] AWERBUCH, L., "Status of sea water desalination technologies" (Nuclear Desalination of Sea Water Proc. Symp., Taejon, 1997), IAEA, Vienna (1997).
[17] AWERBUCH, L., "Importance of the power to water ratio in selecting power desalination technology", Nuclear Desalination of Sea Water (Proc. Symp. Taejon, 1997), IAEA, Vienna (1997).
[18] MISRA, B.,"Status and prospects of nuclear desalination", International Desalination Association Congress, Singapore (2005).
[19] OLIVER, D., "Changing perspectives on desalination with renewable energy", International Desalination Association Congress, Singapore (2005).
[20] INTERNATIONAL ATOMIC ENERGY AGENCY, User Requirements Documents for Small and Medium Reactors and their Applications in Developing Countries: A Guide for their Preparation, IAEA-TECDOC-697, Vienna.

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