Nuclear desalination: Experience, needs, and prospects

A review of demonstration plants and recent studies

by A. Barak, L.A. Kochetkov, M.J. Crijns, and M. Khalid

The world's growing population, expected to reach 11 000 million people by the year 2050, will place even greater pressure on water resources. Large amounts of water are needed for residential, agricultural, and industrial uses, especially in developing countries where supply shortfalls already exist. Water needs are particularly acute in oil-producing countries where major investments and strenuous efforts continue to be made to further industrialize economies. Projections show, however, that the Mediterranean region will experience a fresh water shortage of about 10 million m^3/day by the year 2000.

Relatively speaking, only a small part of the world's water resources can be used in their natural state. In general, surface water with salinity of less than 500 parts per million (ppm) can be used as potable water. For certain agricultural products, water with salinity between 500 and 1000 ppm can be used for irrigation. Other available water — such as brackish water (groundwater, surface water, or waste water with salinity above 1000 ppm) and sea water — cannot be used as it is. Fortunately, technological processes exist to desalt water so that it can be used, including sea water, which offers virtually an inexhaustible water source.

There are various developed sea-water desalination processes but the most promising are the low-temperature, horizontal-tube multi-effect — or multi-stage — distillation (LT-HTMED), vapour compression (VC), and reverse osmosis (RO).

Today, larger plants are being built that consume considerable quantities of heat, raising the question of a reliable, continuous, and affordable heat supply source. Currently, oil is mainly used as the energy source required in the desalination process. But higher oil prices, and the trend toward larger, more energy-intensive desalination plants, are contributing to the search for other sources. Among the options being considered for the long term is the coupling of nuclear power plants with desalination processes. Such "dual purpose" complexes would supply both electricity to help meet energy demands and the heat to help desalt large amounts of water.

While a large number of conventional desalination plants have been commissioned worldwide, experience with nuclear desalination is more limited, having been demonstrated only in the Soviet Union. The technology's feasibility additionally has been studied at national and international levels over the past decades, including work done through the IAEA. *(See box.)*

Mr Barak is on the staff of the Israel Atomic Energy Commission, and Mr Kochetkov is with the Research and Development Institute of Power Engineering in the USSR. Messrs Crijns and Khalid are staff members in the IAEA Division of Nuclear Power.

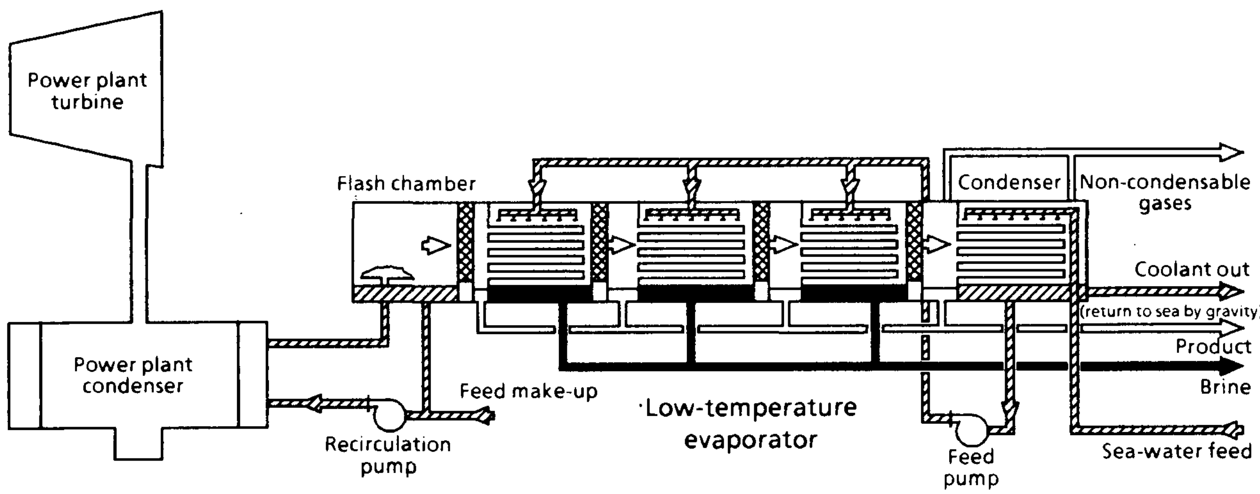
Technical studies and reports

The IAEA has been studying the feasibility of nuclear desalination since the 1960s. Interest among Member States in the technology has been renewed recently following a resolution adopted at the IAEA General Conference in 1989. Sponsored by Arab States, the resolution underscored the reality of national and regional water shortages and the increasing need for potable water, and it *inter alia* requested the Agency to prepare a report on the development and potential role of nuclear desalination to help address problems. A technical study is being prepared and will be submitted to the IAEA General Conference in September 1990.

The IAEA previously has issued a number of technical publications on the technology. They include:

- *Desalination of Water Using Conventional and Nuclear Energy,* Technical Reports Series No. 24 (1964).
- *Guide to the Costing of Water from Nuclear Desalination Plants,* Technical Reports Series No. 80 (1967 and 1973).
- *Heat Utilization from Nuclear Reactors for Desalting of Sea Water,* IAEA-TECDOC-206 (1978).

A schematic flow diagram for the Ashdod multi-effect distillation plant in Israel



This article reviews the USSR's experience with nuclear desalination, as well as a joint project of the United States and Israel, and recent studies in the United States, Japan, and the Federal Republic of Germany.

Experience in the Soviet Union

A large multi-purpose nuclear power complex has been built in the city of Shevchenko that is supplying the population of the town and its industrial enterprises with water, electricity, and thermal energy. The complex includes the BN-350 fast-breeder reactor (FBR), three thermal power stations, and a desalination plant with thermal distillation equipment, as well as units that produce drinking water from the desalted sea water.* Research and development has been carried out on different desalination processes, such as multi-effect, vertical-tube evaporation (VTE), multi-stage flash (MSF) distillation, electrodialysis, and ion exchange.

The FBR was selected as one of the main energy sources for this complex. Another energy source also is erected on the same site in which natural gas is used as fuel. The two facilities have a common turbine hall and, what is particularly important, a unified system of feedwater preparation.

From the standpoint of its water regime, the complex is exceptionally complicated. The generated steam is used for power generation, sea-water desalination, and for various industrial needs. The distillate is used to produce drinking water, industrial process water, and water for heating purposes, and also to compensate for non-recoverable feedwater losses.

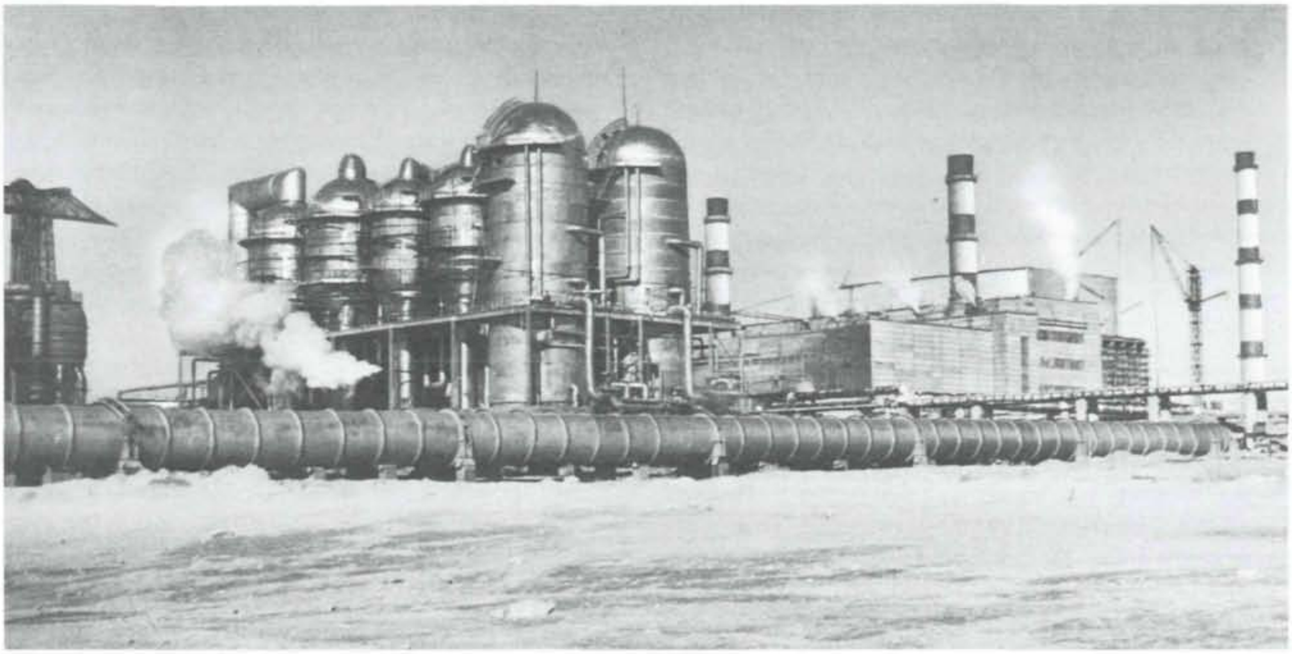
The nuclear reactor, the electric power plant, and the desalting facilities constitute one single technological complex with mutually complementary components, a complex which has a number of obvious advantages.

The presence of facilities which use low-pressure and low-temperature heat — the desalting units — makes it possible to stabilize levels of heat extraction required in different seasons. In winter, the complex operates as a district heating plant, whereas in summer most of the heat is used for desalting. The fairly constant heat extraction means low specific heat input for the production of electric power.

The desalting units, which provide the power plant and the reactor with highly pure desalted water, do much to reduce the capital and operating costs required for steam generator feedwater treatment. This is a particularly valuable characteristic in a hot-water and heat-supply system because it allows scale-free boiler operation and reduces the amount of heat required per unit of distillate (hot distillate is pumped into the heat-supply system).

Furthermore, the availability of significant volumes of desalted water makes it possible to release some of this water to local industrial enterprises for process requirements. This relieves them of the necessity of

* Technical references (in Russian) for this section include "Obzor razvitiya bystrykh reaktorov v SSSR" (Survey of fast reactor development in the USSR), by L. A. Kochetkov and Yu. E. Bagdasarov, proceedings of a symposium in Bologna, IAEA, Vienna (1978); "Itogi desyatiletnej ehkspluatatsii BN-350" (Ten years of BN-350 operation), by D.C. Yurchenko et al., *Atomnaya ehnergiya 55* (1983); "Osnovnye itogi ehkspluatatsii opytno-promyshlennykh AEhS s bystrymi reaktorami BN-350 i BN-600" (Main results obtained in operating nuclear pilot plants equipped with the BN-350 and BN-600 reactors), by L.A. Kochetkov, proceedings of a symposium in Lyon, IAEA, Vienna (1986); and "Vodno-khimicheskij rezhim ehnergeticheskogo kompleksa s bystrym reaktorom" (Water chemistry in a power plant using a fast reactor), by R.N. Musikhin et al, *Atomnaya ehnergiya 55* (1983).



The Shevchenko nuclear power plant in the USSR.

building small desalting facilities of their own. It is not necessary for steam users to return the steam condensate to the reactor power plant cycle.

The BN-350 FBR and associated steam generators went into operation in 1973. In the Soviet Union, this was the first large multi-purpose FBR designed for tests, experiments, and industrial uses simultaneously. The 150-megawatt-electric (MWe) reactor was designed to produce 120 000 m^3/day of distillate. When it went into operation, it was the main source of distillate in the region, producing about 80% of the total. It also generated up to 25% of the region's electric power. Thus, the BN-350 bore heavy responsibility right from the start for normal living and industrial working conditions in the region.

Stability of operation in the whole complex depends on a number of factors, and in particular on the reliability of the reactor installation and the associated steam generators. In the beginning, the steam generators proved to be the Achilles heel of the plant. During the first 6 months after startup, five out of the six steam generators failed. Fairly detailed reports have been written on the causes of this failure and on the repair work undertaken as a result. Faults committed at the factory in manufacturing the endpiece of the pipe system together with faulty welding (of the end component and piping) were the cause of water leaks into the sodium side of the steam generators. The repair was carried out on site without taking the evaporators apart, and was finished in 1975.

Another source of operational instability in the reactor unit was the failure of a large number of fuel elements. This was caused by the unduly small compensation space available to accumulate gaseous fission fragments between the fuel and the cladding, leading to enhanced gas pressure beneath the cladding, increased stresses, and ultimately cladding failure. Design improvements virtually eliminated these losses of fuel element integrity, and resulted in a higher burnup than the design value. Stable steam generator operation was finally attained as well, although the initial reactor power had to be reduced from 1000 MWth to 750 MWth.

Designers and operators initially had a lot of trouble with the water regime in this reactor. Feedwater from the distillation units was contaminated by corrosion products, and in accident situations also by sea-water salts; for this reason it was subjected to additional chemical purification in the gas-fired facility, which included both mechanical and mixed-bed filters. Nevertheless, during the initial period, the quality of both distillate and feedwater were unsatisfactory. Improvements were made in the desalting plant, and a new chemical desalting facility was installed for purifying the distillate passing through the BN-350 steam generators.

In the endeavour to find optimum technical design solutions for thermal desalting facilities, experiments were carried out on a number of process variants.

A seed crystal method, which has been thoroughly developed in the Soviet Union, was used in all these desalting facilities to prevent scale formation. The seed crystals — a finely ground natural chalk — were introduced into the system during startup through a single injection and were afterwards recirculated using a clarifying device (settling tank) and a centrifugal pump.

This method of limiting scale formation by recirculating chalk seed crystals guaranteed scale-free operation of the evaporators in a 10-effect vertical-tube evaporation facility for a year of continuous operation. The linear growth rate of scale on heating surfaces is different in the various evaporators: 0.6–0.8 mm/year for the first evaporator; 0.3–0.4 mm/year for the second; 0.2–0.3 mm/year for the third; 0.1–0.2 mm/year for the fourth; and 0.05 mm/year for all the rest. The 10-effect facility yields the highest quality distillate.

The distillate obtained from the thermal desalination facilities is then converted into drinking water which meets the requirements of the Soviet Government's regulation (GOST 2874-82). The production cost of the distillate was about 50 kopeks/m^3 for the 10-effect facility.

Thus, Shevchenko has yielded extremely abundant and valuable technical material and practical experience in providing high-quality water. If the experience accumulated here would be widely used in future desalination schemes and in the technology for producing "artificial" drinking water, the problems of providing comfortable living conditions in the arid and semi-arid regions of the world, such as Kazakhstan, can be solved not only successfully but quickly.

Experience in Israel: Joint Israel-USA project

In the early 1980s, Israel and the United States started co-operative development of large modules for the desalination process known as LT-HTMED. In Ashdod, Israel, a plant has been built, which was designed to be suitable for integration with a light-water reactor (LWR).

The number and size of the LT-HTMED effects were determined so that the plant would be able to absorb the exhaust heat from the power plant without the expensive complication of changing the nuclear steam turbine. The system of heat supply from the (conventional) power plant to the evaporator simulates the designed coupling of a nuclear dual-purpose plant. It does so by using a pressure reversal barrier to prevent possible leakage from the LWR steam cycle into the desalination plant. This was done by having the turbine exhaust steam condense in a shell and tube condenser at about 65°Celsius. Concentrated sea water with 5.7% total dissolved solids was used as recirculating cooling water (55.5°Celsius inlet, 62°Celsius outlet temperature). The cooling water flows into the evaporator and releases the heat by flashing partly into vapour. The cooling water in the condenser is under higher pressure than the condensing steam so that, in case of a leakage, the steam cannot penetrate the desalination system. The size of the plant was the largest possible for such evaporators. For a large nuclear plant, several modules will be installed in parallel.

The LT-HTMED evaporator, having a production rate of 725 m^3/hour was coupled in 1982 to a 50-MW oil-fired power unit, supplying about 120 tons of steam per hour. The plant started operation in 1983. After a short commissioning time it operated successfully for 1 year. Operation was stopped after obtaining sufficient operational data and because oil prices were too high.

No operational problems have been encountered regarding the plant's control, stability, startup, and shutdown, or with respect to load-following and changing from dual-purpose "mode" to single-purpose, electricity-generation "mode". Under all conditions the plant operated in a stable manner. The startup time, from cold state and empty evaporators with atmospheric pressure until normal operation, took 3 to 3.5 hours. The startup time, after a short shutdown due to a given failure (as long as the vacuum was maintained), was 30 minutes. The shutdown time to allow gradual cooling of the power unit was about 20 minutes. Changing from one "mode" to another, or vice versa, was simple and took about 15 minutes. Load-following was demonstrated successfully without any problems between 35% and 110% of nominal production.

The desalination plant can be restarted even after many months without operation; occasionally it has been operated for a few hours for demonstration to visitors. In 1986 it operated continuously for 3 months due to a severe drought. Unexpected shutdowns during the first year amounted to 749 hours and planned shutdowns to 2665 hours. It is expected that under normal conditions a combined plant-turbine has an availability of at least 88%.

At the beginning, the quality of produced water was acceptable (280 ppm) but not as good as the design value. Since then, at nominal loads, the product's salinity has been decreased to 40–80 ppm. The quantity produced has been above the plant's design level, depending on the sea-water temperature. When the sea-water temperature exceeds the design value by over 4°Celsius, the product quantity decreases to 92%.

At the Ashdod plant, 14 people were employed. In a normal plant fewer will be needed, since in Ashdod many "first of a kind" activities, including data collection, had to be carried out.

The power unit condenser turned out to be cleaner than under single-purpose operation. Very slow-scale formation was discovered in the hot effects (0.1 mm thick after one year). No scaling was detected in the colder effects and no corrosion was found.

Recent studies

Southern California study. The Metropolitan Water District of Southern California, a water utility, together with the US Department of Energy (USDOE), has conducted a study to evaluate the technical and economic viability of using nuclear heat for sea-water desalination. The final report by General Atomics Company was published in December 1988.* In this study, the modular high-temperature gas-cooled reactor (MHTGR) was selected as the heat source and the LT-HTMED as the desalination process.

* *MHTGR Desalination for Southern California*, GA-A19476, General Atomics Co., San Diego, CA (December 1988).

The MHTGR was selected because its small size and modular configuration are more compatible with desalination applications than current water-cooled reactor concepts, and the impact on electrical production is less when the reactor is used in the cogeneration mode. In addition, it can be sited near water distribution systems because of its passive safety characteristics and small unit size.

With respect to the desalination process, a comparison was made among the commercially demonstrated desalination processes, such as MSF distillation, VTE, and LT-HTMED.

The system studied consisted of four 350-MWth reactor modules, two 273-MWe steam turbine energy conversion systems, and eight LT-HTMED units of 50 000 m^3/day each. The net electrical power output of the plant was about 460 MWe and the net water output was approximately 400 000 m^3/day. Levelized water costs would vary between 0.44 and 0.49 US $\$/m^3$ depending on the assumptions made.

German study. Howaldtswerke Deutsche Werft AG and Interatom GmbH of the Federal Republic of Germany have recently studied the technical and economic feasibility of a barge-mounted MHTGR for sea-water desalination using the RO process.* The MHTGR consisted of a helium-cooled, pebble-bed reactor which can provide power from 400 MWth (with two modules) to 1600 MWth (with eight modules).

This study consisted of a dual-purpose power plant with two modules capable of producing 152 MWe of electricity and 100 000 m^3/day of desalted water with a product salinity of 450 ppm (total dissolved solids). The electrical power consumption in the plant is only 30 MWe, so the remaining 122 MWe can be sold to other energy consumers.

The study was based on the salt content of sea water in the Arabian Gulf. Sea water is first preheated up to 38° Celsius in the condenser. Then, after pretreatment, it is fed to the first stage of the RO process. (The first stage consists of 45 trains with 40 RO modules each.) After the first stage, the salt content in the water is reduced to 1470 ppm, which is then fed to the second stage consisting of 9 trains with 60 RO units each. The water produced in this stage contains 190 ppm salt content. It is blended with the output of the first stage to maintain a final salt content of 450 ppm. The total consumption of chemicals for pretreatment amounts to about 5500 tons per year; 250 tons of chemicals are additionally required for cleaning (four to six times per year) of the two RO stages.

The cost for the production of drinking water depends on the selected electricity/drinking water ratio. When the operating concept is to generate electricity as the main product (and to produce drinking water during times of low electricity demand), the drinking water production costs amount to 3.81 to 4.69 DM/m^3. It was assumed that operation time would be 8000 hours per year.

Japanese study. The Central Research Institute of Electric Power Industry (CRIEPI) of Japan has initiated a study to help prevent desertification.* This study can also be applied for the large-scale production of potable water from the sea.

The study consists of the coupling of a liquid-metal-cooled fast-breeder reactor (LMFBR) with the RO sea-water desalination process to produce desalted water at a rate of 300 000 m^3/day.The reactor is of a modular type with a thermal output of 125 MWth; its preliminary design is characterized by compactness, safety, and simplicity, which is why it is named the "4S" reactor (super-safe, small, and simple). The core consists of ductless assemblies with metal fuel pins. The life of the core is designed for 10 years without refuelling.

The RO process was selected because of its low energy consumption, simplicity of operation, low maintenance, short startup period, and ease of partial capacity operation. According to this study, the energy consumption is about 4.1 kWh/m^3 of product water, excluding the required energy for product water delivery pumps.

Needs and prospects in developing countries

In developing countries, where needs are urgent and resources lacking, the introduction of both desalination and nuclear power technologies faces difficulties. Both technologies are investment-intensive, complex and sophisticated, and economical mainly on a large scale.

Consequently, developing countries needing potable water must first consider other steps before desalting sea water on a large scale. These include: (1) developing all natural water resources unless water has to be transported over large distances, which also entails high costs; (2) reclaiming maximum sewage water for irrigation and other applications; and (3) desalting available brackish water, which has lower salinity than sea water, by reverse osmosis or electrodialysis.

These steps are less expensive than sea-water desalination, but provide only limited amounts of water. If more water is needed and sea water is available, desalination should be introduced gradually, starting with single-purpose units. This way, the experience and infrastructure required for desalination will be developed to facilitate the next possible step for nuclear desalination. However, the first nuclear units should generate solely electricity, so that the nuclear infrastruc-

* "Autarke Barge-Montierte Energiestation mit Hochtemperaturreaktor-Module", Howaltswerke Deutsche Werft AG and Interatom GmbH (July 1985).

* "Use of Super-Safe, Small and Simple Liquid-Metal Reactors (LMRs) to create Green Belts in Desertification Areas", by S. Hattori and N. Handa, *Trans. ANS*, Vol. 60 (1989).

ture and experience can also be developed. Later, nuclear units can perform as dual-purpose plants.

Two alternatives may also be considered. One is construction of a nuclear desalination plant early (most likely also for electricity generation) under a turnkey or build-and-operate contract. For the latter contract, the supplier will assume full responsibility for the construction and for the operation and maintenance of the plant during a limited period. The customer will then pay for the water costs rather than for the plant costs.

The other is the design and construction of a nuclear power plant mainly intended for single-purpose use, that is electricity generation. It would include only minimum requirements for a future conversion to a dual-purpose plant (e.g. site planning, turbine selection, etc.). The additional cost would be millions of dollars, but that would enable the unit to be coupled with desalting systems a few years later.

Middle East oil-producing countries

Oil-producing countries in the Middle East have a developed infrastructure for desalination and considerable experience. Moreover, they have sufficient revenues to support desalination's development. The only potential limitation is lack of infrastructure in nuclear technology.

The needs for water in these countries is large and urgent, which explains why many desalination plants already are on line; in early 1988, about 65% of all desalination capacity in the world was installed in these countries (7.9×10^6 out of 12×10^6 m^3/day) and consisted of mostly MSF and RO processes.

Water needs are expected to grow as the population increases. Population growth rates in these countries are very high, ranging between about 2.5%–5% per year (compared to 0.17% in the USA and 1.7% worldwide, on average). Many of the existing desalination units will be replaced within the next decade and afterwards by improved technologies. Over the next decade, this will require about US $10 billion of investment in the water systems and billions of dollars more in the necessary energy generation systems.

One principal question is which primary energy source to use for the desalination systems. Nuclear power and oil are the two most attractive options.

From the economical point of view, oil-producing countries have higher motivation than other countries to prefer oil. However, other aspects, such as environmental, social, and psychological ones, are also considered. One approach is to use the same energy source as the one preferred for baseload electricity generation. The pros and cons of nuclear versus oil are very similar for power generation, as they are for desalination.

Conclusions

- Prolonged operating experience, since 1973, of using a fast-breeder reactor for sea-water desalination in the Soviet town of Shevchenko has proven the technical and economical feasibility of nuclear desalination in that region.
- The attractiveness of nuclear desalination compared to conventional desalination is related to the comparative long-term stability of fuel prices, in contrast to the rising price of fossil fuels, economical benefits due to a high capacity factor, and minimal environmental impact.
- On the basis of improvements and developments of different desalination processes in the 1980s, there seem to be no particular technical problems when these advanced desalination processes are coupled with nuclear power plants.
- Recent major studies in the United States, the Federal Republic of Germany, and Japan have demonstrated the technical and economic potential of nuclear desalination, although for some applications, like agriculture, the desalted water is still too expensive. The prospects for nuclear desalination are difficult to predict, mostly because the final decisions involve factors and governmental policies beyond the technology's own technical and economic potential.