Research projects show nuclear desalination economical

BY GAMINI SENEVIRATNE

Ten designs were developed and examined, with favorable costs based on certain fossil-fuel prices for conventional plants.

THE DESALINATION OF seawater using nuclear power is cost-effective compared with other primary energies, according to researchers in 10 countries who have studied various options at specific sites in their own countries. Their findings show nuclear to be at least competitive in all cases.

Researchers from Argentina, China, Egypt, France, India, Korea, Pakistan, Russia, Syria, and the United States focused on the economics of producing potable water by using various desalination technologies and energy sources at particular sites. The participants followed an agreed procedure throughout a coordinated research project (CRP), Economics of Nuclear Desalination—New Developments and Site-specific Studies, set up by the International Atomic Energy Agency. The findings of the studies, carried out over three years and ending in November 2006, are included in a technical document (IAEA-TECDOC) already at the printer.

"There is a dire shortage of fresh water for drinking in many countries already, and when you realize that 70 percent of the planet is covered with water but only 2.5 percent of that is fresh water, it is hardly surprising," Ibrahim Khamis, who heads the IAEA's desalination unit, told *Nuclear News*. He added that 70 percent of that fresh water is frozen in the polar icecaps and Greenland, and most of the rest is in soil moisture, inaccessible underground aquifers, or comes as heavy rain that is difficult to capture. "So only some 0.008 percent, about 70 000 km^3, is readily available, and even that is very unevenly distributed."

According to Khamis, recent statistics show 2.3 billion people living in water-stressed areas, 1.7 billion of them in areas where the availability is on average less than 1000 m^3 a year. Given human population growth and the increasing demands of industry and agriculture, the projections point to a continuously worsening situation, even if the effects of global warming are not taken into account. Khamis said he foresaw a time when nuclear power will be sought for desalination rather than for electricity generation, at least in some specific regions of the world such as the Middle East. "You can live without electricity for quite a long time; without water, only a matter of days."

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The desalination plant evaporators at Aktau, Kazakhstan. The BN-350 fast reactor at Aktau supplied potable water to local communities until it was shut down in 1999. (Photo: IAEA)

The U.S. study, which was undertaken by Argonne National Laboratory (ANL), notes that "the need for fresh water, high-purity water, and other grades of water for various domestic, industrial, and agricultural applications is ever increasing in the United States." Demand is driven mainly by population, as well as continuous economic and technological growth, and it is predicted that more than an additional 60 billion m^3 of water a year will be needed for municipal and light industrial uses by the year 2020. An additional 11–19 liters per day per person will be needed to generate hydrogen, should transportation be based mainly on hydrogen-powered vehicles in the future. "Cogeneration of water and power could offer a major portion of the additional water needed, in addition to providing much needed energy for maintaining sustainable development and growth," the ANL report says.

The IAEA report says that desalinating seawater is not the only solution under discussion for remedying the water scarcity, but it is an important one. There are essentially two methods: distillation using heat, and the use of membranes and electricity directly. The two main distillation modes, known as multistage flash (MSF) and multieffect distillation (MED), both involve heating seawater to produce steam, followed by evaporation, condensation, and, finally, pure water collection. The method using membranes, which is called reverse osmosis (RO), uses electricity to create a pressure differential across a semipermeable membrane, allowing fresh water to pass through to the low-pressure side, and leaving salty seawater on the high-pressure side.

Desalination plant capacity worldwide is close to 40 million m^3 today, mostly by distillation using fossil energy, and mostly in the Middle East and North Africa. Nuclear desalination has so far been exclusively for use within the nuclear power plants themselves, except at the Soviet-built BN-350 fast reactor in Aktau, Kazakhstan, which supplied potable water to local communities until it was shut down in 1999.

Currently, only India supplies nuclear desalinated water outside the plant site. Having earlier used MSF to get plant-use water, it has also integrated RO to the desalination unit at its Kalpakkam pressurized heavy-water reactor (PHWR) in Chenai, and it has begun (experimentally) supplying some water outside the power station. Pakistan has begun a similar project at its Karachi nuclear power plant (KANUPP) to couple a 1600 m^3/day MED unit to the nuclear plant, which earlier operated a 454 m^3/day RO facility for plant use.

Fresh water is needed for many purposes. Saudi Arabia alone already irrigates crops with desalinated water. A number of countries, notably Egypt, the Persian Gulf States, Israel, Jordan, and Libya, depend on the technology to maintain tourism. Khamis said nuclear desalination has been held back by two key factors: economics, and the unavailability of reactors of appropriate size. The CRP addressed the former, comparing cost performance between reactor plus desalination method combinations. The perception that nuclear is less cost-effective than other energy sources was repudiated by the studies.

The report says that the country case studies "have shown that in general, the nuclear desalination costs can vary from \$0.5 to \$0.94/m^3 for RO, from \$0.6 to \$0.96/m^3 for MED, and from \$1.18 to \$1.48/m^3 for MSF plants. All nuclear options are economically attractive as compared with the gas turbine combined-cycle–based desalination systems, as long as gas prices remain higher than \$150/toe [metric tons oil equivalent] or \$21/bbl [barrel]."

It adds the caveat that results are site-specific and reflect current practices, data, and assumptions specific to each country for the cost evaluations of nuclear and conventional water and energy cogeneration systems and their intercomparisons, and "the values of various economic parameters are therefore not absolute." The case studies, which cover particular nuclear and desalination technologies and specific sites, are quite detailed. The following summarizes the conclusions:

Argentina

CAREM + RO system for the Porto Deseado site

As in most regions of the world, Latin America, and particularly Argentina, has an extensive coastal area with populations lacking fresh water, representing an important restriction for its socioeconomic development. Nuclear desalination is a possible solution to this ongoing scarcity. Using nuclear power to generate fresh water as well as electricity is economically preferable to energy from fossil fuels.

A CAREM plant (a small reactor developed jointly by Investigaciones Aplicadas Sociedad del Estado [INVAP] and the Comisión Nacional de Energia Atómica), coupled to an RO system, is an economical and technically feasible option, as well as a safe and reliable alternative for desalination and energy production in Puerto Deseado and other cities with water scarcity problems.

China

NHR-200 + MED systems for some coastal locations

The cost of water from an integrated desalination plant using the NHR-200 (200-MW high-temperature Nuclear Heat Reactor) may be about \$0.75/m^3 for an NHR-200 + VTE (high-temperature, vertical tube evaporator)–MED version and \$0.79/m^3 for an NHR-200 + LT-HTE (low-temperature, horizontal tube evaporator)–MED version. The case study indicated that the cost of steam produced by the NHR-200 is very competitive in comparison with oil- and gas-fired boilers.

Egypt

PWR-1000 + MSF, MED, and RO for a coastal site

Using a 1000-MWe pressurized water reactor, the cost of water (at an 8 percent discount rate) from an MSF plant is highest, at \$1.48/m^3, compared with \$0.89 and \$0.65/m^3 with the MED and RO plants, respectively. Sensitivity analysis has shown that the variation of discount rate and water availability has the largest impact on the unit production cost. The results of the case study clearly indicate the economic interest of nuclear desalination systems for the Egyptian sites.

France and Tunisia

PWR, GT-MHR, and PBMR + MED, RO, for la Skhira site, Tunisia

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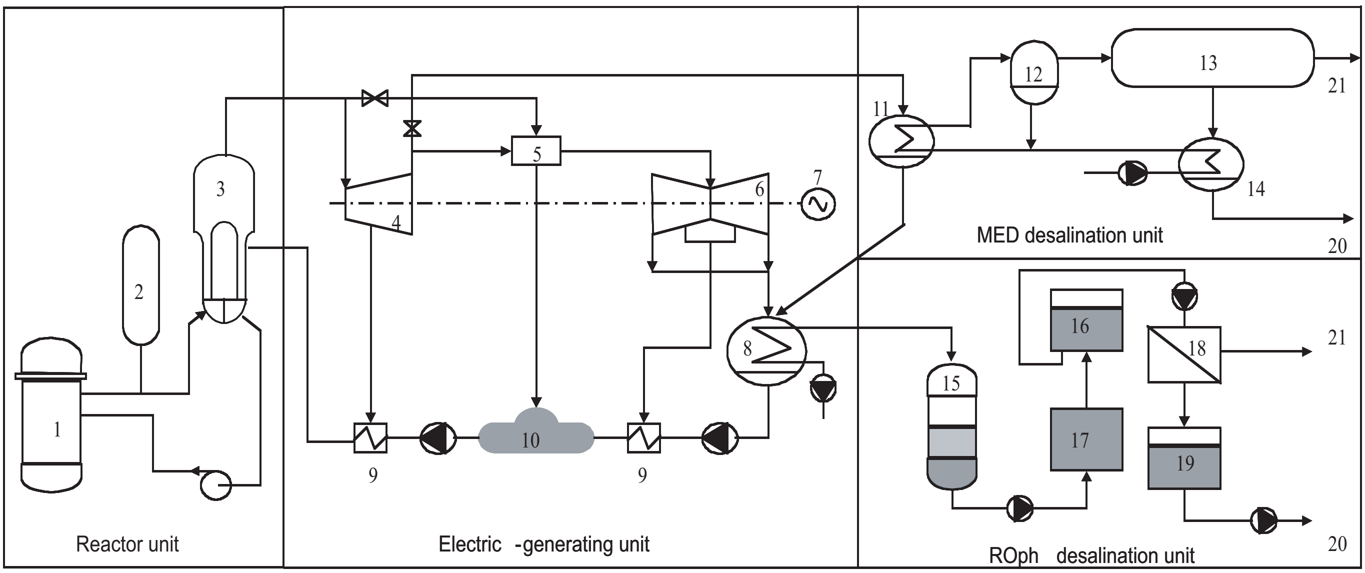

1 – reactor
2 – pressurizer
3 – steam generator
4 – high-pressure turbine
5 – intermediate steam heater
6 – low-pressure turbine
7 – electric generator
8 – condenser
9 – feedwater heater
10 – deaerator
11 – seawater heater
12 – flash chamber
13 – MED stages
14 – condenser
15 – pre-filter
16 – chlorinated water tank
17 – ultra filtration membranes
18 – RO membranes
19 – desalted water tank
20 – product output
21 – brine outflow

Fig. 1. Typical coupling schemes of the PWR + MED and PWR + ROph processes. In the PWR + MED coupling scheme, the vapor extracted from one (or more) turbine stage(s) is fed to a heat exchanger (which may be similar to the condenser), where the incoming water temperature is raised to an appropriate level (70–90 °C). The hot water then passes through a flash tank, where it is partially evaporated. This vapor then serves as the heating fluid in the MED plant. (Diagram: CEA)

Power and desalination costs were obtained with four different reactors: two PWRs—a 900-MWe PWR and the Westinghouse advanced AP600—and two high-temperature reactors—a gas turbine-modular helium reactor (GT-MHR) and a pebble bed modular reactor (PBMR). These were compared with a 600-MW gas turbine, combined-cycle plant (CC-600). All these energy sources were coupled to MED and RO desalination processes, operating in the cogeneration mode. In all conditions, the four nuclear options lead to much lower power and desalination costs, provided gas prices remain above \$150/toe.

The MED desalination cost using the PWR-900 and the AP600 are 46 percent and 42 percent, respectively, lower than the corresponding cost using the CC-600 plant. The lowest costs with the MED plants are obtained by the GT-MHR and the PBMR, utilizing virtually free waste heat. Compared to the cost with the CC-600 + MED system (at a natural gas price of \$60/bbl), these reactors coupled to MED plants lead to desalination costs that are, respectively, 62 percent and 56 percent lower. Compared with the CC-600 + RO system, the corresponding desalination costs of the PWR-900 + RO and AP600 + RO are, respectively, 31 percent and 29 percent lower. With all the energy sources, desalination costs with the RO process are lower than the corresponding costs with the MED plant.

Typical coupling schemes of PWR + MED and PWR + ROph (with preheating of the feedwater) processes are shown in Fig. 1. In the PWR + MED scheme, the vapor extracted from one (or more) turbine stage(s) is fed to a heat exchanger where the incoming water temperature is raised to an appropriate level (70–90 °C). The hot water then passes through a flash tank, where it is partially evaporated. This vapor then serves as the heating fluid in the MED plant.

India

PHWR + hybrid MSF/RO for the Kalpakkam site demonstration plant

Expertise is available in India for the design of large-sized MSF and RO plants for seawater desalination and low-temperature MED technology for utilization of low-grade and waste heat for producing pure water from saline water. The cost of desalted water is a function of specific energy consumption and power tariffs. But because tariffs stay relatively constant, water cost is brought down mainly by reducing the energy consumption.

In the case of RO, higher flux membranes and more efficient energy recovery systems would reduce the specific energy consumption. Scaling up improves the water cost of MSF compared with that of RO. The water cost of MSF is 24 percent higher than the cost of RO, but RO produces better quality water. Permeate water quality from RO deteriorates with time, leading to the need to replace the membrane. In a hybrid system, it is possible to maintain the drinking water quality for a long time by adding the distillate from the MSF, thereby extending the effective life of the membranes.

The experience in implementing the Nuclear Desalination Demonstration Plant at Kalpakkam gave Indian researchers considerable confidence in designing, installing, testing, and commissioning the coupling schemes of nuclear desalination plants (Fig. 2).

Korea

SMART + MED, for a demonstration plant

Korea's SMART reactor, coupled with an MED process, is considered the most likely option for nuclear desalination in Korea. The water cost for a SMART + MED system producing 40 000 m^3/day is \$0.63/m^3 at a 7 percent discount rate. A sensitivity analysis performed with respect to parameters such as interest rate, electricity cost, plant availability, nuclear fuel cycle cost, and capital costs showed the economics to be promising. The discount rate was identified as having the greatest impact on water cost.

Pakistan

Existing CANDU reactor, KANUPP + MED, for Karachi region

This study showed that the discount and interest rates can play an important role in the economics of a desalination project. As for the size factor, for small-sized plants the effect of capacity on water cost is rather small. For large plants (producing > 100 000 m^3/day), however, an appre-

The Nuclear Desalination Demonstration Plant (NDDP), in foreground, at the Madras Atomic Power Station in Kalpakkam, India. (Photo: IAEA)

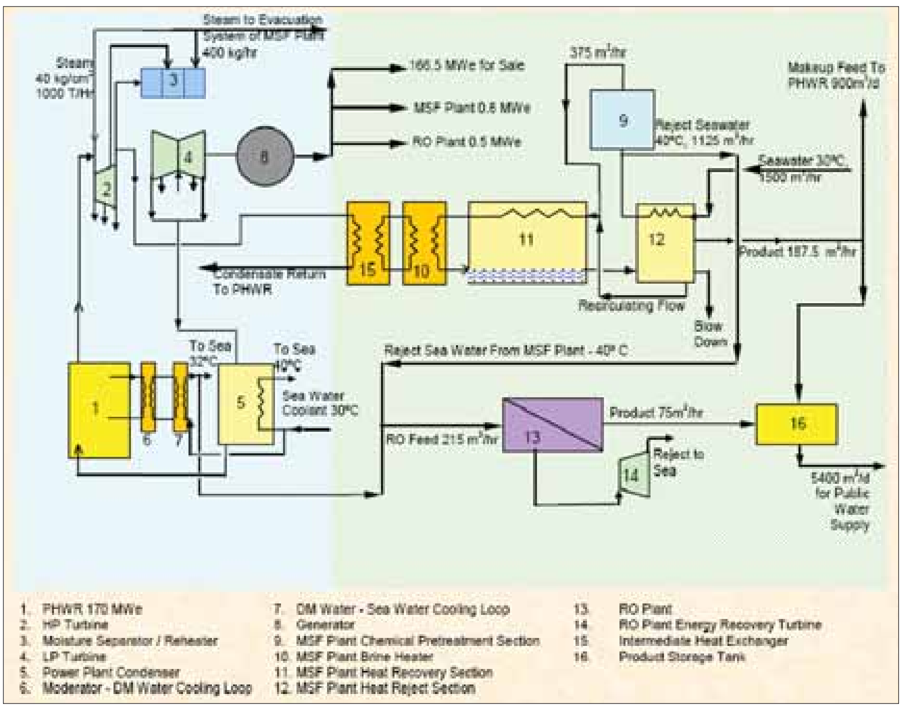

Fig. 2. Coupling arrangement of the NDDP, a hybrid MSF + RO plant, at Kalpakkam. (Diagram: BARC)

ciable reduction in water cost with increase in capacity is observed. Water/power plant availability is another important parameter that appreciably affects the water cost. With a 30 percent increase in the availability factor, the water cost decreases by about 18 percent. The use of nuclear heat to produce potable water from seawater is an attractive option against an oil price even below $45/bbl.

Russia

KLT-40S, RITM-200, GT-MHR + MED, RO for a coastal site

A floating nuclear power desalination complex (FNDC) with Russian KLT-40S reactors coupled with MED plants is considered the most probable option for nuclear desalination in Russia. The cost of desalinated water produced by fossil-fuel desalination complexes was evaluated and the competitiveness of FNDC based on KLT-40S units and the larger RITM-200 reactor was determined and compared with fossil-fuel analogs. Both nuclear options lead to lower power and desalination costs as compared with fossil-fueled systems for oil costs of more than $90–$120/metric ton and coal costs of more than $60–$80/metric ton.

Syria

PBMR + MED/VC, RO, for Damascus region

The water cost for a PBMR + MED/VC (vapor compression) system is $0.52/m^3$, compared with $0.61/m^3$ when using local fossil-fueled thermal energy sources. The water cost for a PBMR + RO system is $0.63/m^3$, compared with $0.67/m^3$ using a local fossil-fueled system. The total potable water cost (including water transport cost and desalination cost) would be in the range of $0.85/m^3$ to $1.40/m^3$.

United States

PWR + MED, RO, and hybrid MED/RO

The study demonstrated the feasibility of the cogeneration of water and power using a nuclear reactor as the energy source. Specific cogeneration options will be evaluated in detail for economic and technical feasibility as a follow-up step to this analysis, which indicates that nuclear desalination can readily be considered a competitive alternative to conventional fossil fuel–powered cogeneration plants.

In addition to providing a range of water products of various qualities and operational flexibility, the hybrid RO/LT (low-temperature)-MED plant option offers water costs that are very close to those of the stand-alone RO seawater plant. The overall energy consumption for the hybrid plant (on the basis of total equivalent MWe and assuming a 30 percent power plant thermal efficiency) is, on average, 60 percent lower than for the stand-alone LT-MED plant. Thus, savings in energy costs are the main contributor to the lower overall product water costs of the hybrid plant.

The nuclear advantage

The main advantage of a nuclear power plant coupled to a desalination plant over a fossil fuel–fired plant is the former's low fuel cycle cost. On the other hand, some additional capital investment may be needed for a nuclear cogeneration plant because of the required isolation loop coupling a thermal or a hybrid plant to the power plant, which is not needed for a coupled fossil fuel–fired plant.

The safety and environmental considerations of a nuclear desalination complex do not pose significant economic or health risks. Some provisions need to be made in order to ensure that when the desalination plant, which serves as a heat sink, is shut down or operated in partial load, there will be a backup heat sink available to accept rejected heat from the power plant and prevent power plant shutdown.

In addition, Khamis mentioned Israel's extensive non-nuclear experience with desalination (reorganized as a national program in 2002), which it reported on at an IAEA technical meeting on integrated nuclear desalination systems in mid-December. The cost of desalination—currently using non-nuclear electricity—at three already commissioned plants provides comparison with the nuclear desalination figures in the 10 earlier reports: Eilat (3 million m^3 per year), $0.9/m^3$; Ashkelon (10 million–11 million m^3/yr), $0.645/m^3$; and Hadera (100 million m^3/yr), $0.595/m^3$.

The report's main conclusions, "from experience accumulated so far," were the following:

- Seawater desalination by RO is "very reliable" for very large amounts from the standpoints of both water quality and overall plant performance.
- Adding improvements to large plants makes them more complex but is economically justified.
- Attention should be paid to environmental issues pertaining to the streams of (brine) concentrate and wash-water of the filters.
- Financing for large projects should be secured as early as possible.

Khamis said that the next big step for nuclear desalination must be for interested countries to set up and run demonstration facilities, coupling reactors and desalination units. India and Pakistan have made a start. Libya has announced the intention to use its research reactor to demonstrate nuclear desalination. He said the IAEA International Conference on Non-electric Applications of Nuclear Power: Seawater Desalination, Hydrogen Production and Other Industrial Applications, being held April 16–19, 2007, in Oarai, Japan, could well be told of further firm developments. NN