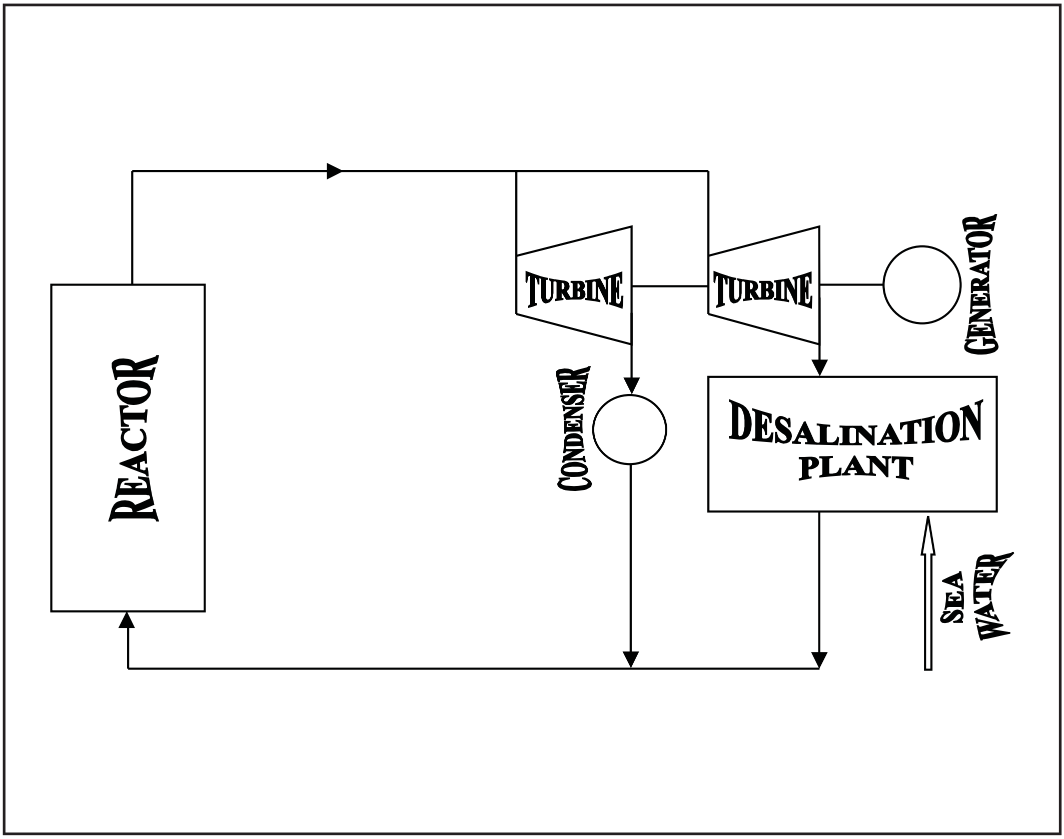

TECHNICAL REPORTS SERIES No. **400**

Introduction of Nuclear Desalination

A Guidebook

INTERNATIONAL ATOMIC ENERGY AGENCY, VIENNA, 2000

INTRODUCTION OF NUCLEAR DESALINATION

A Guidebook

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FOREWORD

Interest in using nuclear energy for producing potable water has been growing worldwide in the past decade. This has been motivated by wide varieties of reasons, inter alia, from economic competitiveness of nuclear energy to energy supply diversification, from conservation of limited fossil fuel resources to environmental protection, and spin-off effect of nuclear technology in the industrial development. In response to this trend, the IAEA has been co-ordinating various feasibility studies on nuclear desalination of seawater with participation of interested Member States since 1989.

The IAEA took steps to update its review of available information on desalination technologies and the coupling of nuclear reactors with desalination plants. Results were reported in an IAEA technical document. After the status review, the IAEA prepared and issued another technical document in 1992, which contained an assessment of the economic viability of seawater desalination by using nuclear energy in various coupling configurations in comparison with fossil fuels. In 1991, in response to a request for technical assistance submitted by five North African States (Algeria, Egypt, Libyan Arab Jamahiriya, Morocco and Tunisia) a regional feasibility study on nuclear desalination was launched. The study was completed in 1995 with an IAEA technical document. Results of these studies led to a general understanding that demonstration of nuclear desalination was necessary in order to build up technical and economical confidence under specific conditions. In the Options Identification Programme for Demonstration of Nuclear Demonstration, the IAEA identified practical options of technical configuration of nuclear and desalination coupling for demonstration. The IAEA held a Symposium on Desalination of Sea Water with Nuclear Energy in 1997 in the Republic of Korea.

Some Member States have, or are planning to launch, demonstration programmes on nuclear desalination. It has been recommended by the International Nuclear Desalination Advisory Group (INDAG) to publish a Guidebook on Introduction of Nuclear Desalination for the benefit of such Member States so that the development could be facilitated as well as their resources could be shared among interested Member States.

This report summarizes all the information collected and provides guidance on decision making for deploying nuclear desalination and on the steps for project implementation.

The Guidebook comprises three major parts: (1) Overview of nuclear desalination, (2) Special aspects and considerations relevant to the introduction of nuclear desalination, and (3) Steps to introduce nuclear desalination.

It is expected that the information contained in this Guidebook will be useful for decision makers, policy planners, engineers and scientists in the area of nuclear seawater desalination.

The IAEA wishes to express its thanks to all those who took part in the review meetings for their efforts and assistance and for many suggestions for improvement of this Guidebook during its preparation. Special thanks are due to the members of INDAG for their comprehensive advice and assistance in the preparation. Special thanks are also due to B.M.Misra (BARC, India) for his extensive efforts in compiling and reviewing the drafts. The IAEA officer responsible for the compilation of the report was T. Konishi of the Division of Nuclear Power.

EDITORIAL NOTE

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INTRODUCTION

1.1. OBJECTIVE

Interest in using nuclear energy for producing potable water has been growing worldwide in the past decade. This has been motivated by wide varieties of reasons, inter alia, from economic competitiveness of nuclear energy to energy supply diversification, from conservation of limited fossil fuel resources to environmental protection, and by nuclear technology in industrial development. IAEA feasibility studies, which have been carried out with participation of interested Member States since 1989, have shown that nuclear desalination of sea water is technically and economically viable in many water shortage regions. In view of its perspectives, several Member States have, or are planning to launch, demonstration programmes on nuclear desalination. This guidebook has been prepared for the benefit of such Member States so that the development could be facilitated as well as their resources could be shared among such interested Member States.

1.2. SCOPE

This guidebook comprises three major parts: Part I — Overview of nuclear desalination, Part II — Special aspects and considerations relevant to the introduction of nuclear desalination, and Part III — Steps to introduce nuclear desalination. In Part I, an overview of relevant technologies and pertinent experience accumulated in the past is presented. The global situation of the freshwater problem is reviewed and incentives for utilizing nuclear energy to contribute to solving the problems are briefly set forth. State-of-the-art relevant technologies and experience with them are summarized. Part II identifies special aspects to be considered in decision making process concerning nuclear desalination. There are technical, safety and environmental and economical aspects as well as national requirements. In Part III necessary steps to be taken once nuclear desalination has been selected are elaborated. Policy issues are discussed, and project planning is summarized. This point also elaborates on project implementation aspects, which include siting, feasibility studies, plant acquisition and, eventually, design, construction and operation. As much as possible[1], the guidebook has been compiled as a stand-alone document, so that decision making in interested Member States is facilitated, with minimum reference to other relevant publications of the Agency. The key contents of each part are presented in the following section.

1.3. OVERVIEW OF NUCLEAR DESALINATION

The world is becoming increasingly aware of critical limitations in the availability of fresh water for agricultural, industrial and domestic uses. Because of the growing population, many regions are faced with increased freshwater demands that greatly exceed the capability of existing supply infrastructures. The problem is compounded by increases in both pollution and salinity of freshwater resources. Development of adequate water resources, their conservation and their preservation have thus become a very important worldwide problem.

Nearly three quarters of the earth's surface are covered with water. The estimated total volume of water is 1.3×10^{18} m^3. However, 97.5% of this amount is represented by the oceans, which are highly saline and unfit for human consumption. Of the remaining 2.5%, a major portion is locked up in polar ice and glaciers. On balance, less than 1% is available for human use. It is estimated that the amount of fresh water that is readily accessible to human use is about 9×10^{12} m^3 and another 3.5×10^{12} m^3 is captured and stored by dams and reservoirs.

About 23 million m^3/d of desalted water is currently produced by 12 500 plants set up in various parts of the world. These plants largely use fossil energy sources. Interest in using nuclear energy for producing potable water has been growing worldwide in the past decade. This has been motivated by a wide variety of reasons, inter alia, from economic competitiveness of nuclear energy to energy supply diversification; from conservation of limited fossil fuel resources to environmental protection; and to the spin-off effects of nuclear technology in industrial development. In response to this trend, the Agency has been co-ordinating various

[1] As recommended by the International Nuclear Desalination Advisory Group (INDAG).

feasibility studies on nuclear desalination[2] of sea water with participation of interested Member States since 1989.

- *Nuclear desalination involves three technologies: nuclear, desalination and their coupling system.*

The adaptation of nuclear energy for desalination has two parts: the selection of the reactor type and the implementation of the nuclear fuel cycle (from the availability of uranium to the disposal of radioactive wastes). Each part involves the selection of technology options, which must be suited not only to water and power production but also to the natural and technological resource availability of the host country. Technically, any reactor type can be used for nuclear desalination, although several types are identified as the most practical and probable for this application. Particular attention is given to the technology of water cooled reactors because of their advanced state of development and deployment. These reactors are well proven, and the fuel, which uses natural uranium (NU) or low enriched uranium (LEU), is widely available.

- *The selection of a particular process depends on saline water quality, product water quality requirement and process economics.*

Commercial seawater desalination processes that are proven and reliable for large scale freshwater production are multi-stage flash (MSF) and multi-effect distillation (MED) for evaporative desalination and reverse osmosis (RO) for membrane desalination. Vapour compression (VC) plants based on thermal and mechanical vapour compression are also employed for small and medium capacity ranges. These processes have their inherent advantages and disadvantages. For desalination plants rated at more than 4000 m^3/d per unit, MSF is still more prevalent than any other process. However, the RO process is increasing its market share every year, and there is likely to be increased use of MED and VC, including hybrid systems.

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[2] 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 system are located on a common site and energy is produced on-site 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 control facilities, and seawater intake and outfall structures.

- ❑ *Desalination plants can be coupled with a single purpose plant to produce only water or a co-generation nuclear plant to produce water and electricity.*

When a nuclear reactor is used to supply steam for desalination, the method of coupling has a significant technical and economic impact. For optimum coupling, the size and type of the reactor, the specific characteristics of the desalination process and the desirability and value of electricity generation as a co-product should be assessed.

- ❑ *The safety of a nuclear desalination plant depends mainly on the safety of the nuclear reactor and the interface between the nuclear plant and the desalination system.*

It must be ensured that any variation in steam demand from the desalination plant would not cause a hazardous situation in the nuclear plant. Adequate safety measures must be introduced to prevent any harmful radioactivity release to the product water. The effectiveness of these measures should be evaluated by a risk assessment analysis, and an agreement on safety and, additionally, quality standards and regulations should be reached by all relevant parties.

Experience with nuclear desalination, as accumulated in Kazakhstan and Japan, has now, as of 1999, exceeded 100 reactor-years. No incidents of safety concern, associated with nuclear desalination, have been reported. Several activities are under way in Member States to demonstrate technical and economical viability of nuclear desalination with state-of-the-art nuclear and desalination technologies. Technical assistance by the IAEA through Technical Co-operation (TC) and Co-ordinated Research Projects (CRP) facilitates these activities, which include experimental work and/or connection of a desalination system to an existing nuclear power plant.

1.4. TECHNICAL, SAFETY, ECONOMIC AND ORGANIZATIONAL ASPECTS OF NUCLEAR DESALINATION

- ❑ *The most important technical aspect to be considered by decision makers is the amount of power and water needed in the region where a nuclear desalination plant is to be built.*

This information will play a key role in selecting either a co-generating or a single purpose heating reactor plant as the energy source. The key considerations for selecting the reactor plant type are:

- Co-generating plants — produce both power and water; have limited operating flexibility; require medium to large investment; and have a long lead time.
- Heating reactors — have a shorter lead time; are best suited to optimizing coupling; have a simpler design; and require less investment.

The selection of the desalination technology depends both on the reactor type considered and the required product water quality as determined by the end use, e.g. drinking, industrial or commercial use. Thermal desalination plants (MSF, MED) provide very pure water that is directly usable for industrial process applications. RO plants provide drinking quality water as per WHO standards.

If co-generating nuclear reactors are chosen, careful consideration should be given to the power-to-water ratio, which is defined as power required per m^3/d of fresh water produced. This parameter can be intrinsically limited by the reactor plant design and could thus affect the reactor plant selection. The required power-to-water ratio varies from country to country and also during the seasons of the year.

The overall safety of an integrated nuclear desalination plant complex is mainly dependent on the safety of the nuclear reactor, the design impact of coupling the reactor plant to the desalination plant, and the transient interactions between the two. A particular concern unique to nuclear desalination plants is the potential for release of radioactive materials into the product water. This can be effectively overcome by suitable design features which make use of multiple barriers and pressure differentials to block the transport of radioactive materials to the desalination plant.

Radioactivity in the intermediate system and in the desalination plant must be continuously monitored. Monitoring of the product water output is an important feedback for safety protection, and this information needs to be transferred rapidly to enable operating personnel to shut down the process before significant quantities of contaminated product water are released.

Proximity to population centres is an advantage for desalination plants from the point of view of water distribution, whereas isolation from population centres is preferable for nuclear plant safety. Balancing these two competing factors is an essential element in the overall water and energy supply policy for a country. If the nuclear desalination plant is located near a population centre, this must be taken into account in civil emergency preparedness planning.

Licensing of nuclear desalination plants requires authorities to deal with water supply and quality regulations in addition to the body of nuclear regulations that applies to conventional nuclear plants. Regulatory authorities must also address the environmental impacts of nuclear desalination systems, because they discharge brine and some chemicals in addition to those from the nuclear plant. Good experience exists on the management of these discharges. Nevertheless, they should be carefully assessed to assure that no significant synergistic impacts can occur.

- *Economic competitiveness is a decisive factor in decision making.*

Cost of product; percentage of local currency; investment; cash flow, payback period and rate of return; the price of the product; and the value of the product to the customer are commonly used economic criteria. Other related aspects such as financing, economy of scale, techno-economical optimization and scheduling are also important elements to be assessed carefully.

The product water cost is most commonly evaluated by summing all principal cost components for desalted water. These include: the capital cost (30–50%), the cost of energy (50–30%), and O&M cost (15–25%). For a single purpose plant with a dedicated heat source, the energy cost is the total cost of constructing and operating the energy source divided by the total energy output in any given period of time. For a co-generation plant, the calculation of the energy cost is more complicated because the power plant produces two products, electricity and heat.

A co-generation plant has several economic advantages over single purpose plants. The specific financial investment is lower, owing to the sharing of facilities. Also, specific fuel and manpower costs are lower because the total costs are distributed to both products; less fuel; less manpower. However, a co-generation plant can also have disadvantages such as less overall flexibility; a slightly lower availability factor; and non-optimal siting and construction schedules.

There are several techniques of allocating costs to the two final products of a co-generation plant, water and electricity, or to an intermediate product such as steam delivered to the desalination plant. These techniques can be complex and tedious. In this regard, the Agency has developed a user friendly computer program (desalination economic evaluation program, DEEP) to assist with these evaluations[3]. The program is embedded in a spreadsheet routine containing simplified nuclear and desalination plant sizing and cost algorithms, which are easy to implement and are generally applicable to a wide variety of equipment and representative state-of-the-art technologies. The program calculates the cost of water (and power) for single as well as dual purpose plants and enables comparison of nuclear versus fossil energy sources. Cost allocation between water and power products at a dual purpose plant is evaluated by using the power credit method.

The spreadsheet serves three important objectives:

(1) It enables side-by-side comparison of a large number of design alternatives on a consistent basis with common assumptions.

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[3] The PC mounted program is available from the Nuclear Power Technology Development Section, IAEA, upon request under a License Agreement.

(2) It enables quick identification of the lowest cost options for providing a specified quantity of desalted water and/or power at a given location.
(3) It gives an approximate cost of desalted water and power as a function of quantity and site specific parameters including temperatures and salinity.

Studies with DEEP have shown that the right source of primary energy for seawater desalination has a large effect on the economics of the desalination system. Nuclear energy becomes increasingly competitive in large installations compared to fossil fuel based desalination plants because fuel cycle costs are considerably lower for nuclear power plants than for fossil fuel plants. The ratio of fuel to total cost in a fossil plant is significantly higher than in a nuclear plant. This is likely to further increase as the inventory of fossil fuel is gradually depleted.

❑ *There are special aspects relevant to the national requirements when a country considers introducing nuclear desalination.*

These include review of the organizational requirements, infrastructure requirements, project requirements, public awareness and acceptance, and the international agreements and commitments on liability, safety and safeguards for nuclear reactors.

For a nuclear desalination programme, organizational structures are needed to manage the required activities at the governmental level as well as within the utilities, industry, research and development, and educational institutes involved. If the nuclear desalination project constitutes a country’s initial introduction to nuclear energy, the first task to be performed is to set up a national organization for planning and co-ordinating the nuclear energy programme.

The total infrastructure of a nation can be viewed as a set of organizations that interact with each other to various degrees. The industrial infrastructure should be developed for services, materials supply and fabrication or construction, so that optimum national participation is achieved. General infrastructure should be available to support the successful operation of national industries. Some key items such as staff development, technical information and services, and licensing and regulations should also be considered.

It is often recognized and pointed out that lack of public support could constrain the introduction of new nuclear facilities. The public should be informed on the precise nature of the planned facility, experience with this kind of facility elsewhere, its costs, safety concept, environmental impact and potential benefits for the local community. The availability of power, waste heat and good quality potable water may also attract additional industries and their employees to the neighbourhood of the nuclear plant site, and allowance should be made to take into account such long range population trends.

When a country decides to start a nuclear desalination programme, the responsibility for the development of all necessary structures to create, regulate and maintain a nuclear desalination programme rests with the government and various national organizations and institutions. There are legal requirements at the national and international levels that will be encountered in the establishment of a nuclear desalination programme. Selected international agreements and conventions, which IAEA Member States have adopted, are as follows:

- Convention on Nuclear Safety (in force since 1996)
- Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management (opened for signature on 29 September 1997);
- Convention on Early Notification of a Nuclear Accident (in force since 1986);
- Convention on Assistance in the Case of a Nuclear Accident or Radiological Emergency (in force since 1987);
- Convention on the Physical Protection of Nuclear Material (in force since 1987);
- Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (in force since 1975).

1.5. STEPS TO INTRODUCE NUCLEAR DESALINATION BY MEMBER STATES

❑ *Once the decision to select nuclear desalination has been made, special aspects relevant to the policy issues should be identified.*

This will include a review of the national energy and water policies, the national development policy and the policies concerning international and regional relations. A national policy should clearly specify the objectives for the national energy and water plans. The policy must be directed towards providing practical and effective solutions on a long term basis. Key aspects to be addressed are:

- Improved energy independence;
- Indigenous exploitation of energy and water resources;
- Optimum management of energy and water supply; and
- Demand projections and environmental protection.

The national development policy should address plans for developing national participation, national infrastructure and human resources. The appropriate level of national participation is strongly relevant to the contract type: build-own-operate (BOO), build-operate-transfer (BOT) turnkey, and others. Policy makers should also consider how the level of national participation evolves together with the overall nuclear programme.

Special consideration should be given to the policy issues concerning water management. Water resource management must be based on rational policies and strategies. Water reuse and wastewater reclamation will be important tools for extending the water supply, whereas desalination of sea water or brackish groundwater can extend the supply of high quality water for potable use or specific industrial uses.

The introduction of water marketing and pricing mechanisms can encourage the private sector to play an increasingly important role in providing the necessary financial resources and management skill needed for the successful development and utilization of the resources. Governments need to establish laws and regulations for the fair and efficient operation of water markets.

Building of human and institutional capabilities is another essential step in preparing sustainable water strategies. Women, youth, non-governmental organizations and indigenous people need to be brought into capability building strategies, as they are essential in building a sustainable water future.

❑ *Since nuclear plants, seawater desalination plants and their accompanying facilities are capital intensive, the commitment of the government to a nuclear and water programme is crucial to reduce the uncertainties and associated risks and to improve the overall climate for financing.*

The government should prepare long term plans for nuclear energy and water development, as well as the associated financial and economic plans. The increasing need for foreign exchange in most developing countries to meet the financing requirements of a nuclear project necessitates seeking additional and complementary mechanisms. An approach most likely to be viable will be a BOT approach.

A careful analysis of the overall water structure of the country should be made before a nuclear desalination programme is included in the national water supply plan. If a national water balance is not available, it should be performed as an integral part of the nuclear desalination planning study. The following factors must be addressed in the detailed development of the plan, which is usually elaborated in the feasibility study:

— Plant capacity
— Type of energy
— Programme schedule
— Financing

— National infrastructure and participation
— Availability of relevant staff resources and training programme
— Siting considerations
— Licensing considerations
— Public acceptance
— Project management
— Expected benefits and constraints
— International/bilateral co-operation

❑ *Selection of a suitable site is an important stage in the implementation of a nuclear desalination project.*

The distance between load centres and possible sites is one of the important factors to be considered in the siting survey. For desalination plants, this distance is generally more meaningful than for power plants, since the water transmission cost is higher than the electricity transmission cost. Furthermore, the oceanographic and topographic conditions, such as seawater quality and elevation rises and falls, need to be considered. The factors related to the potential impact of the plant on the site are also to be assessed before site selection.

The construction and operation of a nuclear desalination plant involve several non-safety-related factors, positive or negative, that influence local population; creation of new jobs; or demands upon local infrastructure resources (housing, schools, transportation, medical services, recreation, etc.). It is desirable that possible adverse social impacts of the plant be minimized and social benefits enhanced.

The applicable standards must be available before site evaluation can start. Different national and international standards concerning siting may apply, depending on the country. In addition, the Code of Practice on Siting and a series of siting safety guides, developed by the IAEA, are possible alternative standards.

There are no safety and siting standards available specifically for seawater desalination plants. Since the desalination plants will be located at nuclear power stations, the standards for protecting nuclear plants against natural events would also encompass the desalination plants. However, the brine and chemicals discharges of nuclear desalination plants need to be carefully controlled to protect the marine environment. The radioactivity content of the desalination plant feed must be carefully controlled because the standards for radioactivity content in the product water are much more stringent.

❑ *After planning studies have established both the demand for desalted water and the use of nuclear energy as a preferred energy source, the next step consists of an in-depth feasibility study.*

The main objective of a feasibility study is to prove that the nuclear desalination project is feasible within the technical, economic and institutional environment of the country. The salient aspects of a feasibility study should include:

(1) Current and future markets for potable water and electricity should be analysed. This inevitably leads to the electricity and water expansion programme.
(2) Supply options for commercially available reactor and desalination plant types and capacities should be identified, taking into account the possibilities for local participation in the project, financing prospects and transfer of technology.
(3) Special attention should be dedicated to a survey of those features, systems, components and equipment that might be supplied by the national industry. This survey will provide input data and information for evaluating the contracting approach that should be adopted. The survey should carefully analyse the possibility for supply of each item. Goods and services to be supplied can be classified into the following categories: Goods and services that must be supplied locally; that could be produced by a national industry; and those of special interest for national supply.
(4) New infrastructures are required for the introduction of nuclear power for electricity generation and seawater desalination. The institutional aspects of a large scale energy and water production programme must be clearly understood and addressed. An organizational structure should be formulated in order to execute the programme by defining the programme's policy, scope, size, schedule, budget and staff requirements.
(5) The safety and regulation of nuclear power plants, with emphasis on their use as energy sources for seawater desalination, is also an institutional issue. The concept of public participation, from an early stage of the nuclear desalination programme, needs to be recognized.
(6) Finally, the feasibility study should define the project schedule for the specific conditions of the country and include a financial analysis of the investment requirements, with a survey of potential sources of project financing.

The financial requirements of the project include the estimated total investment cost of the project, including the owner's cost. Financial requirements should be broken down into foreign and local currency requirements. The importance and difficulties of local financing should not be underestimated.

❑ *The first phase of project implementation is plant acquisition, which includes the steps leading to finalization of the contracts.*

The overall schedule for plant acquisition can be about four to five years, assuming no major delays in decision making. The schedules for construction and commissioning could be about two to three years for a desalination facility, three to four years for a small, dedicated reactor and five to seven years for a medium or large co-generation plant.

The establishment of the local organization for plant acquisition composed of highly qualified engineers and experienced professionals is an immediate and important task to be undertaken. One of the key decisions that the owner must make before the preparation of the specifications and bid documents is the choice of the contractual approach for plant acquisition.

Basically there are several probable types of contract approach for nuclear desalination plants: turnkey; split package; multiple package; and independent projects[4]. If the owner of the first nuclear desalination project is inexperienced, it is advisable to delegate the project management function to an experienced main contractor under a turnkey approach, or to an experienced architect–engineer under a split package approach. However, the owner cannot delegate direct responsibility for control and supervision of the project and should be prepared to fulfil this commitment in the most efficient way.

When the contract type is chosen, bid specifications must be prepared. The preparation of bid specifications constitutes the first stage of the plant acquisition process. It is recommended that the buyer organize a team from his available staff, augmented by others recruited for the specific purpose of preparing the bid specifications.

Upon preparation of bid specifications, the buyer issues the bid invitation to potential vendors. The bid invitation should include a draft contract with the terms and conditions by which the buyer wishes to bind the successful bidder. The draft contract should address the administrative, organizational, commercial, legal and technical matters that are of overall importance to the project and that need to be settled in the final contract document.

The evaluation of the bids received from suppliers is a major task leading to the selection of the supplier(s) and the final decision for construction. Some aspects, especially those affecting national policy and financial matters, would probably involve high governmental levels. Evaluation is to be performed on technical soundness, economics, contractual conditions, organizational aspects, national participation and technology transfer.

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[4] The buyer places a contract with an independent third party for supply of water and/or power. The independent third party constructs and operates the plant. Variants include BOO and BOT. The independent third party takes responsibility for financing, construction and operation.

All the tasks performed during the acquisition phase culminate in the finalization of the contracts. The primary task during contract negotiations is to set out the contractual terms and conditions in a clear and precise manner and to define the supplier's responsibilities regarding the scope of supply, services, warranties, guarantees, code compliance, standards and regulations adopted for the plant. Nothing relevant should be left open, and the temptation to leave details 'to be mutually agreed upon later' should be thoroughly resisted.

A nuclear desalination project is only viable if financing is assured. The financing arrangements have to be negotiated directly between the buyer and the financing institute. The vendor will usually provide assistance. This could be of fundamental importance for obtaining loans on the best possible terms.

- ❑ *The role of project management in ensuring successful transition from project inception to desalted water production is a vital one.*

Project management activities start with the decision to go ahead with a nuclear desalination project and end with the handing over of the operating plant to another body which will be responsible for its operation and maintenance.

The owner is responsible for implementing the overall QA programme for the plant. The regulatory body is also involved in a supervisory capacity by performing inspections and audits to see that the project's QA and QC provisions are effectively implemented.

The owner is responsible for design review, surveillance and control in order to verify that the supply is within the established scope and contractual terms and conditions.

Availability of local infrastructures and the national participation policy determine the scope and the level of the involvement of national industries in manufacturing of nuclear reactor equipment and components, manufacturing of desalination unit equipment and components, and installation of equipment, components and systems.

After the plant has been installed and all inspections and functional tests have been completed, an acceptance test sequence is conducted to demonstrate that the plant is capable of achieving the design electrical output and producing water of the required quantity and quality. The sequence is carried out in four parts: trial operation, initial operation, reliability test and performance test. After the acceptance test sequence, the plant is handed over to the owner. During this commissioning period, final training of the operation and maintenance staff can be carried out on the basis of pre-arranged agreements.

After turnover of the plant to the owner, the owner must take full responsibility for the operation and maintenance of a nuclear desalination plant. He cannot share this responsibility with anyone else, though he can, and normally does, obtain some assistance, especially in the early stages of plant operation, from the plant designer and constructor, and from manufacturers of equipment and components for plant maintenance.

❑ *Having a well designed and constructed plant and a well trained, competent and dedicated operations and maintenance staff will enhance safe and reliable operation of a nuclear desalination plant.*

Desalination plant operation includes the operation of the seawater intake system, pretreatment system, desalination equipment, associated equipment, product water treatment plant and other auxiliaries. A fully equipped chemical control laboratory is also needed for analysis purposes.

For a country introducing its first nuclear desalination plant, it is recommended that a generous approach be applied towards the number of people to be trained and the length and depth of their training. The training and retraining of operation and maintenance personnel is a constant activity during the lifetime of a nuclear desalination plant. The owner should make provisions for performing this activity both to fulfil the needs of the first plant and those of the follow-up units of a nuclear desalination programme. The first nuclear desalination plant in a country constitutes possibly its most valuable training ground. Operation and maintenance staff of the desalination plant should have the capability to analyse plant performance and suggest design improvements in order to enhance process availability.

PART I

OVERVIEW OF NUCLEAR DESALINATION

Chapter 2

STATUS AND PROSPECTS OF NUCLEAR DESALINATION

2.1. INTRODUCTION

The world is becoming more and more aware of critical limitations in the availability of fresh water for agricultural, industrial and domestic uses. From population growth, many regions are experiencing increased freshwater demands which greatly exceed the supply capability of existing infrastructures. The problem is compounded by increases in both the pollution and salinity of freshwater resources. Lack of fresh water is a prime factor in inhibiting regional economic development. Continued shortages resulting from exhaustion and/or pollution of existing water supplies could lead to a general decline in the quality of life as specific daily consumption is reduced. In the extreme, severe freshwater deficiencies could become a question of life or death. Clearly, fresh water is the world's most important basic resource. It must be protected, conserved, developed and enhanced in order to meet the needs of future generations.

2.1.1. Global water availability

Nearly three quarters of the earth's surface are covered with water. The total estimated volume of water is 1.3×10^{18} m^3. However, 97.5% of this amount is represented by the oceans, which are highly saline and unfit for human consumption. Out of the remaining 2.5%, a major portion is locked up in polar ice and glaciers. On balance, less than 1% is available for human use. It is estimated that the amount of fresh water that is readily accessible for human use is about 9×10^{12} m^3 and another 3.5×10^{12} m^3 is captured and stored by dams and reservoirs. Even this small fraction is believed to be adequate to support all life on earth. Table 2.I shows that worldwide annual consumption of fresh water is currently about one third of the accessible water [1].

Given the global water cycle process for replenishing water supplies through seawater evaporation and precipitation, it would appear that the total available water would be sufficient for human needs. Unfortunately, the availability of naturally occurring fresh water for human use is limited. It consists of non-renewable sources such as aquifers and other reservoirs that are not regularly recharged, and renewable sources such as lakes, rivers, reservoirs and other sources that are replenished by the

TABLE 2.I WORLDWIDE ANNUAL FRESHWATER CONSUMPTION (1995)

Continent	Population (million)	Average per capita use (m^3/a)	Total water use (10^{12} m^3/a)
North America	455	1450	0.66
Europe	509	620	0.32
Oceania	27	580	0.02
Asia	3701	530	1.96
South America	319	320	0.10
Africa	721	190	0.14
Total	5732	558	3.2

annual water, or hydrological, cycle. This water is not distributed evenly throughout our planet, neither temporally nor spatially. It is often not available in sufficient quantities either when or where it is needed by humans, resulting in semi-arid or arid regions [2]. The amount of water available in a given location as a result of the natural water cycle is essentially fixed. Thus as the population increases, the annual water supply per person, which is a general indicator of water security, decreases.

Hydrologists have adopted the concept of a 'water stress index', based on an approximate minimum level of water required per capita to maintain an adequate quality of life in a moderately developed country in an arid zone. Although the indicators are only approximate, it has been found that a country or region whose renewable freshwater availability exceeds about 1700–2000 m^3 per person per year will suffer only occasional or local water problems. Below this threshold the lack of water begins to give periodic or regular water stress. Two rough benchmark levels have been adopted:

- ***Water stressed:*** A country or region is considered water stressed if the availability of renewable freshwater supply falls between 1000 and 2000 m^3 per person and year.
- ***Water scarce:*** A country or region is considered water scarce if the availability of renewable fresh water supply is less than 1000 m^3 per person and year. At this level, the chronic lack of water begins to hamper human health and well-being and is a severe restraint on food production, economic development and protection of natural systems. Below 500 m^3 per person and year, there is considered to be an absolute scarcity of fresh water.

Figure 2.1 illustrates a sampling of countries projected to experience water stress or water scarcity by the year 2025, based on a United Nations medium population projection. A complete list of countries expected to reach the threshold of water stress or water scarcity by the year 2025 is given in Ref. [3].

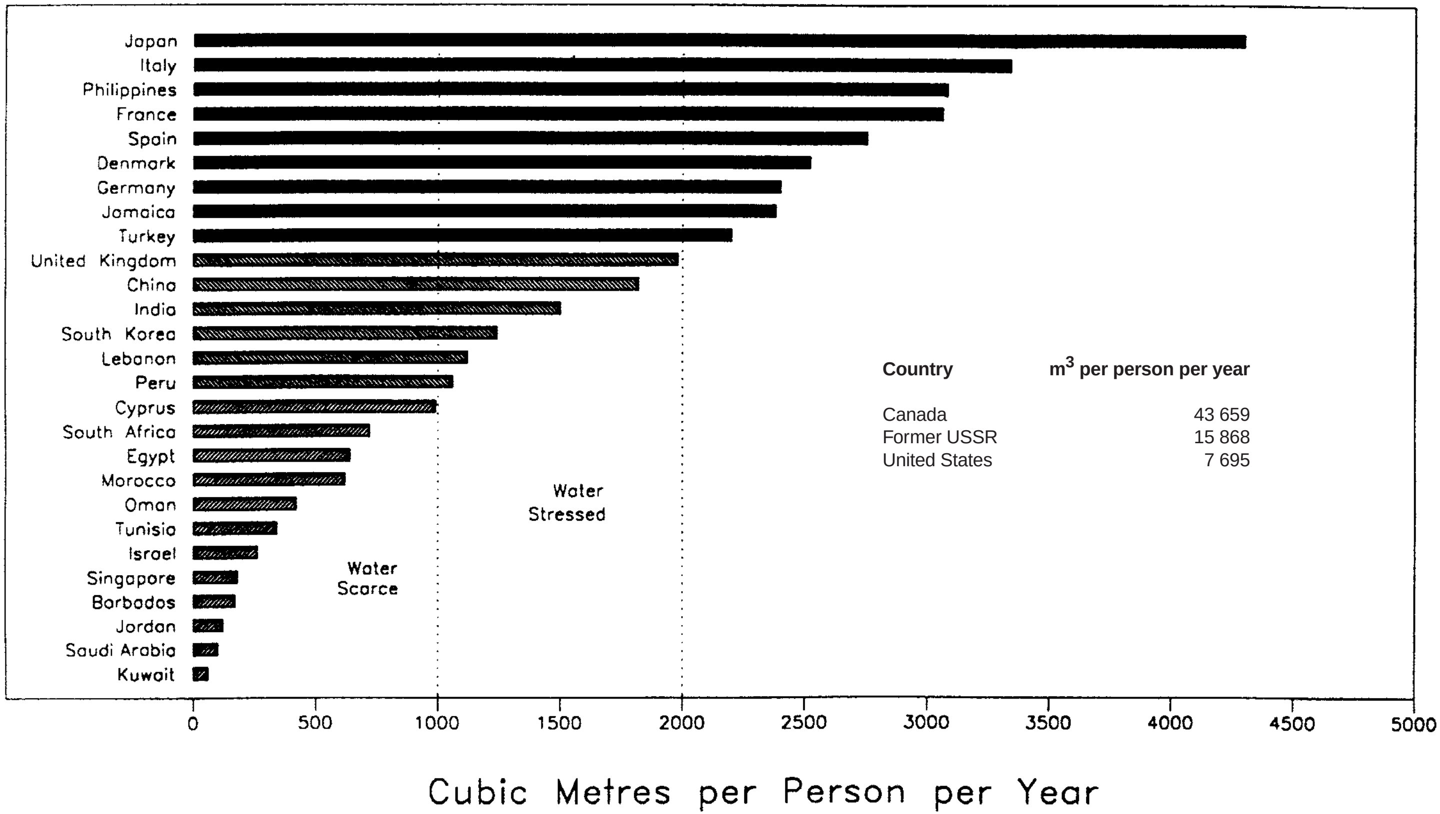

FIG. 2.1. Countries expected to experience water stress or scarcity by 2025.

Water demand is also fast increasing, because of population growth, rapid industrialization and urbanization. Given an expected population increase of about 50% in the next 50 years, coupled with expected increases in demand as a result of economic growth and life-style changes, this does not leave enough for increased consumption.

2.1.2. Global water withdrawals

When the global water picture is examined at a country level some countries still enjoy large amounts of water per capita, but others are already facing serious difficulties. In preparing the comprehensive assessment report for the UN Commission on Sustainable Development, four different categories of increasing water stress, shown in Fig. 2.2, are defined. These definitions, which differ from the definitions given above, are based on water withdrawals as follows:

- ***Low water stress:*** Countries that use less than 10% of their available fresh water generally do not experience major stresses on the available resources.
- ***Moderate water stress:*** Use in the range of 10 to 20% of available water generally indicates that availability is becoming a limiting factor, and significant effort and investments are needed to increase supply and reduce demand.
- ***Medium to high water stress:*** When water withdrawals are in the range of 20 to 40% of the water available, management of both supply and demand will be required to ensure that the uses remain sustainable. There will be a need to resolve competing human uses, and aquatic ecosystems will require special attention to ensure they have adequate water flows.
- ***High water stress:*** Use of more than 40% of available water indicates serious scarcity, and usually an increasing dependence on alternate sources and use of groundwater faster than it is replenished. This means that there is an urgent need for intensive management of supply and demand. Present use patterns and withdrawals may not be sustainable, and water scarcity can become the limiting factor to economic growth.

2.1.3. Water quality

Water quality is also an important aspect that is heretofore not well recognized in many parts of the world. Table 2.II gives WHO and EC standards for potable water quality [4]. In the same table, standards of other countries are added for comparison. Water quality requirements vary depending on the end use such as irrigation, domestic use, commercial or industrial applications. The water quality and quantity have fallen, because of poor water allocation, wasteful use and lack of adequate protective action. As a result of human activities, the water quality has been progressively deteriorating, resulting in reduced freshwater availability.

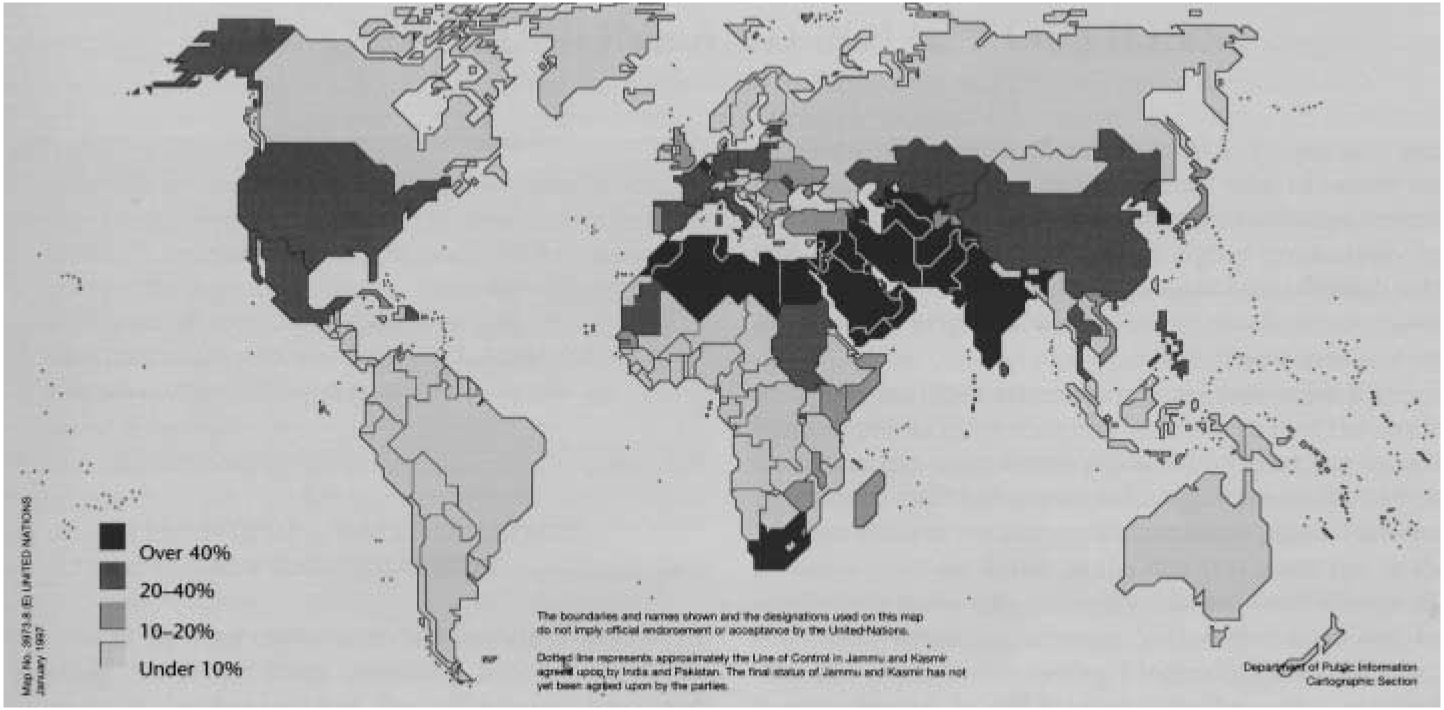

FIG.2.2. Worldwide water withdrawal as a percentage of water availability.

TABLE 2.II. STANDARDS FOR DRINKING WATER

		WHO 1993	EEC 1980 80/778/E WG			USA 12/89	Japan	Germany	Canada
Unit	Constituent	GV	RV	MALC	NMC	MCL	MALC	MALC	MACC
Important to aesthetic quality									
°C	Temperature	NGV		25				25	15
—	pH	<8	6.5–8.5			6.5–8.5	6.8–8.6	6.5–9.5	6.5–8.5
	Taste and odour	NGV							
TCU	Colour	15	1	20			5		15
NTU	Turbidity	5	0.4	4			2	1.5	5
	Detergent	NGV		0.2					
mg/L	Oxygen dissolved	NGV			>75% sat				
µS/cm	Conductivity		400					2000	
mg/L	TDS	1000		1500		500	500		500
mg/L	Total hardness	NGV			60		300		
mg/L	Alkalinity				30				
mg/L	Calcium		100					400	
mg/L	Magnesium		30	50				50	
mg/L	Strontium								
mg/L	Sodium	200	20	(150)				150	
mg/L	Potassium		10	12				12	
mg/L	Ammonium	1.5	0.05	0.5				0.05	
mg/L	Phosphate		0.4	5				5	
mg/L	Iron	0.3	0.05	0.2		0.3	0.3	0.2	0.3
mg/L	Manganese	0.1	0.02	0.05		0.05	0.3	0.05	0.05
mg/L	Zinc	3	0.1			5	1	5	5
mg/L	Copper	1	0.1			1	1	3	1
mg/L	Aluminium	0.2	0.05	0.2				0.2	
mg/L	Chloride	250	25	(200)		250	200	250	250
mg/L	Sulphate	250	25	250		250		240	500
mg/L	Hydrogen carbonate								
Important to health									
mg/L	Antimony	0.005		0.01				0.01	
mg/L	Arsenic	0.01		0.05		0.05	0.05	0.01	0.05
mg/L	Barium	0.7	0.1			1		1	1
mg/L	Beryllium								
mg/L	Boron	0.3	1					1	5
mg/L	Cadmium	0.003		0.005		0.01	0.01	0.005	0.005
mg/L	Chromium	0.05		0.05		0.05	0.05	0.05	0.05
mg/L	Cyanide	0.07		0.05			NTD	0.05	0.2
mg/L	Fluoride	1.5		1.5		2	0.8	1.5	1.5

TABLE 2.II. (cont.)

		WHO 1993	EEC 1980 80/778/E WG			USA 12/89	Japan	Ger-many	Cana-da
Unit	Constituent	GV	RV	MALC	NMC	MCL	MALC	MALC	MACC
mg/L	Lead	0.01		0.05		0.05		0.04	0.05
mg/L	Manganese	0.5							
mg/L	Mercury	0.001		0.001		0.002	NTD	0.001	0.001
mg/L	Nickel	0.02		0.05				0.05	
mg/L	Nitrate	50	25	50		10	>10	50	10
mg/L	Nitrite	3		0.1				0.1	1
mg/L	Kjeldahl-Nitrogen			1				1	
mg/L	Oxidability $KMnO_4$		2	5			10	5	
mg/L	Selenium	0.01		0.01		0.01		0.01	0.01
mg/L	Silver	NGV		0.01		0.05		0.01	0.05
Bq/l	Gross α	0.1							
Bq/l	Gross β	1.0							

NMC = necessary minimum concentration
RV = recommended value
NGV = no guideline value Set
MACC = maximum acceptable concentration
MCL = maximum containment level
GV = guideline value
MALC = maximum allowable concentration
NTD = not to be detected

The world's water supply, already threatened by rising levels of pollution, is growing so scarce in some areas that, if current trends continue, two thirds of humanity will suffer from severe to moderate water stress in coming years. The excessive exploitation of underground water sources for agriculture has led to significant lowering of the water table. The process has caused seawater intrusion into coastal groundwater in many parts of the world, thus affecting the potable water quality and its availability.

Industrial water use is expected to more than double by the year 2025, accompanied by a quadrupling of industrial pollution discharges. A nearly 400–500 million tonnes increase in hazardous waste is reported since the 1992 Rio Conference. Introduction of more water efficient and clean production technologies could, however, contain industrial water demands and curb the pollution of water sources.

2.1.4. Importance of seawater desalination

Seawater desalination is an important option for satisfying current and future demands for fresh water in arid regions with close proximity to the sea. Seawater desalination is energy intensive and most directly applicable to arid regions. Some of the arid regions are rich in fossil resources whereas others are not. The scenario is quite different for the two cases. For arid regions that have abundant fossil fuels, such as the Arabian Peninsula, desalination is well established and produces good quality water to augment existing water resources. In arid regions that are poor in fossil fuels, the existing scarce water resources are augmented by transporting good quality water from long distances. This is an unsatisfactory solution. Water supply schemes involving transporting water over long distances require large financial outlays and long periods of construction. The appropriation of land and displacement of inhabitants can cause serious socio-environmental concern. If the distribution networks are open and/or unlined, they will incur substantial loss of water due to seepage and evaporation. Water supply schemes based on transferring water from one region to another region are also open to public dispute because of the impact of water supply on regional growth and prosperity. Consequently, both desalination and water reuse are now seriously considered in such regions as long-term solutions for meeting increasing water needs.

Desalination of sea water on a large scale has long been envisaged. The oceans constitute an inexhaustible source of water but are unfit for human consumption because of a salt content in the range of 3 to 5%. Evaporation of sea water to produce fresh water was known even to the ancient Greeks, while small distillation devices were first used on ships in the early seventeenth century. Desalination by selective permeation through membranes was known only in the early twentieth century. During the last 25 years, the combination of R&D work and operating experience has established evaporative and membrane desalination as the most promising of the various possible methods of desalting. Desalination is now successfully practised in numerous countries in the Middle East, North Africa, Southern and Western USA and Southern Europe to meet industrial and domestic water requirements. The deployment of desalination plants in Asia and the Pacific Region is also increasing. The current number of desalination plants is about 12 500, with a combined capacity of nearly 22.8 million m^3/d (5 billion gallons/d) of fresh water, i.e. about 1 gallon/d of desalted water per person. Approximately 60% of the installed desalination capacity is in the Middle East. The installed capacity has been rapidly growing not only due to increasing numbers of plants but also to the increasing sizes of plants. The largest individual operating plant capacity is nearly 454 000 m^3/d.

It is worth mentioning here that fresh water produced from seawater desalination plants based on either evaporative or membrane process fully meets the drinking water quality criteria formulated by WHO, EC, USPHS or other standards set by various countries in the world. Desalination is a very safe source of water and is comparable to conventional water supply schemes.

2.1.5. Energy sources for desalination

Desalination plants require energy to separate salt from saline waters. The energy can be either heat for seawater distillation or electrical or mechanical energy to drive the pumps for pressurization of sea water across membranes. The major source of heat energy comes from fossil fuels — coal, oil and gas. Most of the large size plants based on thermal and membrane processes are located near thermal power stations, which utilize fossil fuels to supply both steam and electrical power for desalination. The use of fossil fuels to supply current and future water needs has several drawbacks. Combustion of these fuels emits large amount of greenhouse gases to the environment, which contributes to global warming. These fuels are also non-renewable resources and their known reserves are projected to be exhausted in about 30 to 50 years (for oil and gas). Because of their versatility as an energy source and hydrocarbon feedstock, there is a keen interest in conserving fossil fuels for other industrial applications, especially in countries with inadequate sources of energy.

In recent years, use of renewable energy sources has been considered for desalination application, as well. These renewable sources include solar thermal and photovoltaic, wind energy, tidal, ocean thermal energy and biomass and require large areas for harnessing the energy; they also involve high capital cost. Only a few small capacity desalination plants are set up on the basis of these energy sources, particularly in remote locations where no other primary energy sources are available. The ocean thermal energy converter (OTEC) could be attractive for setting up large size power and desalination plants.

2.2. POTENTIAL ROLE OF NUCLEAR REACTORS FOR SEAWATER DESALINATION

As mentioned earlier, most large desalination plants are located near power stations which provide heat for evaporation of sea water and electricity to drive pumps and other desalination plant equipment. Most of the power plants use fossil fuels — coal or oil fired boilers and gas turbines, including combined cycles. For some plants, the fossil fuel sources are located at long distances from the power station so that the fuel cost must include transportation. Future power and desalination plants that rely on fossil fuels must make provisions for fuel transportation. It often happens that proposed projects are economically not feasible because of the cost of building the fuel transportation infrastructure.

Over the long term it is not practical to establish a future desalting economy solely on fossil fuels because they have limited availability, whereas fresh water must be available for the duration of humanity. Long term reliance on desalting should only occur if the availability of the energy supply is comparable to the required availability of the product. This criterion can be satisfied by nuclear energy.

Today, nuclear power plants produce about 17% of the world's electrical power. There are 434 nuclear reactors operating in various countries. These are of different capacities ranging from 100 to 1450 MW(e) capacity. Large nuclear power plants with near base load operations produce power at costs that are comparable to those of fossil power stations. In the 1960s, it was considered that large desalination plants could be built near large size nuclear power plants in coastal areas. However, it was soon realized that in many areas where desalination was a necessity, the existing infrastructures and technologies were not adequate. To be economically competitive, nuclear plants had to be large. The electric power grids could not accommodate large size power stations. Desalination of sea water using nuclear power as the energy source thus could not be adopted on a large scale, at that time.

The development of cost competitive small and medium size nuclear power reactors is more suitable for grid sizes in developing countries as well as for coupling with desalination plants of 10 000 to 100 000 m^3/d capacities. On the basis of the experience with district heating plants utilizing steam from nuclear power stations and a few desalination plants set up at nuclear power stations, some experience is available on the reliability and safety of using nuclear energy for desalination. This experience is useful in promoting a reasonable degree of public awareness of nuclear desalination as a source of fresh water.

The cost of desalted water has been a constraint to large scale adoption of desalination plants in many parts of the world even though there has been little increase in the cost of energy over the last decade, or so. Combined cycle based power stations are now proven to be more economic for co-generation plants producing power and water. Reduced cost and improved performance of membranes have resulted in significant cost reductions for new seawater reverse osmosis plants. Hybrid plants based on combined thermal and membrane processes provide yet another means of cost reduction for meeting both drinking water and industrial needs. The result is that large scale desalination is becoming less expensive, whether the energy source is fossil or nuclear. However, future developments in desalination favour the use of nuclear energy, as fossil fuels will inevitably become more expensive. On the basis of economic studies performed by the IAEA, it is expected that nuclear desalination will become a viable option for large scale desalination in various parts of the world.

There is a need to understand the coupling aspects of nuclear reactors of different sizes with desalination plants of varying capacities based on selected desalination processes. The various aspects of coupling fossil fuelled power stations to desalination plants based on different process types have been studied extensively, and these experiences are adaptable, with modifications to nuclear power based desalination plants. Depending on the desalination process, one or more nuclear desalination demonstration plants would provide useful experience.

The IAEA has provided the following definition of a nuclear desalination system:

> ***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 system are located on a common site and energy is produced on-site 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 control facilities and seawater intake and outfall structures.*

2.3. NUCLEAR PLANTS IN OPERATION AND UNDER CONSTRUCTION

A total of 434 nuclear power reactors in 32 countries around the world produced 2291 TW(e)·h of electricity in 1998, which was approximately 17% of the world's total electricity generation, according to annual statistics issued by the Power Reactor Information System (PRIS) at the IAEA. Detailed information on the nuclear reactors in operation and under construction worldwide is published yearly by the IAEA. Table 2.III shows the nuclear plants under operation and construction by December 1998. The accumulated operating experience had reached 9012 reactor-years by the end of 1998 [5].

2.4. DESALINATION PLANTS IN OPERATION AND UNDER CONSTRUCTION

According to 1997 IDA Worldwide Desalting Plants Inventory Report No.-15 prepared by Wangnick Consulting GmbH for the International Desalination Association, there are 12 506 desalting units installed or under construction with a total capacity of 22.8 million m^3/d (Fig. 2.3). Roughly 60% of this capacity is for seawater desalination, 25% for brackish water desalination and remaining for river water treatment and other applications. Around 60% of desalting plants are located in the Middle East, followed by North America (20%) and Europe and Asia (around 8 to 10% each). The desalting capacity is expected to increase by one million m^3/d per year by the year 2000. Beyond 2000, the annual increment is likely to be 1.5 to 2 million m^3/d. Desalination plants with a capacity of 4000 m^3/d and above are

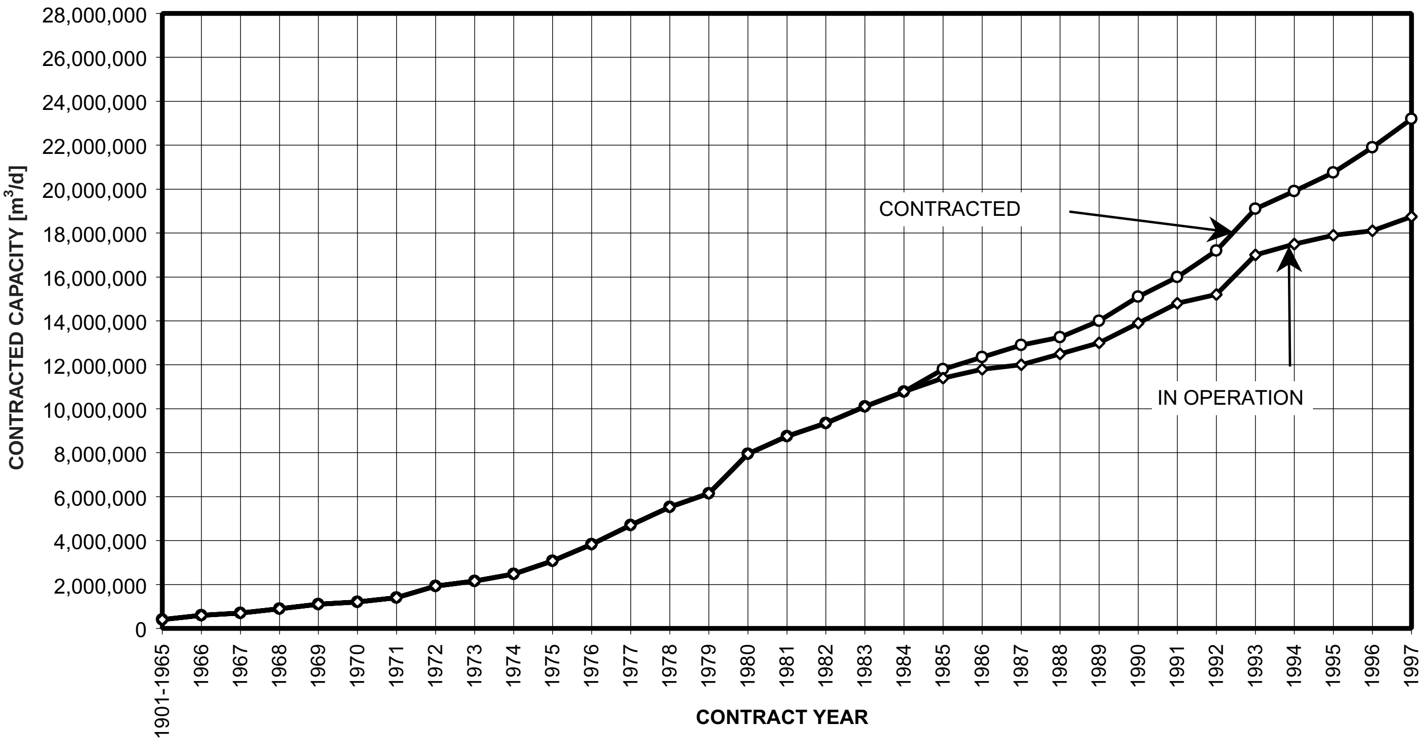

FIG. 2.3. Cumulative capacity of all land based desalting plants capable of producing 100 m^3/d and per unit or more fresh water versus contract year.

TABLE 2.III. NUCLEAR REACTORS IN OPERATION AND UNDER CONSTRUCTION AT THE END OF 1998

Country	Reactors in operation		Reactors under construction		Nuclear electricity supplied in 1998		Total operating experience up to 31 Dec. 1998	
	No. of units	Total MW(e)	No. of units	Total MW(e)	TW(e)·h	% of total	Years	Months
Argentina	2	935	1	692	6.93	10.04	40	7
Armenia	1	376			1.42	24.69	31	3
Belgium	7	5712			43.89	55.16	156	7
Brazil	1	626	1	1229	3.27	1.08	16	9
Bulgaria	6	3538			15.49	41.50	101	1
Canada	14	9998			67.50	12.44	405	2
China	3	2167	6	4420	13.46	1.16	17	5
Czech Republic	4	1648	2	1824	12.35	20.50	50	8
Finland	4	2656			20.98	27.44	79	4
France	58	61653	1	1450	368.40	75.77	1052	1
Germany	20	22282			145.20	28.29	570	7
Hungary	4	1729			13.12	35.62	54	2
India	10	1695	4	808	10.15	2.51	159	1
Iran			2	2111				
Japan	53	43691	2	1863	306.94	35.86	863	5
Kazakhstan	1	70			0.09	0.18	25	6

TABLE 2.III. (cont.)

Country	Reactors in operation		Reactors under construction		Nuclear electricity supplied in 1998		Total operating experience up to 31 Dec. 1998	
	No. of units	Total MW(e)	No. of units	Total MW(e)	TW(e)·h	% of total	Years	Months
Korea, Republic of	15	12340	3	2550	85.19	41.39	137	5
Lithuania	2	2370			12.29	77.21	26	6
Mexico	2	1308			8.83	5.41	13	11
Netherlands	1	449			3.59	4.13	54	
Pakistan	1	125	1	300	0.34	0.65	27	3
Romania	1	650	1	650	4.90	10.35	2	6
Russia	29	19843	4	3375	95.38	13.08	613	6
South Africa	2	1842			13.58	7.25	28	3
Slovakia	5	2020	3	1164	11.39	43.80	73	11
Slovenia	1	632			4.79	38.33	17	3
Spain	9	7350			59.00	37.15	174	2
Sweden	12	10040			70.00	45.75	255	2
Switzerland	5	3079			24.37	41.07	118	10
UK	35	12968			91.14	27.09	1168	4
Ukraine	16	13765	4	3800	70.64	45.42	222	1
USA	104	96423			673.70	18.69	2351	8
Total	434	348891	36	27536	2291.41		9012	6

largely based on the multistage flash (MSF) process (69%), followed by RO (23%), multi-effect distillation (MED) (3%), electrodialysis (ED) (2%) and the rest by other processes (3%). The large size seawater desalination plants are located in Saudi Arabia, Kuwait and the UAE. A number of plants based on the MSF process of a size of 180 000 m^3/d to 250 000 m^3/d are successfully operating in these countries. Large size seawater RO plants with a capacity range of 100 000 to 150 000 m^3/d are in operation. Several MED seawater desalination plants with 5000 m^3/d capacity range were built in a number of countries. A few countries have ordered MED plants of 20 000–50 000 m^3/d capacity in recent years. Table 2.IV lists some of the large size

TABLE 2.IV. LARGE MSF AND RO DESALINATION PLANTS

Country	Location	Capacity (m^3/d)	Process
Saudi Arabia	Al-Jubail	236 180	MSF
Saudi Arabia	Al-Jubail	236 390	MSF
Saudi Arabia	Al-Jubail	237 000	MSF
Saudi Arabia	Al-Jubail	235 000	MSF
Saudi Arabia	Alkhobar II	267 000	MSF
Saudi Arabia	Alkhobar III	280 000	MSF
Saudi Arabia	Jeddah I	56 800	SWRO
Saudi Arabia	Jeddah IV	227 100	MSF
Saudi Arabia	Makkah	223 000	MSF
Saudi Arabia	Shouiba II	454 000	MSF
Saudi Arabia	Yanbu-Madina II	128 000	SWRO
		144 000	MSF
USA	Yuma	81 750	RO
USA	Yuma	276 672	RO
UAE	Taweelah B	345 600	MSF
UAE	Dubai	272 760	MSF
Kuwait	Az Zour	262 400	MSF
Kuwait	Doha West	392 400	MSF
Maldives	Male	13 440	MED
India	Jamnagar, Gujarat	48 000	MED
Italy	Trapani, Sicily	36 000	MED
Antigua	Crabbs Peninsula	9 000	MED
Malta	Gar Lapsi	20 000	RO

desalination plants in operation or under construction in various parts of the world [6].

There have been a large number of brackish water and water treatment plants operating in Florida and California, USA, and in Australia, Southern Europe and Asia. The 300 000 m^3/d Yuma RO plant in Arizona was commissioned in 1997. This plant treats saline water streams flowing into the Colorado River at the US–Mexican border in order to prevent the river water salinity from exceeding a certain limit before it enters Mexico. A number of river water and waste water treatment plants based on ultrafiltration (UF) or microfiltration (MF) membrane processes have been in operation, and a few are being installed in the USA, Europe and Australia. There appears to be a large potential for such plants to supplement conventional water supply schemes for supply of municipal water.

The above desalination plants have provided long term operational experience with respect to performance and reliability. However, large scale adoption of seawater desalination as a major water source in developing countries is dependent upon affordability. Water cost reduction is therefore the prime concern for manufacturers of desalination plants based on either evaporative or membrane processes. The current typical specific cost of desalination plants is in the range of US $1000 to 1200 per m^3/d plant capacity. The water cost derived from these plants ranges between US $1.00 and US $1.30/$m^3$ of fresh water. A 25–30% cost reduction in both capital and water costs appears possible in the next five to six years, owing to many innovations currently under consideration.

2.5. STATUS OF NUCLEAR DESALINATION EXPERIENCES AND ACTIVITIES

2.5.1. Experiences in Kazakhstan and Japan

Integrated nuclear desalination plants have been operated in Japan and Kazakhstan for many years. This experience will be briefly described below. A more detailed description is given in Chapter 5.

In Aktau, Kazakhstan, the liquid metal cooled fast reactor BN-350 has been operating as an energy source for a multipurpose energy complex since 1973, supplying electricity, potable water and heat to the local population and industries. The complex consists of a nuclear reactor, a gas and/or oil fired thermal power station, and MED and MSF desalination units. The sea water is taken from the Caspian Sea. The nuclear desalination capacity is about 80 000 m^3/d. Part of this capacity has now been decommissioned.

In Japan, all of the nuclear power plants are located at sea sites. Several nuclear power plants of the electric power companies of Kansai, Shikoku and Kyushu have seawater desalination systems using heat and/or electricity from the nuclear plant to produce feedwater make-up for the steam generators and for on-site supply of potable water. MED, MSF and RO desalination processes have been used. The individual desalination capacities range from about 1000 to 3000 m^3/d.

The experience gained so far with nuclear desalination is encouraging. Specific features of interest to future operators and designers will be summarized in Chapter 5. Most of these features are also relevant to non-nuclear desalination processes.

2.5.2. Ongoing national programmes and activities

Nuclear desalination programme in Argentina

Argentina has been working on the development of an advanced small NPP named CAREM since 1992. It is a small integrated self-pressurized PWR (100 MW(h)), with natural circulation of primary coolant and passive safety features. The status of the project may be summed up as close to the construction phase. Most development activities on innovative features have been completed, and a preliminary safety analysis report has already been issued and presented to the national regulatory authority.

One of the siting alternatives for the prototype construction (Sierra Grande, Río Negro Province) foresees the coupling with a preheated RO desalination plant. The project owner is the Comisión Nacional de Energía Atómica, and main developments have been under the charge of INVAP S.E., a nuclear vendor. The country has a good deal of experience in exporting nuclear facilities, technology transfer and licensing abroad.

The design of a coupling system with an MED desalination plant has been opened for international co-operation.

Nuclear desalination in Canada

Canada’s nuclear desalination/co-generation development programme, CANDESAL, is based on integrating a CANDU reactor, as a source of electrical and thermal energy, with a seawater RO plant. Both the currently available CANDU-6 and the newer, higher power CANDU-9 designs will be well suited to nuclear desalination applications. An integrated plant concept has been evolved which uses the reactor condenser cooling water discharge stream as preheated feedwater to the RO system in addition to its electrical coupling with the reactor. This provides a significant improvement in RO system output, thereby reducing both capital and unit water production costs. Additional improvements are achieved by using advanced feedwater pretreatment, energy recovery and sophisticated RO system design optimization.

Predesign feasibility studies have been completed, and economic studies have been carried out.

Nuclear desalination programme in China

China's programme on nuclear desalination involves coupling an indigenously developed nuclear heating reactor to a MED based seawater desalination plant. The first 5 MW(th) heating reactor has been in operation since 1989. A 3500 m^3/d MED desalination plant will be built and coupled to the 5 MW(th) heating reactor in Chandao county. A demonstration heating reactor with an output of 200 MW(th) has been approved for construction in the northern part of China. A commercial nuclear desalination plant based on coupling the 200 MW(th) nuclear heating reactor with a 150 000 m^3/d MED plant is planned for construction in Dalian City at the end of this century.

Nuclear desalination demonstration project in India

India has been engaged in desalination research over the past 15–20 years. During the last few years, a number of pilot plants have been operated at the Bhabha Atomic Research Centre, Mumbai. Using the operational experience from these plants, a 6300 m^3/d hybrid MSF–RO desalination demonstration plant has been designed for coupling with an operating pressurized heavy water reactor (PHWR). The hybrid design is being pursued as it is considered to be one of the most economic systems to build and operate under the conditions prevailing in India. The plant is to be located at the existing 170 MW(e) PHWR power station, Kalpakkam. It will meet both process water and potable water needs of the nearby complex. The plant is to be completed by end 2001.

Nuclear desalination simulation experience in Israel

In Ashdod, an integrated plant was designed and built to simulate the coupling of a MED plant with a nuclear reactor. A low temperature, horizontal tube, multi-effect (LT-MED) unit with a production capacity of 17 400 m^3/d was coupled to an old 50 MW(e) oil fired power plant. The Ashdod unit operated continuously for over a year as a demonstration plant and fulfilled its design goals.

In particular, the behaviour of the specially designed coupling system was investigated. It was found satisfactory from points of view of flexibility, partial load, transients and modes of operation (single purpose, dual purpose and changing from single to dual purpose operation). Also, no problems of corrosion and scaling deposition were detected in the power plant condenser, which operated with about 1.5 times of concentration of sea water at above 60°C.

Nuclear desalination programme in Korea

In late 1996, Korea launched an R&D programme for nuclear desalination. The purpose of the programme primarily lies in the development of a relatively small sized advanced nuclear reactor as an energy source for seawater desalination. The initial effort is focused on the design of a new advanced light water cooled reactor, SMART (system-integrated modular advanced ReacTor), which has a thermal power output of 330 MW(th) and utilizes enhanced safety features. The well established domestic desalination technology is ready to be coupled with SMART as an integrated nuclear desalination system. The MED process is currently being considered for the desalination plant, with a target water production of approximately 40 000 m^3/d for demonstration purposes. The excess energy produced in the form of electricity will be supplied to the grid.

The basic design of SMART with an integrated nuclear desalination system for co-generation of water and electricity has started in early 1999 and will continue until 2002. The licensing application for design certification is planned after completion of the basic design.

Nuclear desalination project in Morocco

In the framework of co-operation between Morocco and China and with technical assistance from the IAEA, Morocco has undertaken a feasibility study involving coupling a MED plant with a capacity of 8000 m^3/d to a nuclear heating reactor with a capacity of 10 MW(th). In the event that feasibility studies prove promising, construction of the plant could be undertaken as a demonstration project in order to establish technical confidence in the use of a nuclear heating reactor (NHR) for seawater desalination. In addition, the project would establish a database for reliable extrapolation of water production costs to a commercial nuclear desalination plant with a capacity of 40 000 m^3/d MED, coupled to a 200 MW(th) NHR.

Nuclear desalination programme in the Russian Federation

The goal of the Russian Federation desalination programme has been to develop a small power floating nuclear seawater desalination complex based on the KLT-40 reactor, which was originally developed as an energy source for ship propulsion. The development programme is mostly oriented towards the external market. KLT-40 type reactors have been used for years in Russia’s nuclear powered icebreakers, accumulating 150 reactor-years of successful operation. The main design performance characteristics of the KLT-40 are: a thermal power up to 160 MW(th), a steam production capacity up to 240 t/h, a steam temperature of 285°C and a steam pressure of 3.5 MPa.

Design and manufacturing of sea and brackish water desalination systems has been available for about 40 years. One of the systems under development is a high temperature multi-effect distillation (HT-MED) unit with a capacity of 20 000 m^3/d, suitable for nuclear floating desalination plants. The integrated plant concept under consideration is equipped with two KLT-40 coupled to the MED desalination plant.

A floating nuclear desalination capability is also being developed jointly with CANDESAL Technologies of Canada. The floating nuclear power unit, consisting of two KLT-40 reactors, will be coupled with an RO seawater desalination barge designed to take advantage of the waste heat from the energy generation process to optimize the performance of the RO system. The integrated, two-barge nuclear desalination system will produce about 100 000 m^3/d of potable water in addition to its electricity production of about 65 MW(e).

2.5.3. IAEA activities

The IAEA's activities on assessing the feasibility of using nuclear energy for seawater desalination were resumed in 1989, when several Member States expressed renewed interest at the General Conference. After the review of available information on desalination technologies and the coupling of nuclear reactors with desalination plants, the IAEA conducted an assessment of the economic viability of seawater desalination by using nuclear energy in comparison with fossil fuels [7]. Subsequently, five North African states (Algeria, Egypt, Libyan Arab Jamahiriya, Morocco and Tunisia) carried out a regional feasibility study on nuclear desalination with the assistance of IAEA from 1991 to 1996 [8]. Furthermore, in 1998, Morocco completed its preproject study jointly with China for the specific country conditions for demonstration with the technical assistance through the IAEA Technical Co-operation (TC) framework. Egypt also initiated, in 1998, its feasibility study on a nuclear desalination plant at El-Dabaa site, with the Agency's technical assistance. Another study was performed from 1994 to 1996 to identify, define and characterize a practical set of options for demonstration of nuclear desalination [9]. In 1999 the Agency launched a new interregional project on demonstration projects in the framework of Technical Co-operation. More than ten Member States are participating in this TC project worldwide.

The IAEA’s economic evaluations have continued with new input data and an improvement of methodology. A key outcome of these studies has been the development of a spreadsheet methodology for economic evaluation and comparison of various desalination and energy source options. The spreadsheet programme output contains the levelized unit cost of water and power, and a breakdown of cost components, energy consumption and net saleable power for each selected option

[10]. Results of these studies have shown that nuclear seawater desalination can be economically feasible.

The IAEA has carried out a study to establish a methodology for economic ranking of different co-generation plants for electricity and potable water, including an allocation method for determining the cost of electricity and potable water based on exergy prorating. An IAEA technical document was published in 1997 which describes the methodology and illustrates its use for a representative site in the Arabian Peninsula [11].

The IAEA is also co-ordinating a research programme on “optimization of the coupling of nuclear reactors and desalination systems.” The goal of the programme is to show the optimum coupling configurations with respect to performance and transient plant behaviour.

The Agency’s continued activities in these and other areas related to nuclear desalination are intended to contribute to the solution of the world’s freshwater scarcity problems in the coming century.

2.6. PROSPECTS FOR NUCLEAR DESALINATION

According to the market survey performed by the World Resources Institute on the future growth of seawater desalination, the worldwide demand for desalination is expected to double approximately every ten years in the foreseeable future. Most of the demand would arise in the Gulf and North African regions, but this is likely to expand to other areas. Figure 2.4 shows the projected incremental seawater desalination capacity between 1996 and 2015 in various parts of the world [12].

It is expected that most future desalination plants will be built in three distinct sizes: small (capacity of less than 10 000 m^3/d), medium (50 000–100 000 m^3/d) and large (greater than 200 000 m^3/d). Owing to the relatively high cost of water transport, it is doubtful whether plants larger than 500 000 m^3/d would be economic, except under unique circumstances.

The prospects of using nuclear energy for seawater desalination on a large scale remain very attractive since desalination is an energy intensive process that can utilize the waste heat from a nuclear reactor and/or the electricity produced by such plants. Nuclear reactors are competitive in a range of situations requiring large electric plants (900 MW(e) or more) if low interest rates for capital and a strong national power grid are available and where low cost fossil fuels or hydropower sources are lacking. Many years of successful operation have proved the technical feasibility, compliance with safety requirements and reliability of co-generation nuclear reactors. Also, a few small scale nuclear desalination plants have been operated successfully. Large scale commercial deployment of nuclear desalination will mainly depend on its economic competitiveness with alternate energy supply options. For example, the IAEA’s

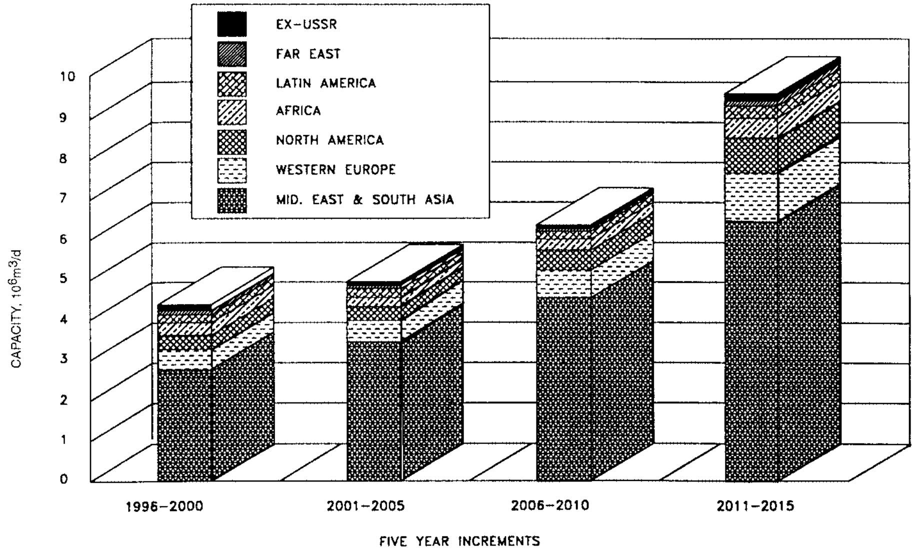

FIG. 2.4. Incremental seawater desalination capacity — 1996 to 2015.

economic studies have shown that the nuclear desalination option can offer potable water at a cost that is competitive with fossil fuelled plants on the North African coast or at other sites with similar conditions.

However, additional effort is required to take advantage of the nuclear option for future production of fresh water. More research funding is directed towards reduction of both nuclear and desalination costs. International and regional co-operation is needed to promote desalination R&D and to assist future owners of desalination plants with their technology selection, installation and management. It is also important to share the knowledge and experience gained among interested IAEA Member States.

Chapter 3

NUCLEAR ENERGY FOR DESALINATION

3.1. INTRODUCTION

Nuclear power for electricity generation was introduced nearly four decades ago and currently contributes about 17% of the total global electricity generation. The first demonstration of nuclear power for electricity generation took place in the early 1950s. Since then the technology of nuclear power generation has passed through many stages, leading to several types of nuclear reactor systems being used for large scale electricity generation. Nuclear power generation requires a complex and sophisticated technology with strict safety and quality standards. It is accepted as a reliable, safe and fully competitive source of electricity generation.

The adaptation of nuclear energy to desalination has two parts, the selection of the reactor type and the implementation of the nuclear fuel cycle evaluated from the availability of uranium to the disposal of radioactive wastes. Each part involves selection of technology options, which not only must be suited to water and power production but also to the natural and technological resource availabilities of the host country. This chapter presents information on various types of nuclear reactor, including both those in operation and under development, for potential use as an energy source for desalination. Technically, any reactor type can be used for nuclear desalination although several types are identified as the most practical and probable for this application. Particular attention is given to the technology of water cooled reactors because of their advanced state of development and deployment. These reactors are well proven and available from several vendors. These reactors use natural uranium (NU) or low enriched uranium (LEU) as their fuel, which likewise is widely available.

3.2. SURVEY OF NUCLEAR REACTORS IN OPERATION AND UNDER CONSTRUCTION

Many nuclear reactor concepts and types have been conceived throughout the various stages of development of nuclear reactor technology [13]. A brief review of the types of nuclear reactor that have been developed and used in large scale generation of electricity, heat or for nuclear desalination is presented below.

3.2.1. Nuclear reactors for electricity generation

In a nuclear power plant the reactor system constitutes the heat source that replaces the boiler in a fossil fuelled generating station. The remaining part is a conventional energy conversion system consisting of a steam/water circuit feeding steam to a turbine driving an electrical generator. This principle is embodied in several types of technologically proven and commercially available power reactor systems.

In a pressurized light water moderated and cooled reactor (PWR, WWER), the reactor core is contained in a pressure vessel in which light water is used as coolant and moderator. The water circulates through a closed primary circuit in which heat is transported from the nuclear fuel to a steam generator. High pressure steam is produced in the secondary circuit and is used to drive the turbine to generate electric power. The operating pressure and temperatures in the primary circuit are about 160 bar and 300°C, respectively. The reactor is fuelled with uranium, with an average enrichment of up to 5% ^{235}U.

PWR and WWER have been the most widely developed systems among the proven types of reactor that are commercially available today. Out of 434 operating nuclear reactors connected to the grid as of 31 December 1998, 206 reactors belong to the PWR type and 48 to WWER [5]. The total capacity of operating PWRs in 15 countries is 195 848 MW(e) and that of WWERs in eight countries is 30 541 MW(e). Out of 36 reactors under construction as of 31 December 1998, 11 are PWRs and 10 WWERs.

The development of the boiling light water cooled and moderated reactor (BWR) was originally motivated by the desire to reduce costs and to avoid technological difficulties by eliminating the steam generators used in the PWR design. The BWR direct cycle system has many similarities to the PWR system, but differs from it in one important respect: it generates steam in the reactor and passes it to the turbine without using an intermediate steam generator. Boiling is allowed in the system, and the operating pressure inside the pressure vessel, approximately 70 bar, is much lower than in the PWR system. Out of 434 operating nuclear reactors connected to the grid as of 31 December 1998, 92 reactors belong to the BWR type [5]. The total operating capacity of BWRs in nine countries is 79 242 MW(e). As of 31 December 1998, two BWRs are under construction.

In pressurized heavy water moderated and cooled reactors (PHWRs), natural uranium in the form of uranium oxide is used as a fuel. Heavy water is used as the moderator and, in a separate circuit, as the coolant. The coolant must be maintained at high pressure to prevent boiling. As of December 1998, 29 PHWR reactors were in operation in six countries, with a total output of 15 032 MW(e). In addition, there were nine reactors under construction in five countries [5].

In the former Soviet Union, graphite moderated and pressurized light water cooled reactors (RBMKs) were operated. As of December 1998, 20 reactors of this type have a capacity of 15 164 MW(e), and one reactor is under construction.

In gas cooled reactors (GCRs), natural uranium is used as a fuel, with graphite as moderator and CO_2 gas as coolant. The GCR, also known as the Magnox system, was developed in the United Kingdom and in France. As of December 1998, 20 reactors belonging to the GCR type are connected to the electrical grid, with a total operating capacity of 3400 MW(e) [5]. The advanced gas cooled reactors (AGRs) were developed in the United Kingdom as the successor to the GCR. The AGR uses slightly enriched uranium in oxide form to achieve a higher power density and better steam conditions. This leads to a smaller reactor size while retaining the graphite moderator and CO_2 gas coolant. The prototype was put into operation in 1963 (32 MW(e)) and was followed by the construction of 14 units — all of them in the United Kingdom, which is the only country using this system. As of December 1998, 14 reactors of the AGR type with a total capacity of 8380 MW(e) were connected to the grid.

3.2.2. Nuclear reactors for co-generation

Desalination processes require energy in the form of heat and/or electricity, which can be supplied by nuclear reactors. The energy source can be a dedicated or non-dedicated (co-generation) plant. The former provides energy exclusively for the desalination process, and water is the only product coming out of the complex. The latter provides only part of its energy to the desalination process, and the rest of the energy is used to generate electricity.

Only desalination processes which use heat energy, such as MSF and MED, can be considered for co-generation. RO normally uses only electricity. Co-location of a power plant and an RO desalination plant would not normally be considered a co-generation plant unless heat from the power plant is used in the RO process, such as for preheating feed or powering steam driven pumps. Nevertheless, there are some economic advantages to co-locating large RO plants with power plants in order to take advantage of shared facilities.

Co-generation/desalination with a nuclear reactor requires careful consideration of how the desalination process is coupled to the power source. Safety, economic and operational factors are involved. The main safety concern is the prevention of radioactivity from migrating from the nuclear reactor to the desalination process, even under accident conditions. Yet another consideration is the ingress of salinity into the turbine circuit. In most of the couplings, this is prevented by an additional isolation loop.

Among the various reactor types available for co-generation of electricity and water, in the BWR the reactor primary coolant circulates through the turbine and condenser, which are the typical interface points for supplying heat to the desalination plant. Thus, only one barrier exists between the primary coolant and the desalination process. A BWR would require the addition of an isolation loop for coupling with a desalination plant. For co-generation in a nuclear plant, it is prudent to have at least two barriers between the primary coolant and the process fluid. In PWR and PHWR an additional barrier exists between the reactor coolant and the desalination process.

Apart from dual purpose nuclear reactors for electricity generation and desalination, there are a number of reactors dedicated to electricity generation and district heating. These reactors are larger in size, and a large number of them are located in the Russian Federation and are operating on a commercial basis. A few of them are in Bulgaria, Hungary, Germany, Slovakia and Switzerland.

Table 3.I gives a list of reactor types which are licensed or in the licensing process and have been identified by the IAEA between 1992 and 1995 as possible candidates for co-generation [9]. The table also gives the design status of each reactor.

3.2.3. Nuclear reactors for heat generation

Nuclear reactors for heat generation alone are simpler in construction and operation as they do not require a turbine and other auxiliary systems for electricity. However, the safety requirements are the same. Nuclear heat generating reactors are used for district and process heating. Nuclear reactors are used for district heating mostly in the Russian Federation and in China, whereas they are used for supplying process heat in Canada and also in the Russian Federation. Generally, nuclear district heating reactors are smaller in size and more compact, but a few larger size district heating reactors will be built in the Russian Federation. There appear to be no technical or safety problems with nuclear heat application systems and no special concerns regarding possible radioactive contamination of either district heating or process systems.

3.3. SURVEY OF NUCLEAR REACTORS UNDER DEVELOPMENT

Table 3.II is a list of reactors being deployed or in various design stages [14].

3.3.1. Design and development status of SMRs

Over the last three decades, about 9000 reactor-years of operating experience have been accumulated with the current nuclear energy systems. Building upon this background of success, new small and medium reactor systems (SMRs) are being developed and built. SMRs generally incorporate improved safety features, including those that will allow operators more time to perform safety actions and will provide increased protection against release of radioactivity to the environment. The new

TABLE 3.I. REACTORS SCREENED FOR POSSIBLE CO-GENERATION

Reactor	Reactor type	Thermal power (MW(th))	Electrical Output, (MW(e))	Design status
ABWR	BWR	3900	1356	2
BWR 600	BWR	2200	600	2
BWR 800	BWR		800	2
BWR 90	BWR	2350	720	1
SBWR	BWR	2000	600	1
AGR	GCR		610	2
GCR	GCR		555	2
MHTGR	GCR	4 × 450	4 × 173	1
BN-350 [a]	LMR	520	90	2
BN-600	LMR	1470	600	2
BN-800	LMR	2100	800	2
PHENIX	LMR	568	250	2
CANDU 9 [b]	PHWR	2824	880	1
CANDU 6	PHWR	2158	660	2
PHWR 220	PHWR	743	220	2
PHWR 500	PHWR	1673	500	1
PHWR 700	PHWR		700	2
PHWR 900	PHWR		915	2
AP 600	PWR	1933	600	1
KLT-40	PWR	160	35	2
NHR 200	PWR	200	—	2
PWR	PWR		600	2
PWR	PWR		900/1000	2
PWR	PWR		1200/1500	2
SES 10	PWR	10	—	1
WWER 1000	PWR	3200	1000	2
WWER 440	PWR	1335	440	2

Design status—2: in operation or under construction; 1: detailed design.
[a] Programmed for decommissioning as from April 1999.
[b] These data have been added to the table since its original publication in Ref. [9].

SMR systems also have incorporated features to make them simpler to build, operate, inspect, maintain and repair.

Currently, SMRs are defined as nuclear power reactors of ‘less than 700 MW(e)’ but are generally thought of having power outputs in the range of 100 to 400 MW(e) [14]. Since many countries have grids that can admit only SMRs, there is

TABLE 3.II. REACTORS UNDER DEVELOPMENT

Design name	Designer/ supplier	Reactor type	Gross thermal power (MW(th))	Net electrical power (MW(e))
Reactors in the basic design stage				
PIUS	ABB	PWR	2000	610–640
NHR-200	INET	—	200	—
CAREM 25	CNEA/INVAP	PWR	100	27
MRX	JAERI	PWR	100	30
ABV	OKBM	PWR	38	6
SMART[a]	KAERI	PWR	300	100
GT-MHR	GA	HTR	600	286
MHTR	ABB/Siemens	HTR	200	85.5
PMBR	ESCOM	HGTR	220	100
Reactors being deployed or in the detailed design stage				
BWR-90	ABB	BWR	2350	720–850
AP-600	W	PWR	1940	600
SBWR	GE	BWR	2000	600
AST-500	OKBM	PWR	500	Not relevant
KLT-40	OKBM	PWR	Up to 160	Up to 35
CANDU-6	AECL	PHWR	2158	666
PHWR-500	NPC	PHWR	1673	500 (gross)
PHWR-220	NPC	PHWR	743	194
Reactors in the conceptual design stage				
BWR-600	Siemens-AG	BWR	2200	750
VPBER	OKBM	PWR	1800	630
HSBWR	HITACHI	BWR	1800	600
SPWR	JAERI	PWR	1800	600
SIR	Consortium	Integrated PWR	1000	320
ISIS	ANSALDO	PWR	650	205
ATS-150	OKBM	PWR	536	Up to 180
MARS	U. of Rome, ENEA	PWR	600	Up to 180
RUTA	RDIPE	Pool type	20–55	Not relevant
SAKHA-92	OKBM	PWR	7	Up to 1
MDPR	CRIEPI	LMR	840	325
4S	CRIEPI	LMR	125	50

Abbreviations used:

ABB	ABB Atom AB, Sweden
AECL	Atomic Energy of Canada Ltd.
CNEA	Comisión Nacional de Energía Atómica, Argentina
CRIEPI	Central Research Institute of Electric Power Industry, Japan
GA	General Atomic, USA

GE	General Electric, USA
HTR	High temperature reactor
INET	Institute of Nuclear Energy and Technology, Tsinghua University, China
INVAP	INVAP Company, Argentina
JAERI	Japan Atomic Energy Research Institute
KAERI	Korea Atomic Energy Research Institute
NPC	Nuclear Power Corporation, India
OKBM	Special Design Bureau for Mechanical Engineering, Russian Federation
RDIPE	Research and Development Institute of Power Engineering, Russian Federation
W	Westinghouse, USA

[a] These data were added to the table since its original publication in Ref. [14].
The data were mainly compiled from Refs [2, 4] and updated from information provided by designers/suppliers.

widespread interest in SMRs. The market for SMRs until 2015 was assessed by individual countries, and the corresponding overall market is estimated at about 60 to 100 SMRs. It is expected that over two thirds of the SMRs would be in the range from 300 to 700 MW(e); the rest would be smaller. About one third of the SMRs under construction are expected to supply heat or electricity or both to integrated seawater desalination plants.

3.3.2. Reactors with other than water coolants

There has been widespread interest in the development of fast breeder reactors (FBRs) since the early development of nuclear power. The design of a fast breeder reactor is based on a chain reaction sustained by the fast neutrons released in the fission process of ^{235}U or ^{239}Pu. The excess neutrons accompanying fission are effectively used to transform fertile material such as ^{238}U or ^{232}Th to fissile material such as ^{239}Pu or ^{233}U. The present development of FBR technology is based on reactor designs using liquid sodium as coolant and plutonium as fuel (LMFBR).

The high temperature gas cooled reactor (HTGR) is another advanced reactor system under development. The main interest in this system lies in the possibility of achieving very high temperatures by using helium gas as a coolant in order to attain higher thermal efficiencies.

Several reactor concepts which use heavy water as moderator but are cooled by other fluids have been developed to the stage of industrial prototypes. The interest in these types of reactor concept has originated from the desire of reducing the heavy water inventory and the risk of heavy water losses. Though technical feasibility has been demonstrated, the heavy water moderated and light water or gas cooled systems have not been widely deployed as commercial plants.

3.3.3. Barge mounted reactors

A barge mounted nuclear seawater desalination plant offers the opportunity for a low cost, potable water supply compared to conventional land based desalination plants in cases where populations in coastal arid regions are relatively isolated from each other and extensive distribution networks would substantially raise the cost of desalted water. A floating nuclear desalination complex offers several advantages. It can be quickly installed anywhere, depending on the need in coastal regions. It can supply potable water to remote coastal regions or islands where both fresh water and energy sources are severely lacking. It does not require seawater intake/outfall infrastructures. However, the design and safety considerations of a barge mounted nuclear desalination unit, such as the KLT-40 reactors, are different from those of a land based desalination unit.

The Russian Federation has unique experience in the development and use of lead–bismuth coolant in marine reactors. A conceptual design was developed for a floating nuclear desalination plant, Cruise-M, in which a fast reactor with lead–bismuth coolant is used. The Cruise-M uses two nuclear reactors, which can produce 25 MW(e) and 80 000 m^3/d of fresh water. The lead–bismuth coolant has a high boiling point (1670°C), which prevents coolant boiling in the high fuel power assemblies. The low vapour pressure and low chemical reactivity of lead–bismuth provide a high degree of safety.

The conceptual design of a small floating seawater desalination plant using a nuclear heating reactor coupled with a MED process has been developed in China. The NHR-10 is a pressurized water reactor rated at 10 MW(th). It couples two proven technologies, the nuclear heating reactor (NHR-10) and a low temperature MED process. This floating plant could provide 4000 m^3/d of fresh water and 750 kW(e) of electricity. The MED plant has two units, each with a water production capacity of 2000 m^3/d.

3.4. ELEMENTS OF THE NUCLEAR FUEL CYCLE

The nuclear fuel cycle consists of the various steps involved in processing fissile materials for nuclear reactor fuel. The cycle may be divided into the following main elements:

(1) Provision of fresh fuel for the reactors. This is usually called the 'front end of the fuel cycle'. It includes:
   - Exploration, mining and milling of uranium
   - Uranium conversion and enrichment (only for enriched U fuelled reactors)
   - Fuel element fabrication

(2) Fuel management at the power plant

(3) Spent fuel management is usually called the 'back end of the fuel cycle'. It includes:
   - Spent fuel transport and storage (temporary or permanent)
   - Reprocessing of spent fuel (optional)
   - Management and disposal of radioactive wastes.

Nuclear fuel cycles can be either open or closed. In an open (or once-through) fuel cycle strategy, the fuel passes through the reactor only once. The spent fuel is not reprocessed to recover the unused ^{235}U or ^{239}Pu that has been produced. The spent fuel is stored and ultimately disposed of as waste. In a closed cycle, unspent fissile material is recovered in a reprocessing plant and then recycled to fuel thermal or fast reactors. The reprocessing plant recovers the unused ^{235}U and freshly produced plutonium. The separated plutonium is used for fuel enrichment by combining it with natural or depleted uranium in mixed oxide (MOX) fuel pellets. Figure 3.1 shows a

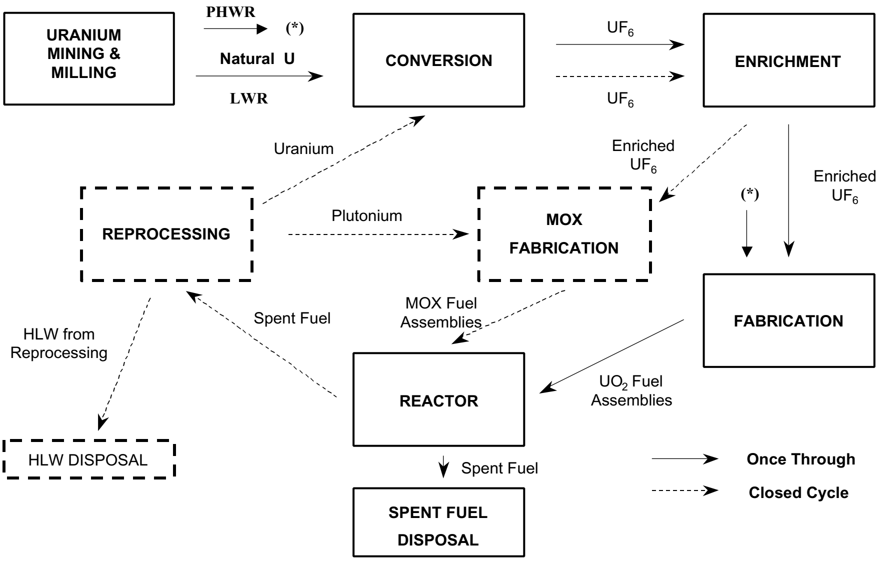

FIG. 3.1. Schematic representation of LWR once-through and closed fuel cycles.

schematic representation of once-through and closed fuel cycles for light water reactors.

3.4.1. Exploration, mining and milling of uranium

Since uranium is the only naturally occurring fissile material, it is the indispensable starting point for the production of fuel for nuclear reactors. Natural uranium contains the fissile (with thermal neutrons) isotope ^{235}U (0.7%) and also the more abundant isotope ^{238}U (99.3%), which is the fertile material. The technology and equipment for exploration, mining and milling of uranium are not difficult to acquire. The mining techniques are similar to those applied in conventional mining operations, except for the special features and precautions associated with radioactivity.

Current technologies use ores having a recoverable uranium concentration in the range of 0.02 to 0.2%, but recently rich deposits have been discovered having ores with up to 3% uranium. Following the removal of uranium ore from the mine, it is concentrated and chemically processed or milled to produce a commercial product, yellow cake, a concentrate of uranates containing about 80% of U_3O_8. Uranium milling is based primarily on hydro-metallurgical operations such as leaching, solvent extraction or ion exchange, and precipitation.

3.4.2. Conversion and enrichment of uranium

Uranium conversion and enrichment processes are required if the reactor is fuelled by enriched uranium. Before enrichment, the ‘yellow cake’ concentrate is purified and converted to uranium hexafluoride, UF_6, which is a solid uranium compound at room temperature but vaporizes at about 60°C. With this process, a gaseous uranium compound is obtained for subsequent enrichment of uranium isotope ^{235}U. Through the enrichment process, the concentration of ^{235}U in natural uranium (0.7%) is increased to the required degree of enrichment. This varies from low enriched uranium (LEU) with up to 5% ^{235}U for light water power reactors and up to high enriched uranium (HEU) with 20 to 90% for fast breeders and some types of research and test reactors.

3.4.3. Fuel element fabrication

The fuel element fabrication process may vary depending on the reactor type. The most common process is that shared by most water cooled reactors. This starts with either the conversion of enriched UF_6 into uranium dioxide powder (UO_2) or the conversion of natural uranium into UO_2. The UO_2 powder is compacted into small cylindrical pellets by cold pressing and then sintered to attain the required density and structural stability. Several important features are incorporated in the mechanical design and fabrication of fuel elements for power plants to ensure their integrity, stability and long-life performance. Extensive tests and inspections are carried out on fuel pellets, tubes, rods and finished assemblies to ensure high standards of reliability during operation.

3.4.4. Fuel management in reactor operation

Fuel management at the reactor constitutes the central technical activities of the overall fuel cycle, because at this stage the whole purpose of the fuel cycle is fulfilled, i.e. energy is produced from the nuclear fuel. The activities start with receiving the fresh fuel at the power plant and end with the removal of the spent fuel from the plant fuel cooling basins. Fuel is inspected, stored, loaded into the reactor, burned, removed when spent and temporarily stored until it is transported away from the power plant. In-core fuel management includes long term fuel cycle planning, development of the refuelling schedule, operational monitoring and guidance, and the economic optimization of the fuel cycle. Sophisticated computer models and reactor analysis techniques are used to perform these functions.

3.4.5. Spent fuel transport and storage

The back end of the fuel cycle starts with the transport of highly radioactive spent fuel away from the power plant site. Spent fuel is temporarily stored at the power plant for a period of a few months to several years. Afterwards, the fuel is loaded into specially designed, shielded shipping containers and transported to an interim (or permanent) storage facility or fuel reprocessing facility, depending on the fuel cycle strategy. Thousands of spent fuel shipments have been made, with only few minor incidents, not imposing any danger to the public.

3.4.6. Reprocessing of spent fuel

If the spent fuel is to be reprocessed, it is transferred from the temporary storage pool to a reprocessing plant after a cooling period of about one year in order to allow the most intense short and intermediate half-life radioactive fission products to decay. The reprocessing operations involve a series of mechanical and chemical operations conducted in specially designed hot cell facilities, which provide protection against the radiation hazards of the highly radioactive materials. All operations are carried out with remotely operated equipment and instrumentation for control. During the reprocessing operation, the unspent uranium and plutonium are separated from the fission products by solvent extraction. The fission products constituting the radioactive waste are stabilized, packaged and disposed of.

3.4.7. Management and disposal of radioactive wastes

Management and disposal of radioactive wastes involve a variety of treatment processes for rendering the wastes into a safe form for long term disposal. The processes include:

- chemical precipitation;
- use of highly selective solvents;
- ion exchangers and membrane processes for volume reduction of low and intermediate level wastes;
- partitioning actinides from high level wastes by extraction to reduce the need for their long term isolation;
- immobilization of high level radioactive wastes in glass/ceramic matrices.

The conditioned waste forms are disposed of by storage in engineered, multibarrier containers away from the public.

3.5. AVAILABILITY OF FUEL (SUPPLY AND DEMAND)

Operation of various types of reactor requires a continuous supply of fuel and other special materials, e.g. heavy water, graphite, zirconium. This section will address only the supply and demand of fuel, as it is the common necessity of all nuclear reactor types.

3.5.1. Uranium resources

The most practical nuclear reactor options for desalination use natural uranium (NU) or low enriched uranium (LEU) as their fuel. Thus, the long term availability of these fuels is an important consideration. The demand for uranium will depend on the worldwide nuclear power growth rates and also on the reactor types deployed in the future.

Several sources of uranium might be called upon for meeting the projected requirements over the long term future. These include existing inventories as well as known and undiscovered conventional and unconventional resources. Existing inventories include civilian stockpiles of producers and consumers, and military inventories. The latter consist of fissile material in a variety of forms, including high enriched uranium and plutonium contained in nuclear weapons that are being or will be dismantled. Additional conventional resources, which are likely to be discovered and economically exploited in the future, could complement the uranium supply. Beyond conventional resources, unconventional resources such as uranium in phosphate rocks or sea water could complement the uranium supply in the long term.

The OECD and IAEA publish a report on uranium resources, production and demand, commonly known as the Red Book, which is updated every two years [15].

The sale of uranium produced in the CIS countries to the Western world has been a major factor in the nuclear fuel market since the late 1980s. Significant amounts of uranium and plutonium from demilitarized nuclear weapons are expected to enter the civilian market after 2000 as the result of a purchase agreement between the USA and the Russian Federation. The 500 tonnes of high enriched uranium (HEU) warhead material under purchase contract are estimated to be equivalent to about 153 000 tonnes of natural uranium.

Over the period from 1988 to 1994, there have been capacity reductions in the world uranium industry. This was caused by an oversupply situation and accompanied by continuous reduction in world uranium prices. Consequently, uranium production has decreased dramatically in several countries. As of 1996, uranium was produced in 25 countries [15], and nearly 90% of world uranium production occurred in ten countries, each of which produced 1000 tonnes of uranium or more (Fig. 3.2).

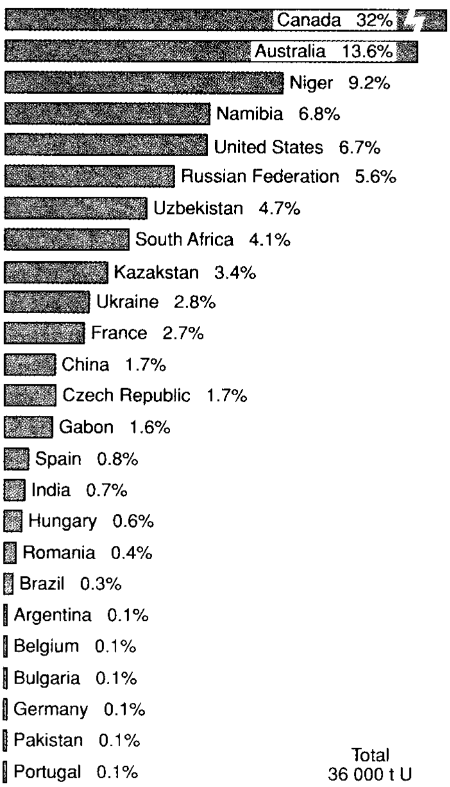

FIG. 3.2. Estimated 1996 world uranium production and ranking of producers.

Sales on the world uranium market consist of two types: immediate or near term delivery, referred to as spot sales, and longer term sales made under contract. The most commonly quoted market indicator for the spot price is the NUEXCO exchange value. Figure 3.3 shows selected annual average uranium prices from 1972 to 1996.

3.5.2. Uranium conversion and enrichment services

The worldwide uranium conversion market has remained relatively stable over the past several years. In the past, the market was characterized by the large inventory of UF_6 and by an oversupply of capacity as a consequence of the previously overestimated demand in the 1970s. However, the shutdown of the Sequoyah Fuels Corporation plant in the USA (1992), which had a conversion capacity of 9090 tonnes U/a, contributed to reducing the supply–demand imbalance. The spot market conversion price in 1996 was $5.50–6.40/kg U. According to IAEA estimates, the worldwide 1996 conversion demand was about 55 000 tonnes U, assuming a 0.25% ^{235}U tail assay for enrichment. The world conversion demand is supplied by five major conversion facilities with a total nameplate capacity of about 65 000 tonnes U/a.

In addition to weapons grade Pu, Pu recovered through reprocessing of civilian spent fuel will greatly extend the existing uranium supply. Reactors fuelled with MOX

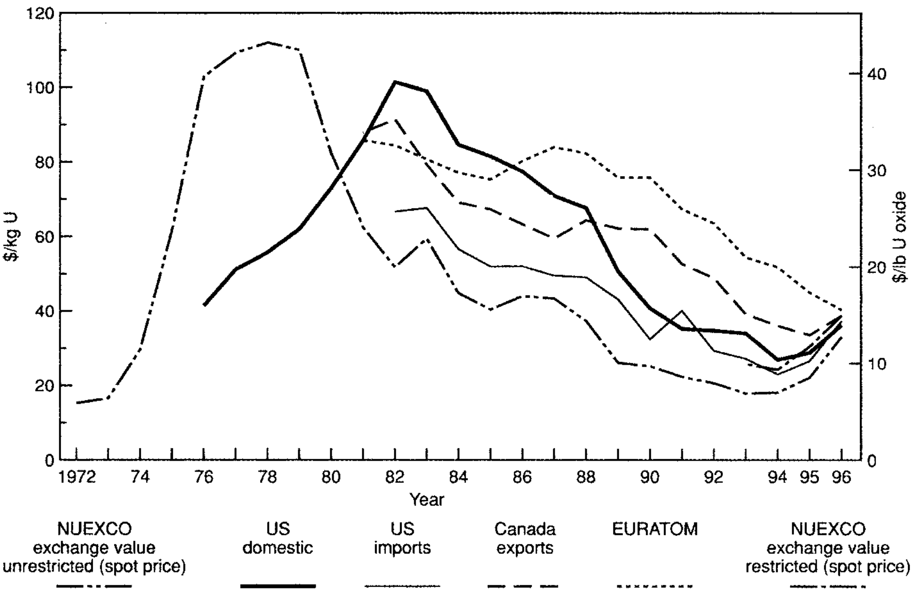

FIG. 3.3 Selected annual average uranium prices.

fuel (mixed Pu and uranium oxide) produce nearly as much Pu as is being burnt. This greatly reduces the need for ^{235}U and extends the availability of nuclear fuel beyond any planning horizon. The practical conclusion is that the availability of uranium fuel should have no influence on the decision to adopt nuclear energy for desalination.

At present, there are four major international suppliers of uranium enrichment services: the USEC, Cogéma/Eurodif, the Russian Federation Ministry for Atomic Energy (Minatom) and Urenco Ltd. The world total capacity was about 45 MSWU per annum in 1996.

3.5.3. Fuel fabrication

In 1996, nearly 95% of the world's nuclear electricity was generated by water cooled reactors, and more than 85% of this capacity was provided by PWRs and BWRs. Fuels for these reactors were fabricated in 21 countries. Uranium fuel requirements worldwide in 1994 were estimated to be 9837 tonnes of fuel material, equivalent to about 60% of the total fabrication capacity space. Nevertheless, a number of countries are embarking on national programmes to set up domestic capabilities for reactor fuel fabrication. These include both countries with established nuclear programmes and those planning to begin nuclear programmes.

3.6. RADIOACTIVE WASTE MANAGEMENT

Radioactive waste differs from other industrial wastes as a result of its radiation and its radiological toxicity to human beings and their environment. Radioactive wastes (solid, liquid and gaseous) arising from nuclear installations under normal operations must be safely disposed of in order to protect the public and their environment from any unacceptable risks. The objective of nuclear waste management is the effective isolation of radionuclides from the environment to ensure adequate safety and welfare of the public. The philosophy of radioactive waste management embodies three basic principles [16]:

- Delay and decay (for short lived radionuclides)
- Dilute and disperse (for very low active effluents)
- Concentrate and contain (intermediate and high active waste).

3.6.1. Categorization of wastes

Radioactive waste may arise in a wide variety of physical and chemical forms. Hence, the classification parameter is typically related to the physicochemical characteristics and the radionuclide content of a particular waste, which is identified for the disposal purpose. In this system, the radioactive wastes are categorized into low, intermediate and high level wastes. The disposal requirements are mainly based on the required duration of isolation of a particular radionuclide from the environment to decay to a level of insignificant radiological risk. The classification system may also depend upon the local disposal conditions and the possibilities for handling and storage.

Solid, liquid and gaseous wastes embodied in various matrix forms may contain different activity levels. Different types of wastes require a variety of treatment and conditioning methods before disposal. Owing to these physicochemical and radioactive differences, the International Commission of Radiological Protection has categorized these wastes according to internationally acceptable norms and standards (Table 3.III).

3.6.2. Solid waste

Radioactive solid wastes are generated by nuclear power reactors, nuclear fuel cycle facilities, radioisotope manufacturers and users of radioactive materials. These wastes can be classified in various ways according to their chemical and physical stability, chemical content, density, flammability, radionuclide content and potential risk of radiation hazards. Physicochemical properties of the wastes influence the required structural integrity of the waste repository. The waste material should be chemically inert and physically stable. An appropriately conditioned waste can be disposed of in underground repositories. The generic options for disposal of solid wastes are:

- Storage of solid waste at shallow depth with or without engineered barrier(s) above or below the ground surface, where the final protective covering is of the order of a few metres thickness.

TABLE 3.III. CATEGORIZATION OF RADIOACTIVE WASTE

Category	Solid	Liquid	Gaseous
	Surface dose (mSv/h)	Activity level (Bq/m^3)	Activity level (Bq/m^3)
I	<2	$<3.7 \times 10^4$	<3.7
II	2–20	3.7×10^4 to $< 3.7 \times 10^7$	3.7 to $< 3.7 \times 10^4$
III	<20	3.7×10^7 to $< 3.7 \times 10^9$	$> 3.7 \times 10^4$
IV	Alpha bearing	3.7×10^9 to $< 3.7 \times 10^{14}$	—
V	—	$> 3.7 \times 10^{14}$	—

- Storage of solid wastes in mined repositories specially designed and excavated for waste disposal at a suitable depth in continental geological formations.
- Storage of solid wastes in artificial or natural rock cavities at various depths.

Shallow land disposal facilities are generally employed for low and intermediate level wastes, and geological repositories are intended for high active wastes. The shallow land facilities may generally consist of earth trenches, reinforced concrete vaults and tile holes. The natural and engineered barriers along with the waste form and the backfill material retard the migration of radionuclides into the biosphere by isolating them within the facility.

3.6.3. Liquid wastes

Liquid wastes are classified on the basis of radioactivity content, ionic impurity levels, dissolved or suspended solid content, organic impurities, detergent and chemicals. Irrespective of the origin, radioactive liquid wastes can be broadly classified into five categories based on the activity levels in Table 3.III. The main sources of liquid wastes from nuclear industries are active floor drains from different areas, decontamination centres, chemical laboratories, upgrading plant rejects, detergent waste from active laundry and drains from changing room and showers, etc. These waste streams require treatment to reduce their activity concentration to a level at which discharges would be allowed by the national regulations.

3.6.4. Gaseous wastes

Gaseous wastes from any nuclear installation can be classified into primary system gas, secondary system gas and the building ventilation. The primary system gases include fission products and hydrogen and nitrogen generated due to radiolysis. The secondary system gases arise from the leakage of various component systems and the activity levels are low compared to the primary gas system. The third category of gaseous waste is the large volume of ventilation air, most of which arises from auxiliary buildings where radioactivity exists. This air is often discharged to the atmosphere at sufficient height through various filters in order to reduce the radionuclide concentrations.

Chapter 4

DESALINATION PROCESSES

4.1. INTRODUCTION

The separation of water or salt from saline water is a thermodynamic process requiring an input of energy. An ideal desalination process is regarded as a steady flow reversible separation process in which the incoming and outgoing streams are at the same temperature and pressure as the environment while heat and/or work are being applied. The minimum work requirement is around 0.7 kWh/m^3 to desalinate 35 000 ppm saline water with zero recovery, assuming complete thermodynamic reversibility. In practice, desalination processes are far from being reversible. Applied heat and/or work results in exit streams at different pressures and temperatures from the feed streams. Recovery methods help to minimize irreversibility. Nevertheless, the most efficient desalination technologies have a comparable energy requirement of 4–5 kW(e)·h/m^3.

Desalination processes can be classified on the basis of phase change, type of energy used and separation of solvent and solute [17].

Phase change

- Processes without phase change, such as reverse osmosis (RO) and electrodialysis (ED).
- Processes with phase change, such as multi-stage flash (MSF), multi-effect distillation (MED), vapour compression (VC), solar distillation, freezing.

Type of energy used

- Processes using heat, such as distillation processes, MSF, MED, thermal VC and solar distillation.
- Processes using mechanical energy, such as RO and mechanical VC.
- Processes using electricity, such as ED.

Separation of solvent and solute

- Processes separating water from the solution, such as MSF, MED, thermal VC, mechanical VC and RO.
- Processes separating salts from the solution, such as ED and ion exchange (IX).

4.2. COMMON DESALINATION PROCESSES

The commercial seawater desalination processes which are proven and reliable for large scale freshwater production are MSF and MED for evaporative desalination and RO for membrane desalination [18]. Vapour compression plants based on thermal and mechanical compression are also employed for the small and medium capacity ranges.

4.2.1. Multistage flash

About 60% of the world's desalting capacity comes from MSF plants. This has been one of the leading desalination processes, because of operational simplicity, proven performance and availability of standard designs and equipment. It is advantageous in large capacity ranges where thermal energy in the form of low pressure steam is available. The world's largest operating desalination plant, located in the Al Jubail Phase II complex, Saudi Arabia, is based on the MSF process and produces around 0.9 million m^3/d desalted water from sea water.

In the MSF process, the seawater feed is first sent to a chemical pretreatment system where either a chemical additive or acid treatment is given to suppress the formation of alkaline scales in the heat transfer tubes. It is de-aerated to reduce dissolved oxygen and carbon dioxide to minimize corrosion and improve heat transfer performance. The sea water is preheated in the MSF modules. It is further heated to the maximum brine temperature in a brine heater and then subjected to a flashing process in the flash evaporator. An MSF evaporator is divided into several chambers called flash stages (usually less than 40). These stages are maintained at successively reduced pressures. When the heated brine enters into a chamber (flash stage) maintained below the saturation vapour pressure of water, a fraction of its content flashes into vapour. The vapour passes through the mist eliminator and condenses on the outer surface of the heat transfer tubes, giving its latent heat to incoming sea water flowing inside the tubes. The unflashed brine moves to the next flash stage, and the process is repeated. The condensate is collected as product water.

There are two major arrangements used in MSF, the brine recirculation and once-through arrangements. The majority of the operating MSF plants are based on brine recirculation. Figure 4.1 gives the simplified flow diagram of the MSF process with recirculation. In the recirculation type, the make-up feed is mixed with recycle brine and preheated in the heat recovery section by recovering the energy of the condensing vapour. It has a heat rejection section at the cooling end of the plant to remove the required quantity of waste heat for steady operation. The once-through system requires a large amount of chemicals and feed sea water compared to the recirculation system.

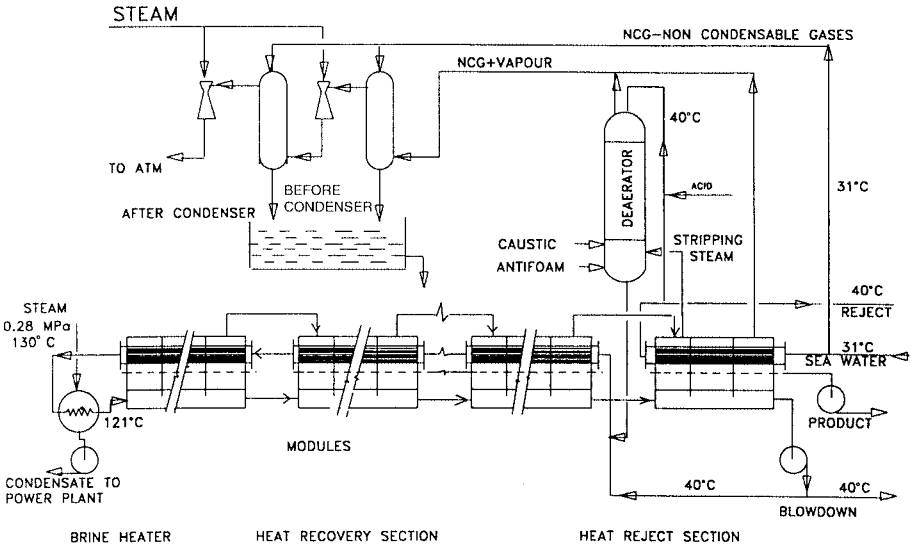

FIG. 4.1. Schematic flow diagram of the multistage flash (MSF) desalination process with brine recirculation.

Sea water contains sulphate, bicarbonate, calcium and magnesium ions, which contribute to scaling. On heating, the bicarbonate ions decompose to carbonate ions resulting in alkaline ($CaCO_3$ and Mg $(OH)_2$) scale formation. Formation of scale leads to a sharp fall in overall heat transfer performance and production rate. In order to control the alkaline scaling tendency, the feed sea water is pretreated with acid or chemical additives. In the case of acid treatment, the bicarbonate ions are decomposed to carbon dioxide by adding a small quantity of acid. In chemical additive dosing, certain proprietary compounds are added to the seawater feed, changing the scale characteristics so that very loose scale is formed and easily removed.

Calcium sulphate ($CaSO_4$) scale formation, which is also sometimes referred to as hard scale, must be avoided in desalination plants. It is insoluble in mineral acids and cannot be removed by acid cleaning. Only mechanical methods or expensive chemical pretreatment can be used for its removal. The allowable top brine temperature and concentration is limited, owing to $CaSO_4$ scaling. The top brine temperature in additive based plants is maintained between 90–110^{o}C, whereas in acid type plants it is limited to 121^{o}C.

The temperature rise across the brine heater is fixed on the basis of optimization of water production cost with respect to the gain output ratio (GOR) and the number of flash stages. The GOR is the ratio of the mass of desalted water produced per mass of steam consumed. The highest GOR value which can be achieved in MSF is limited to around 12, because of loss in vapour temperature due to boiling point elevation, pressure drop through demisters, condenser tube bundle and non-equilibration losses. The GOR varies only slightly with the salinity of the feed.

Two types of tube bundle configurations are used in commercial MSF plants. The majority of them use a cross-tube arrangement where tubes are laid at right angles to the flow direction of flashing brine. In the long-tube configurations, tubes are parallel to the flow direction of flashing brine, and they pass through several flash stages. MSF heat transfer area requirements are usually in the range of 20–140 $m^2/(m^3/h)$ desalted water depending on GOR. The overall heat transfer coefficient varies from 2.2 to 5 $kW \cdot m^{-2} \cdot K^{-1}$. Copper based alloys or titanium are used for tubes and tube sheets. MSF evaporator and brine heater shell are made of stainless steel, cupronickel or carbon steel with lining/cladding. Centrifugal pumps made of stainless steel (SS316) are used for pumping the brine.

MSF plants produce practically pure water having about 5–25 ppm TDS from sea water containing 35 000 to 45 000 ppm TDS. The capital cost of MSF plants varies from US \$1000 to 3000 per m^3/d installed capacity [19]. Several companies can supply MSF plants internationally with guaranteed performance. The major advantage of MSF is that it can be designed for large unit size. MSF is still the major seawater desalination process on the basis of installed capacity, but market data show inroads by other desalination technologies.

4.2.2. Multi-effect distillation

The MED process has a fairly long history. It is the oldest large scale evaporative process used for the concentration of chemicals and food products, and it was the first process used for producing significant amounts of desalted water from sea water. However, its large scale application to desalination began only during the past two decades.

Figure 4.2 shows a schematic of a MED process. The feed sea water is heated by the steam in the first effect, resulting in evaporation of a fraction of the water content. The feed may be inside the heat transfer tube and the steam outside or vice versa. The concentrated brine is sent to the second effect maintained at slightly lower pressure than the previous effect. The vapour produced in the first effect condenses on the heat transfer tubes in the second effect, giving up its latent heat and generating an almost equal amount of vapour from the brine. The process is repeated from effect to effect at successively lower pressures. The condensate is collected as product water. The MED process produces around 5–25 ppm TDS product water quality from 35 000 to 45 000 ppm of sea water. The energy efficiency of the MED plant increases by increasing the number of effects. The GOR for MED is theoretically equal to the number of effects, but practically somewhat less, because of heat losses. As for MSF, the GOR for MED varies only slightly with the salinity of the feed.

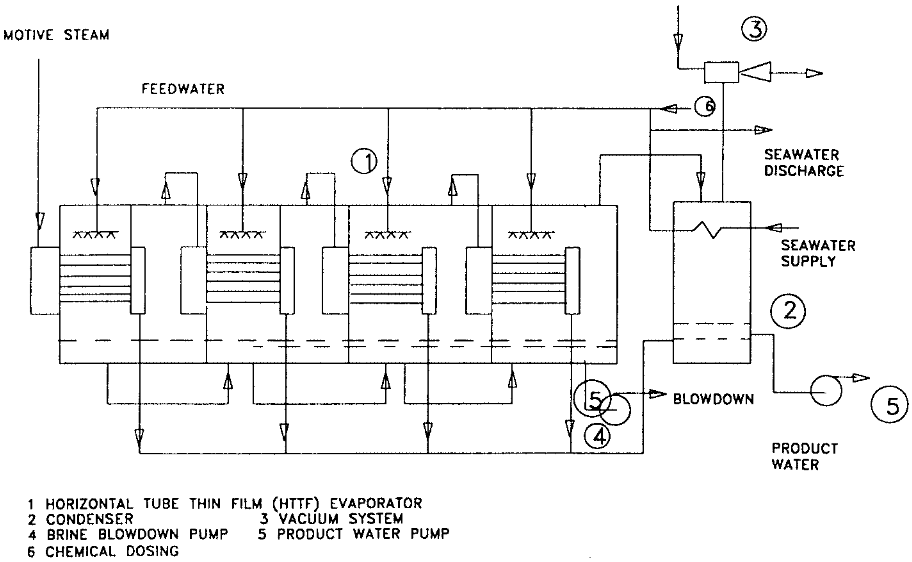

FIG. 4.2. Schematic flow diagram of the multiflect (MED) desalination process.

MED plants have been built in vertical tube or horizontal tube arrangements. In the vertical tube evaporator (VTE), the sea water boils in a thin film flowing inside the tubes and steam condenses on the heat transfer tubes. VTE processes include falling film evaporators, rising film evaporators and evaporators with forced and natural circulation. A significant improvement in heat transfer is achieved by using double fluted tubes to extend the surface and reduce the film thickness. Normally, several effects are used in series along the direction of vapour flow in a desalination plant.

In the horizontal tube thin film (HTTF) evaporator, the seawater feed is sprayed on the outer surface of the tubes and vapour flows inside the horizontal tubes, where it condenses, giving product water. The advantage is that the overall heat transfer coefficient is about three times that of a submerged tube desalination plant. However, HTTF evaporation is sensitive to the distribution of brine on tubes, and the seawater supply to each effect should be large enough to prevent dry spots. A significant improvement in heat transfer is achieved by using oval tubes for distribution and film thinning.

A low temperature (up to 70°C) version of the HTTF is the LT-MED, which is gaining ground for low and medium capacity desalination plants, owing to following advantages:

- lower energy consumption,
- higher heat transfer coefficient,

- compactness,
- high product water quality,
- reduced pre-treatment.

Low temperature operation reduces the susceptibility to corrosion and scaling. It reduces the demand for anti-scalant, maintenance and expensive corrosion resistant materials of construction. In the unlikely event of a leak in the tube wall, the vapour leaks into the brine chamber, thereby avoiding the contamination of product water. Aluminium, copper based alloys and titanium are used for the tubes and tube sheets. Epoxy lined carbon steel and stainless steel (SS 316) are used for the shell.

HTTF evaporators, however, can operate at higher temperatures (up to 130°C) using more expensive materials. High temperature MED (HT-MED) can incorporate a larger number of effects and, therefore, have a greater GOR. The number of effects in MED generally varies from 2 to 24. Current MED plants usually have a GOR in the range of 6 to12, and some HT-MED plants may have GORs of 20 or higher. As in the MSF process, selection of the GOR for MED is a matter of economic optimization. The MED process can be made more energy efficient by increasing the number of effects and heat transfer areas, or by increasing the operating brine temperature. On the other hand, it is often the case that lower water costs are achieved by operating at lower temperatures (e.g. LT-MED), because of the resultant decrease in corrosion and scaling, which permits use of cheaper materials of construction.

MED has a proven record of experience in industrial applications for several years at many locations worldwide. The major advantage of the MED process is the ability to produce a significantly higher GOR than MSF for a given source steam temperature. According to current trends and expectations, it may likely be one of the dominating processes for thermal desalination in the small and medium capacity ranges. Current MED capital costs vary from US $900 to 2000 per m^3/d capacity. MED has recently received a great deal of attention for medium size plants in the United Arab Emirates and for large scale plants in India (4 × 12 000 m^3/d).

4.2.3. Vapour compression

Figure 4.3 shows a schematic flow diagram of a VC desalination process. A steam compressor maintains a pressure difference across the heat transfer surface. Seawater feed is pumped to the low pressure side of the surface, where it picks up heat and boils. The compressor heats the water vapour via the heat of compression and delivers it to the high pressure side of the heat transfer surface, where it condenses by giving up its latent heat to the boiling sea water. The efficiency is governed by the effectiveness of the heat transfer surface, the compressor efficiency and the effectiveness of heat recovery from the reject brine and product water streams. Efforts are being directed towards development of high efficiency compressors and

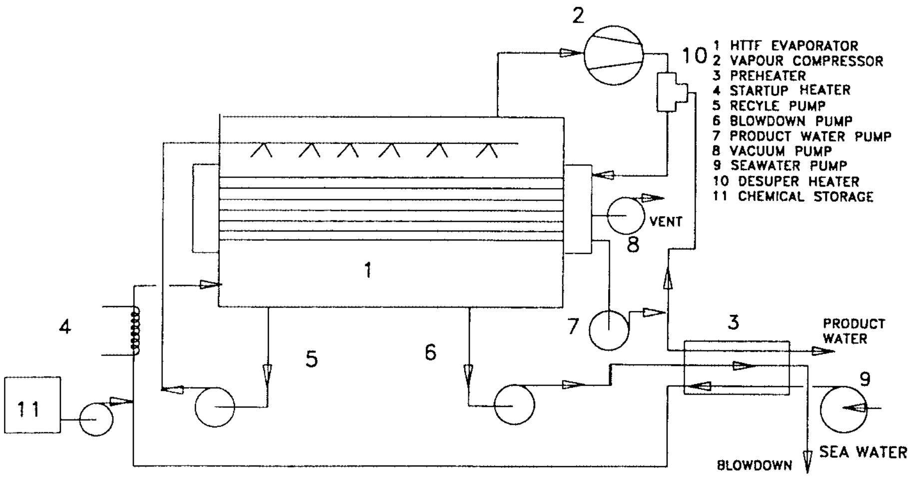

FIG. 4.3. Schematic flow diagram for the vapour compression (VC) desalination process.

thin film boiling surfaces. The thermocompressors for compressing and heating the low temperature vapour, using high pressure steam, are being increasingly used in VC desalination.

Low temperature VC is a simple, reliable process and produces high quality product water (5–25 ppm TDS). A number of desalination plants are installed worldwide for producing good quality water from saline water for industrial and municipal use. VC plants have the disadvantage of limited plant capacity due to non-availability of large size vapour compressors. Currently, the largest VC unit is 3000 m^3/d, consisting of three evaporator–condenser effects coupled to a compressor. The larger size VC plants have a unit specific electricity consumption of 7.5–8.5 kW(e)·h/m^3 of product water.

4.2.4. Reverse osmosis

Reverse osmosis (RO) is a pressure driven membrane process utilizing a semi-permeable membrane that prefers solvent permeation against salt. Osmosis is a natural phenomenon by which water flows through a semi-permeable membrane from a dilute to a concentrate solution. Osmotic equilibrium is achieved when the flow due to osmosis is just stopped by application of pressure to the high solute concentration side. The corresponding pressure is called the osmotic pressure. When the pressure of saline water is higher than the osmotic pressure, pure water is forced through the semi-permeable membrane, leaving the concentrate stream behind. The mechanism of water permeation through the semi-permeable membrane in RO is related to the membrane's chemical nature and morphology. As a rule of thumb, the osmotic pressure of the sodium chloride solution (expressed in psi) is 1% of the salt concentration (expressed in ppm).

The performance of an RO plant is evaluated in terms of the recovery factor, the permeate flux and the per cent salt rejection. The recovery factor is the ratio of permeate flow rate to seawater feed flow rate. The permeate flux is the flow rate of permeate water across a unit of membrane area. The per cent salt rejection is given by:

$$\%SR = (C_{hp} - C_{lp})/C_{hp} \times 100$$

where %SR in the per cent salt rejection, C_{hp} the concentration of solute on the high pressure side and C_{lp} the concentration of solute on the low pressure side.

RO membranes are made of natural or synthetic polymer. The RO membranes should possess good selectivity, low resistance to water flow and adequate chemical and mechanical stability. The first desalination membranes were made of cellulose acetate and used for brackish water. Current seawater RO membranes are based on polyamide. With the development of thin film composite (TFC) membranes, the skin thickness has been reduced to a few hundred Å, giving high permeate flux at low pressure without sacrificing salt rejection.

The membranes are housed in modules. There are four types of RO module configurations, which are designed to provide adequate membrane area and appropriate feed velocity to achieve the requisite permeate flux and salt rejection. These configurations are tubular, plate, spiral and hollow fibre. The spiral and hollow fibre configurations are now predominant in most RO plants. Several companies manufacture spiral and hollow fibre membrane elements of capacities, ranging from 30 to 100 m^3/d. The selection of a particular configuration depends on feedwater quality, space constraints and local factors.

A typical RO desalination plant consists of a pretreatment section, a high pressure pump, RO modules and a post-treatment section as shown in Fig. 4.4. On the basis of feedwater analysis, a suitable pre-treatment system is designed to eliminate suspended solids, biofouling organisms and scaling minerals. Fouling and scaling reduce both the performance and life of the membrane. The silt density index (SDI) is a measure of the fouling constituents in the seawater feed consisting of iron, manganese, organics and fine suspension. Feedwater with an SDI value of two to three is preferred; a value of four is on the high side; and five is undesirable, because of its fouling and scaling tendencies on the membrane surface.

RO normally uses only electrical energy, and the largest power consumer is the high-pressure pump, which delivers flow at a head of 60–80 bar. In large capacity RO desalination plants, it is possible to recover around 30–40% of the energy from high

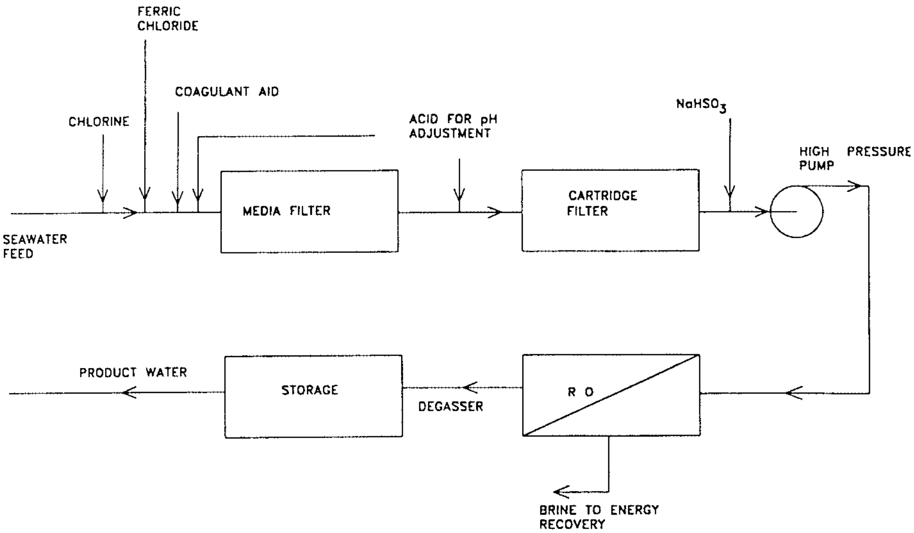

FIG. 4.4. Schematic flow diagram of a reverse osmosis (RO) desalination plant.

pressure reject brine by energy recovery systems such as pelton wheels, hydroturbines or turbochargers. The energy consumption in seawater RO plants using energy recovery units is around 4–6 kW(e)·h/m^3 of product water.

The arrangement of RO modules either in series, parallel or staggered configuration is governed by the seawater conditions and the desired recovery ratio and product water quality. Elevated feed temperatures yield both high flux and high salt passage. Using the waste heat discharged from a power plant or thermal desalination plant to preheat the RO feed water may be economically attractive as long as the upper temperature limit of the membrane is not exceeded.

The post-treatment of permeate water depends on its end use. The salt content of the permeate water from single stage RO plants is normally within the permissible limit of drinking water quality. For very pure water of around 20–50 ppm, a second membrane stage is necessary. If low conductivity process water is required for industrial applications, the product water from RO plants is demineralized by using ion exchange to achieve 0.1 µS/cm conductance.

With a carefully designed pre-treatment unit and good plant design and construction, a well maintained RO plant can achieve high reliability. RO plants experience a proportional increase in energy demand as the feedwater salinity rises. In addition, the RO process is sensitive to specific types of contaminants in the feed.

The percentage of desalination plants using RO has been increasing, owing to rapid improvements in RO technology and associated equipment. A number of large seawater RO desalination plants have been installed in the past few years. The total capacity of RO plants installed in the world is around 6 million m^3/d. Out of this, 2 million m^3/d is for brackish water and the rest for seawater desalination. The capital costs of RO plants vary from US $900 to 1700 per m^3/d capacity [19].

4.3. OTHER TECHNOLOGIES

4.3.1. Freezing

In 1786, Anton Maria Lorgna gave the first description of a working method for desalination by freezing [20]. Extensive work was done in this area in the 1950s and 1960s. Desalination by freezing process is carried out by cooling the saline water to form ice crystals under controlled conditions and then melting the ice to get pure water. It has several advantages such as low energy consumption, minimal potential for corrosion and low scaling probability. However, it involves handling of ice and water mixtures. In practice, the surface of the ice remains coated with brine, resulting in high salinity of the product water. To avoid this, the ice is washed with pure water. The amount of pure water required for washing is large. Several pilot plants have been built by using freezing for desalination. However, it has still not met commercial success.

4.3.2. Ion exchange

Ion exchange is described as the removal of one type of ion from the solution and its replacement by an equivalent quantity of another ion of the same charge. This process is widely used for water treatment for process application, boiler feedwater and in semiconductor industry. The use of ion exchange for desalination systems is technically feasible but commercially not viable so far.

4.3.3. Electrodialysis

Electrodialysis (ED) uses permselective membranes having fixed ionogenic groups in their matrix. Two types of selective membranes for cation exchange and anion exchange are used. In the presence of an electric field, the respective membranes allow the cations and anions to pass through. The feed saline water flows through a stack of membranes across which an electric voltage is applied. Ions migrate to the respective electrodes through the membranes, leading to an ion depleted product and a concentrated reject brine stream in alternate compartments between the membranes. The basic separation mechanism involves the removal of salts, leaving the desalted water behind as shown in Fig. 4.5. The mode of operation is unidirectional, requiring a direct current power supply.

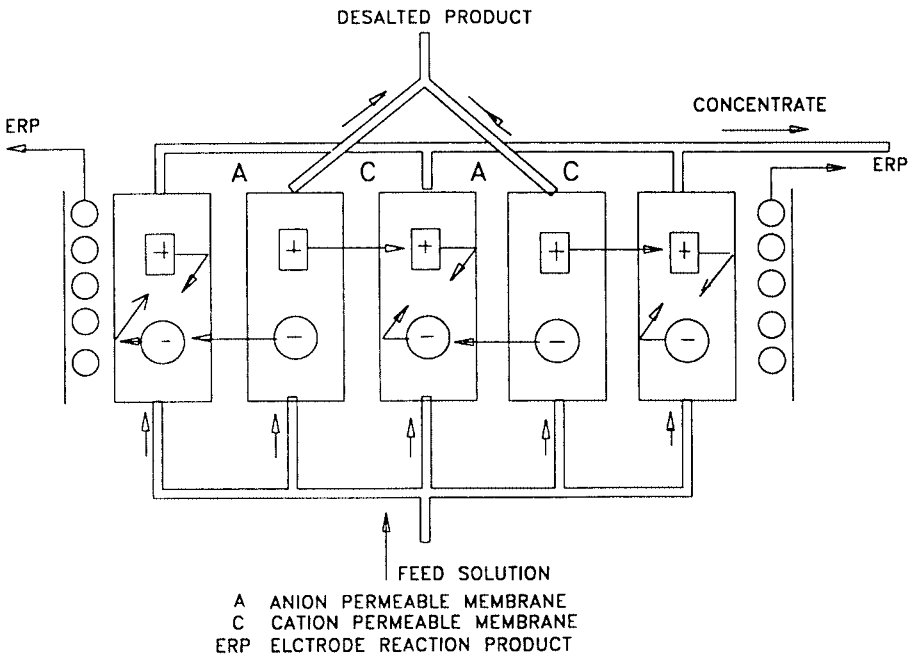

FIG. 4.5. Schematic diagram of the electrodialysis (ED) desalination process.

A modification in this process is electrodialysis reversal (EDR) incorporating periodic reversal of the direct current polarity. It has several advantages over unidirectional ED. It provides a flushing operation for the deposits and controls membrane scaling and fouling.

The main parts of the ED system are the stacks with electrodes, power supply unit and feed/product circulating pumps. The membranes are prepared by dispersing ion exchange resins in suitable binders. Fabric supports are used to mechanically strengthen the membranes. The spacers are used to provide turbulence and minimize concentration polarization. Effective chemical pretreatment of the feed is required for longer membrane life.

ED is widely used for desalination of 1000–5000 ppm TDS brackish water. High temperature ED up to 50°C is also being explored. At higher feedwater temperature it is useful for seawater desalination because both the membrane and solution resistances are reduced and higher current densities are achieved. Approximately, 1 kW(e)·h of energy is required to remove 1 kg of salt from brackish water feed.

4.3.4. Low temperature vacuum evaporation

Energy cost contributes a significant fraction to the desalted water cost. Therefore, reducing the energy cost is an important goal for any desalination technology. Low temperature waste heat from nuclear research reactors and power plants is an abundant source of low cost energy for those desalination technologies, which can operate effectively at low temperatures. Such a system is low temperature vacuum evaporation (LTE), which operates at around 710 mm Hg vacuum and 40°C, which is close to the reject heat temperature of a typical power plant. A schematic diagram of LTE is shown in Fig. 4.6. It produces fresh water having less than 10 ppm TDS from sea water without any chemical pretreatment of the feed. It uses less expensive materials of construction such as epoxy lined carbon steel for the evaporator shell. However, the overall efficiency of LTE is low owing to low temperature operation. Therefore, the capacity of these systems tends to be low. Nevertheless, the LTE process shows good potential for small capacity applications such as supplying the in-house water requirements of coastal industries and commercial centres.

4.4. HYBRID DESALINATION SYSTEMS

There are many ways to improve the efficiency and cost of product water of desalination plants. One means is to combine two or more desalination systems resulting in a hybrid plant. Hybrid systems can offer performance improvement, savings in pretreatment and overall water cost reduction.

4.4.1. Combination of RO with distillation processes

Integration of MSF and RO or MED and RO systems at the same location offers the opportunity to reduce cost and meet diverse requirements for product water quality when industrial plants are part of the customer base. The ideal application is one with a definite demand for two types of product water such as very low TDS process water for industrial use and moderate TDS water for municipal use. A part of desalted water from the distillation plant can be used as process water where high purity is required. The remaining water can be blended with the high TDS product water of the RO plant for other uses. Different rates of blending can be achieved, depending on the type of water quality requirement.

Cost can be reduced by using the reject brine of the RO plant as feed in the distillation plant (MSF or MED), thereby reducing chemical pretreatment and intake/outfall costs. Another option is to use the reject brine stream of the distillation plant as feed for the RO plant. Although a higher TDS at the inlet of the RO plant

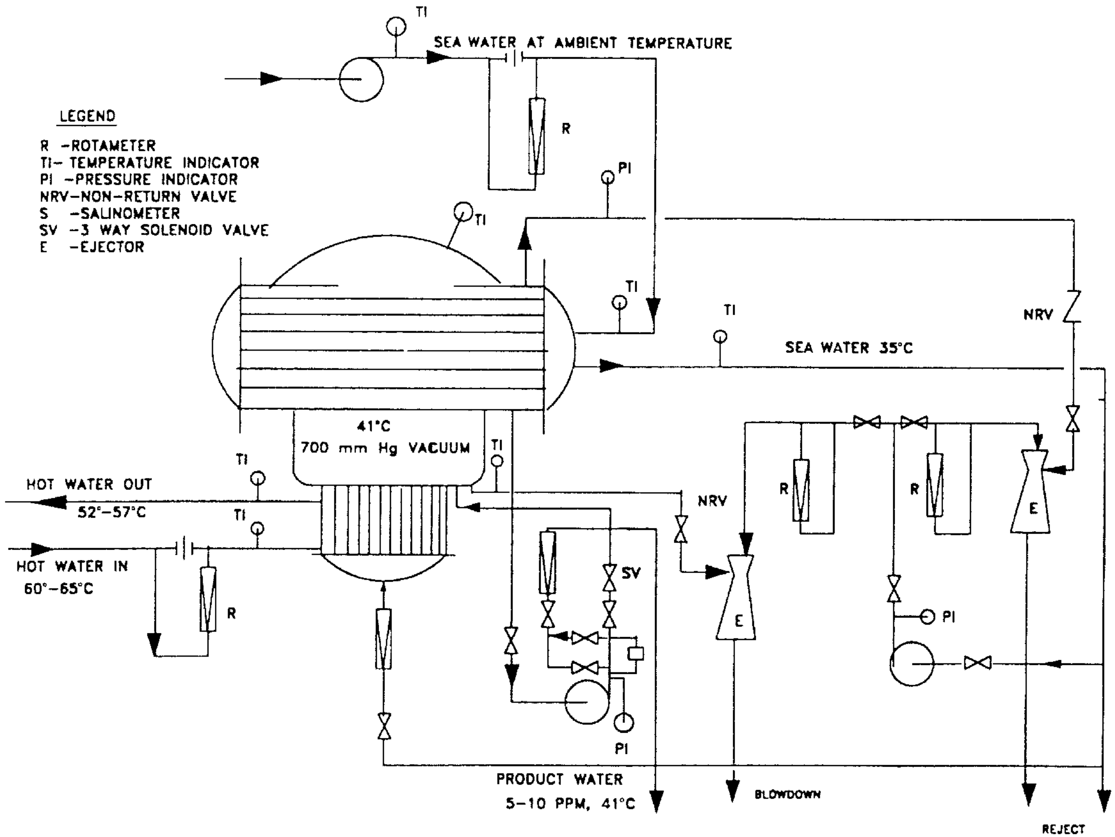

FIG. 4.6. Schematic flow diagram of a low temperature vacuum evaporation (LTE) desalination system.

decreases the membrane flux, the higher temperature of the blowdown increases the flux and compensates the negative effect. Additionally, reject brine from the distillation plant is chemically treated, fully sterile and de-aerated. It requires only filtration (<5 μm), reducing the overall pretreatment cost for the hybrid plant.

In the case of MED, the sea water, required as cooling water for the condenser effect (last effect), is heated up by 3–5ºC. This slightly heated seawater can be used as feedwater for RO. A 5ºC temperature rise of feedwater means about 15–20% less membrane area requirement. In addition, the reject brine from the RO plant can be used as feed for the LT-MED, producing high quality product water.

The hybrid MSF-RO and MED-RO systems offer several interesting prospects for water cost reduction and, therefore, deserve further exploration.

4.4.2. Combination of vapour compression with distillation processes

The coupling of vapour compression (VC) to a distillation process offers the possibility for increasing the GOR. Several such schemes have been proposed in this regard. The multi-effect vapour compression (ME-VC) process has been demonstrated in a 3790 m^3/d plant in Roswell, New Mexico. It consists of a multi-effect VTE coupled to a VC system. In this process, the amount of heat to be rejected is reduced by reduction of the cooling requirement with the VC system. Another combination of multi-stage/multi-effect VC (MSF/ME-VC) proposed by Structhers Co. includes a gas turbine, a steam turbine and a boiler. The advantage is the reduction in energy consumption, higher GOR, less chemical pretreatment and higher operating temperature. A number of hybrid VC desalination plants are operating throughout the world for industrial and municipal use.

4.4.3. Other combinations

VC and RO technologies can be integrated into a hybrid system with the same set of advantages as offered by the hybrid distillation and RO plant. In addition, both units consume electricity so that no heat source is required.

Preliminary investigations have been carried out on using ultrafiltration (UF) as pretreatment for RO plants and nanofiltration (NF) as a means to improve the performance of MSF and RO. Adoption of the UF system reduces the fouling and scaling in RO plants, improving its membrane life. Recent studies indicate that NF improves the product recovery in RO plants by partial removal of salt and most of the scaling constituents. It can also overcome the top brine temperature limitation in the case of MSF. A combination of NF, seawater RO and MSF appears promising for the future.

Other combinations are also possible but at present are not economical for low cost water production. Where by-product production is considered, such as manufacture of magnesium or sodium chloride from sea water, the addition of an ED system for the production of desalted water becomes economical, as well. ED with polarity reversal is less sensitive to high TDS and saturation than other systems.

4.5. COMPARISON OF COMMERCIAL DESALINATION PROCESSES

Though many methods have been proposed for seawater desalination, only a few have been developed to a stage where they may be commercially deployed. Among the available commercial processes which currently appear as the most interesting for desalination are MSF, MED, RO and MED/VC [7]. The selection of a particular process depends on the saline water quality, the product water quality requirements and the process economics. All the processes have their inherent advantages and disadvantages. Table 4.I. gives salient characteristics of the commercial desalination processes. For desalination plants rated at more than 4000 m^3/d per unit, MSF is still prevalent over any other process. However, the RO process is increasing its market share every year, and there is likely to be increased use of MED and VC, including hybrid systems.

Studies are now directed towards reducing product water cost by increasing heat transfer coefficients, using cheaper materials and utilizing waste heat in thermal processes and, likewise, reducing chemical pre-treatment, increasing product recovery, adopting high temperature operation and enhancing energy recovery in the membrane processes. The future of desalination technology will largely depend on reducing the energy costs and making further improvements to both the technology and unit sizes.

In many cases, the hybrid systems combining the best features of both the technologies may be developed and utilized. Selection of the most suitable desalination technology requires understanding of the different processes and knowledge of effective coupling and hybridisation.

4.6. TECHNOLOGIES UNDER DEVELOPMENT

4.6.1. Long tube vertical evaporator

The Metropolitan Water District (MWD) of Southern California is developing the next generation of large capacity seawater MED plants based on long tube vertical evaporator technology. Figure 4.7 shows a schematic process flow diagram of a stacked vertical tube evaporation plant. It uses aluminium materials for high performance heat transfer surfaces and a concrete shell. The advantage of this technology is claimed to be high heat transfer performance and reduced cost of

TABLE 4.I. SALIENT CHARACTERISTICS OF COMMERCIAL DESALINATION PROCESSES

Characteristics	RO	MSF	MED	MED-VC
Possible unit size (m^3/d)				
present	10 000	50 000	20 000	3000
future	15 000	50 000	30 000	—
Total equivalent energy consumption (kW(e)·h/m^3)				
without energy recovery	7–10	12–18	4.5–12.5	7–9
with energy recovery	4–6	12–18	4.5–12.5	7–9
Limiting factor	Pumps	Pumps, vacuum system	Plant reliability	Vapour compressor
Manufacturing requirement	High (especially for membranes)	Medium	Low	Medium
Engineering requirement (quantitative)	Low	Medium	Medium	High
Scaling potential	High	Low	Low	Low
Experience available	Medium	Highest	High	Medium
Scale-up advantage	Marginal	Significant	Significant	Marginal
Commercially viable capacity	Large	Large	Medium	Small
Feedwater	Seawater	Seawater	Seawater	Seawater
Product quality (ppm)	250–500	10–20	10–20	10–20
Feed pretreatment	Significant	Moderate	Less	Less
Top brine temperature (°C)	Ambient	85–130	55–130	55–75
Startup time (hrs)	Low	High	Low	Low
Fully automatic and unattended operation	Possible	Possible	Possible	Possible
Tolerance to operator failure	Low	High	High	Medium
Tolerance to changing sea-water composition and pollution	Very low	High	High	High maintenance
Maintenance requirement	High	Low	Low	Medium
Spare parts or replacement requirement	Membrane replacement every 3–5 years.	Low	Low	High (vapour compressor)
Heat transfer area requirement	Not applicable	High	Low	Low

TABLE 4.I. (cont.)

Characteristics	RO	MSF	MED	MED-VC
Failure potential if corrosion occurs	High (some membranes are sensitive to dissolved metals)	Low	Low	Low
Ratio between product and total seawater flow	0.3–0.5	0.1–0.15	0.1–0.25	0.4–0.6
Capital cost	Lower	High	Low	Medium

construction material. The technology was demonstrated earlier by operating a 8000 L/day test unit on the coast of Southern California. The results from the operating test unit support the technical feasibility of the enhanced distillation design.

In co-operation with IDE Technologies Ltd. and Parsons (USA), the MWD is working on detailed design of a 18 500 m^3/d demonstration plant. This plant will demonstrate full scale components of a single module of future plants with capacities greater than 110 000 m^3/d. Detailed design and plans for construction of a 47 700 m^3/d MED plant using fluted aluminium tube bundles vertically stacked in a concrete vacuum tower are in progress.

4.6.2. Orbital tube evaporators

Orbital tube evaporators (OTEs) have an overall heat transfer coefficient around three times greater than horizontal tube units. Their superior performance results from a shaking motion imparted to the entire heat exchanger. The flexible legs of the heat exchanger allow the unit to move from side to side. The heat exchanger follows a small circular orbit about 2 cm in diameter as the two counterweights on the side of the heat exchanger revolve. A whip rod is placed in the tube; it moves in synchrony with rotating counterweights leading to formation of thinner film. The thin film accounts for the OTEs high boiling side film coefficient and its non-scaling performance. Vertical ribs outside each tube collect the condensate and promote better drainage. It makes the condensing film thinner between ribs, thereby increasing the condensing side film coefficient. This leads to enhancement of the overall heat transfer coefficient. The OTE, owing to its higher heat transfer coefficient, has the potential to be a low cost, compact desalination device [21].

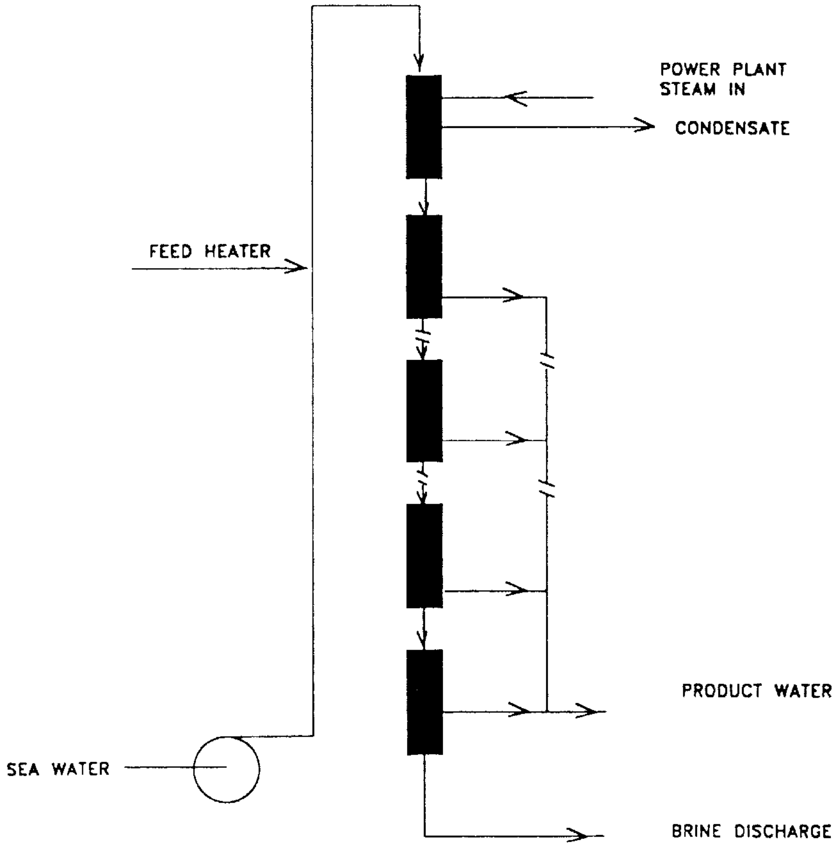

FIG. 4.7. Schematic process flow diagram of a stacked vertical tube evaporation plant.

4.6.3. Long tube MSF

It is well known that the thermodynamic efficiency of MSF is determined by the number of flash stages and the specific heat transfer area for a given flash range. The efficiency increases with the number of flash stages. It is easier and less expensive to have a large number of flash stages in a long-tube design than in a cross-tube design. In a cross-tube design, the incoming brine flows at right angles to the flashing brine whereas, in a long-tube design, the incoming brine flow path is parallel to the flashing brine. The geometry of the flash chamber is considerably different in the two cases. Three to five flash stages can be accommodated in a single vessel (module). A long-tube MSF requires significantly fewer tube sheets and low pumping power, because of lower pressure drop. It requires less capital cost, lower energy requirement and lower operating cost. A long tube design is a modular design depending on the availability of tube length. The 8000 m^3/d Sirte MSF plant uses a long tube design with 6 modules arranged in parallel to each other. MSF suppliers are now considering the potential of long-tube MSF for their future designs.

4.6.4. Membrane distillation (MD)

Membrane distillation appears to have enough potential to be adopted for desalination. It is a thermally driven process in which a hydrophobic microporous membrane separates a warm saline water stream from a cold water stream. The temperature difference between the cold and warm streams produces the motive force through the membrane. Water vapour produced at the warm saline feed side of the membrane passes through the pores and condenses in the cold side. The passage of liquid water is prevented by the hydrophobic nature of the membrane. Membrane distillation proved very effective in removing 99.99% of the salt from sea water and from a 30 000 ppm NaCl solution [22]. Membrane distillation appears to have future potential for economic desalination using waste heat or warm seawater. Recent studies suggest utilizing the blowdown stream from distillation plants as feed for membrane distillation units.

4.6.5. Solar powered MED

The utilization of direct solar energy for desalination has been investigated for quite some time. Considerable work has been carried out during World War II in small solar stills for use in life rafts. Solar energy is available free of cost. However, the technology is still awaiting wide commercial acceptance because of high installation costs and large space requirements. Experimental desalination units have been set up using energy derived from the solar energy, such as wind energy and ocean thermal energy. A 120 m^3/d solar powered MED plant at Abu Dhabi is used for supplying potable water to the city [23].

Chapter 5

COUPLING OF NUCLEAR REACTORS WITH DESALINATION SYSTEMS

5.1. INTRODUCTION

The nuclear reactor supplies energy to desalination systems either in the form of heat or of the mechanical/electrical energy. It supplies thermal energy for distillation processes such as MSF or MED and provides mechanical/electrical energy for the processes which are based on mechanical energy such as RO, MVC or MED/VC. Apart from the basic energy for desalination, all desalination processes require electricity for pumping, auxiliaries and other services.

Nuclear energy is used to produce electricity in 32 countries. 434 nuclear plants, with a total capacity of 349 GW(e) were in operation in December 1998, and their share of the world's electricity production was about 17%. A few of these plants are being used for co-generation of hot water and/or steam for district heating, seawater desalination or industrial processes. The total heat capacity of these plants is about 5 GW(th). Significant experience in the co-generation of electricity and heat exists in Bulgaria, Canada, Germany, Hungary, Japan, Kazakhstan, the Russian Federation, Slovakia, Switzerland, Ukraine and the United States of America. Experience with dedicated nuclear heating plants has been gained in China and in the Russian Federation.

As of 1998, there has been over 500 reactor-years of combined experience in existing nuclear desalination plants and in the related coupling of nuclear reactors with non-electrical heat applications such as district heating and process heat production. This experience has shown that radioactivity levels in the heat consuming parts of these industrial complexes have always been maintained within regulatory limits.

5.2. TECHNICAL DESCRIPTIONS OF VARIOUS COUPLING CONCEPTS

Desalination plants can be coupled as a single purpose plant or a co-generation plant. In the case of a single purpose nuclear desalination plant, energy is exclusively used for the desalination process, and the desalted water is the only product output. The nuclear reactor is fully dedicated to supplying energy for desalting. In case of a co-generation plant, only a part of the energy is utilised for desalting. A co-generation plant produces both electricity and water simultaneously. Figure 5.1 shows simplified flow diagrams of the steam cycles of a single purpose desalination plant, a single purpose power plant and a co-generation plant.

When a nuclear reactor is used to supply steam for desalination, the method of coupling has a significant technical and economic impact. The optimum method of coupling depends on the size and type of the reactor, the specific characteristics of the desalination process and the desirability and value of electricity generation as a co-product.

5.2.1. Desalination plant coupled to power reactors

Power reactors are suitable for desalination processes that require energy in the form of electricity such as RO and MVC. The power is supplied from a dedicated plant/electrical grid to drive the high pressure pump for the RO process and the main compressor of MVC. Electrical coupling of the nuclear power plant with a RO or MVC desalination plant is simple, requiring only an electrical connection. There is little interdependence between the power plant generating electricity and the desalination plant producing desalted water. It allows flexibility with respect to siting and plant size. As such, it is not essential to co-locate the nuclear power plant with desalination plants using processes that require only electricity. Since the electrical connection is the only interface, the risk of radioactive contamination reaching the desalted water is minimal.

However, co-location of the nuclear plant and desalination plant at the same location offers some important advantages. The plants can share seawater intake/outfall structures, other facilities and staff. In this arrangement the plant is referred to as a ‘contiguous plant’.

The power plant condenser cooling water is usually discharged to the sea as waste heat. In a contiguous plant, it is possible to use this heated sea water as feed to an RO desalination plant, thereby improving the performance of the desalination plant. In this arrangement, waste heat from the power reactor is used to improve the efficiency of the RO plant. The increase of operating temperature leads to a higher RO membrane flux and produces more desalted water from the same membrane area. By using appropriate feed pretreatment, system design and optimization techniques, overall improvements in efficiency and cost can be achieved. Contiguous RO plants must be optimized differently than standalone RO plants.

5.2.2. Desalination plant coupled to heating reactors

In this type of reactor, the steam (or hot water) produced by the reactor is directly supplied to a thermal desalination process without producing electricity.

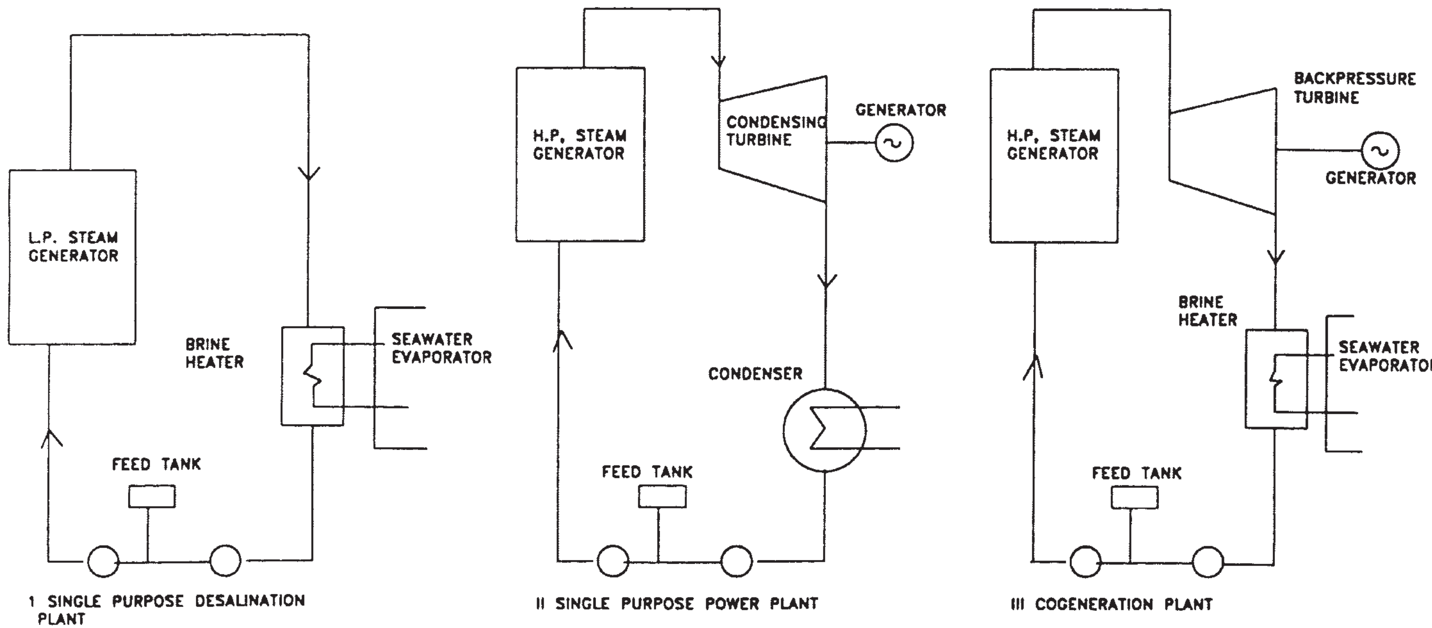

FIG. 5.1. Schematic representation of single purpose plants and a co-generation plant.

Electricity is required for pumping water and for auxiliaries and, therefore, must be supplied from another source (e.g. the electrical grid). It is desirable to have the nuclear reactor and desalination plant adjacent to each other to minimize piping and heat loss.

In nuclear power reactors, the steam is generated at high temperature and pressure, whereas heating reactors need only produce low temperature steam or hot water for thermal desalination processes. Thermal desalination processes have an upper temperature limit of about 140ºC, owing to excessive scaling beyond this temperature. Efforts to operate desalination plants at higher maximum brine temperatures by implementing improved scale control were not found to be cost effective. Thus, heating reactors, which are designed to supply steam at 130°C or lower, have the best potential for coupling to desalination plants [24].

Typical coupling considerations including steam conditions, which are of interest to various thermal desalination technologies, are illustrated by the following cases:

Case I – LT-MED

Steam at 2.0–3.7 bar (120–140ºC) can be used in MSF and HT-MED desalination plants to give a high GOR. To avoid scale formation, the maximum brine temperature is limited to about 121ºC for recycle type MSF; to 135°C for once-through MSF; and to 130ºC for HT-MED, depending on seawater conditions. At these temperatures, acid pretreatment of feed is required to prevent alkaline scale. The use of high temperature additives also permits satisfactory operation with a maximum brine temperature of up to 110ºC. Sponge ball cleaning is required if high temperature additives are used.

In case of MSF desalination, the brine heater serves as a second barrier (Fig. 5.2). The brine in the brine heater is maintained at a higher pressure than the heating fluid (pressure reversal) so that the direction of flow in case of leakage will be from the desalination system and not into it. Contamination is possible only when both the barriers leak and reversal pressure ceases to exist.

Case II – LT-MED

Steam at 0.3–0.4 bar (69–76ºC) can be effectively used in LT-MED desalination plants, operating at about 60–65ºC maximum brine temperature. The conditions for thermal coupling in this case are milder due to low temperature and pressure operation.

The thermal coupling in case of MED must include an isolation loop using high quality water in a closed loop and brine circulation in an open loop (Fig. 5.3). In the isolation loop, the steam is condensed, transferring its heat to another heat transfer

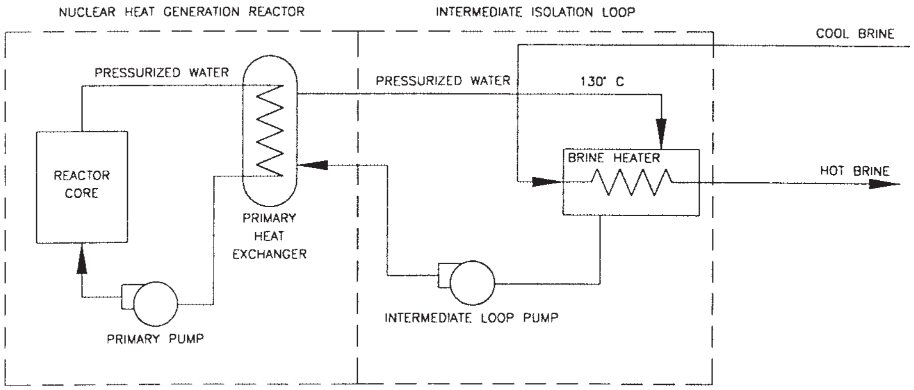

FIG. 5.2. Intermediate isolation loop between heating reactor and MSF plamt.

medium that is used to heat the brine. The heat transfer medium can be pressurized water or boiling water. However, since the pressurized water isolation loop would increase both capital and operating costs, a boiling water/flash loop would tend to be more economic.

Case III – LTE

The waste heat from a nuclear reactor and from the heavy water (D_2O) moderator in a PHWR system can be effectively utilized in a low temperature vacuum evaporation (LTE) plant for seawater desalination.

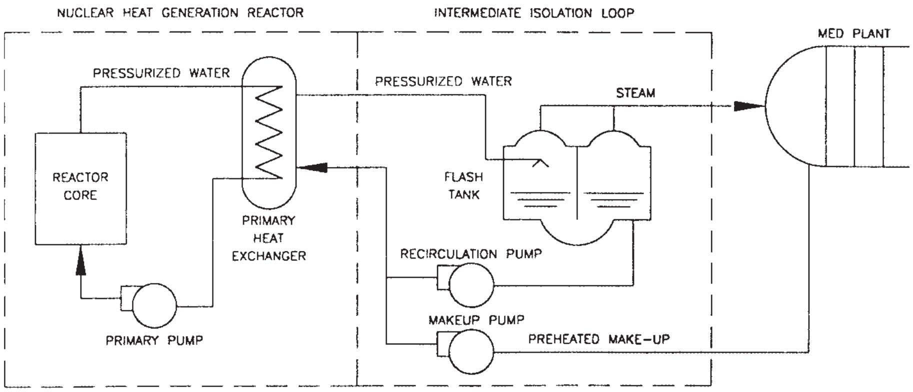

FIG. 5.3. Intermediate isolation loop between heating reactor and MED plant.

5.2.3. Desalination plant coupled to co-generation reactors

In the case of nuclear plants that co-generate heat and electric power, the steam can be bled off at suitable points in the secondary circuit of the power plant for use by the desalination plant. However, protective barriers must be included in all co-generation modes to prevent potential carry-over of radioactivity [10].

There are two types of co-generation mode:

- Parallel co-generation,
- Series co-generation.

In parallel co-generation, electricity is produced as co-product along with desalted water by diverting a part of the steam to the turbine to produce electricity in the conventional manner and part of the steam to the desalination plant. This configuration allows increased flexibility in energy use. However, the total energy consumption would be the same as if the steam for desalination and electricity had been produced separately.

In series co-generation, electricity is produced by expanding the steam first through a turbine with an elevated backpressure and then to the desalination process. This form of co-generation results in reduced total energy consumption as compared to parallel co-generation. From the thermodynamic point of view, it is useful to convert most of the steam enthalpy to mechanical/electrical energy in the turbogenerator before using it as a heating medium in a thermal desalination plant for producing desalted water. Raising the turbine backpressure increases the temperature of the heat available to the desalination plant but reduces the amount of electricity generated. Therefore, in series co-generation the turbine backpressure must be optimized relative to overall plant economics.

Figure 5.4 gives a schematic diagram of the coupling arrangement of an MSF plant with a nuclear power reactor along with an intermediate heat exchanger as an additional isolation loop. A coupling arrangement for a nuclear power reactor with a MED plant is shown in Figure 5.5. It uses the flash loop as an isolation barrier.

It can be advantageous to use part of the electricity generated by the nuclear co-generation plant to operate RO or MVC desalination plants in addition to thermal desalination plants. The hybrid system at the same location can play an important role in bringing down the water cost as well as making multiple product water qualities available (see Chapter 3 for a discussion of hybrid advantages). Figure 5.6 shows a schematic coupling arrangement for a hybrid MSF-RO plant.

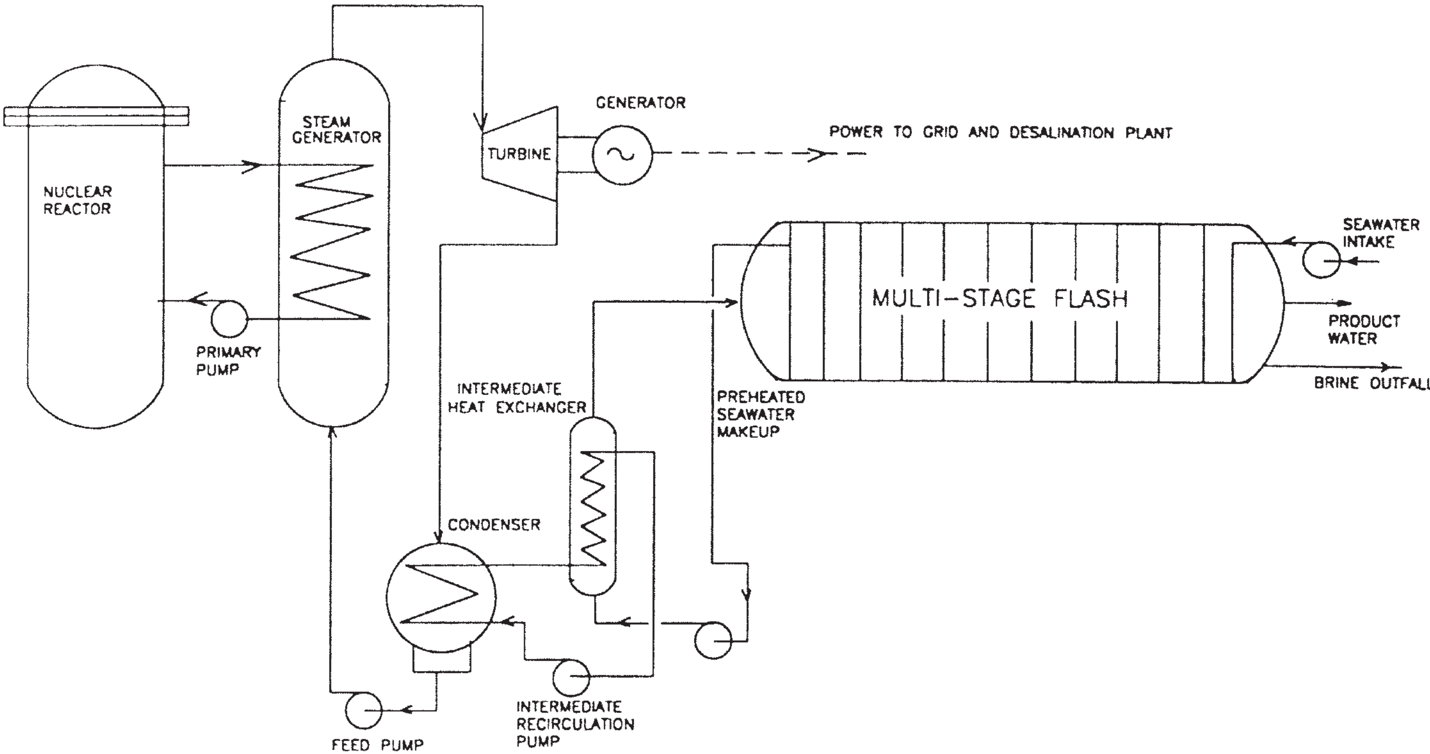

FIG. 5.4. Schematic diagram of a nuclear power reactor coupled to an MSF plant.

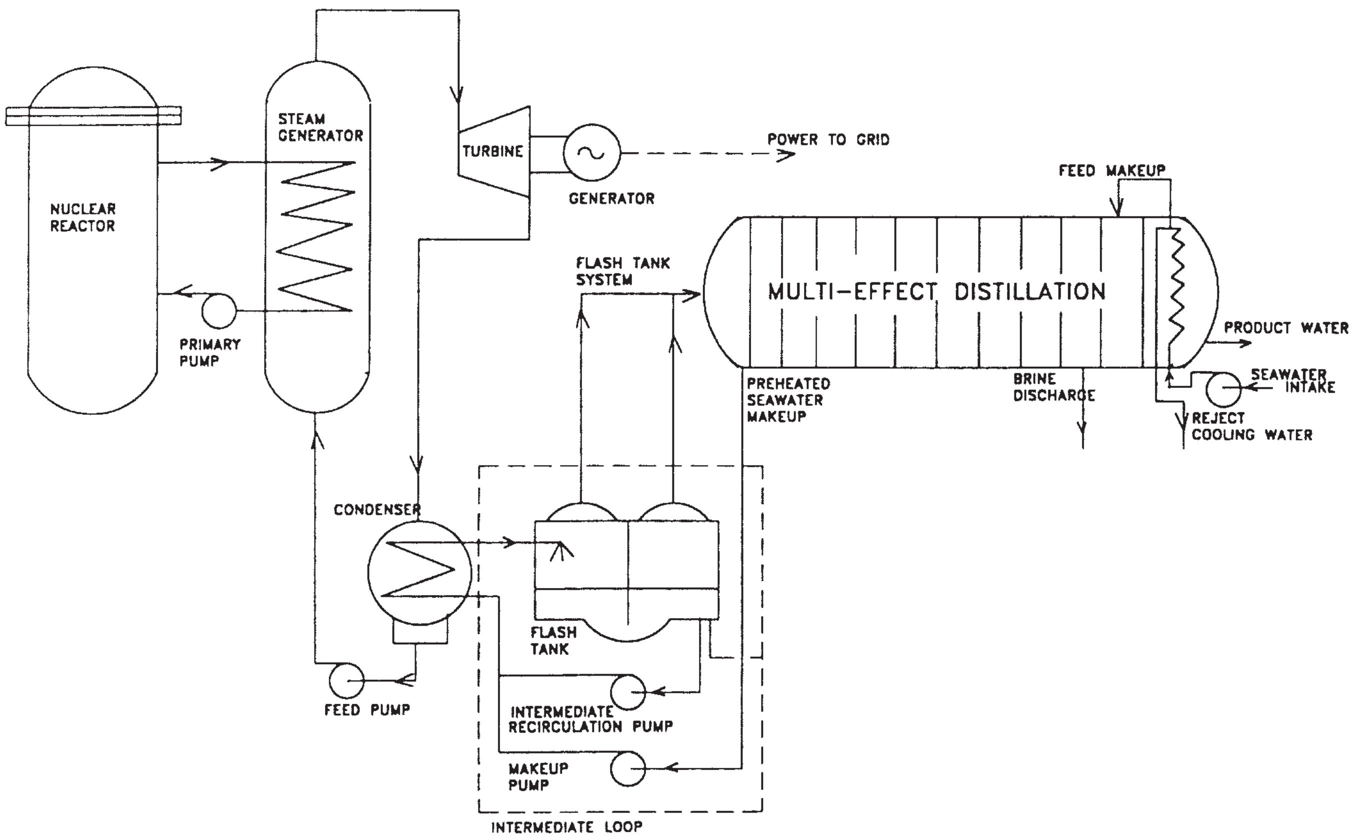

FIG. 5.5. Schematic diagram of a nuclear power reactor coupled to an MED plant.

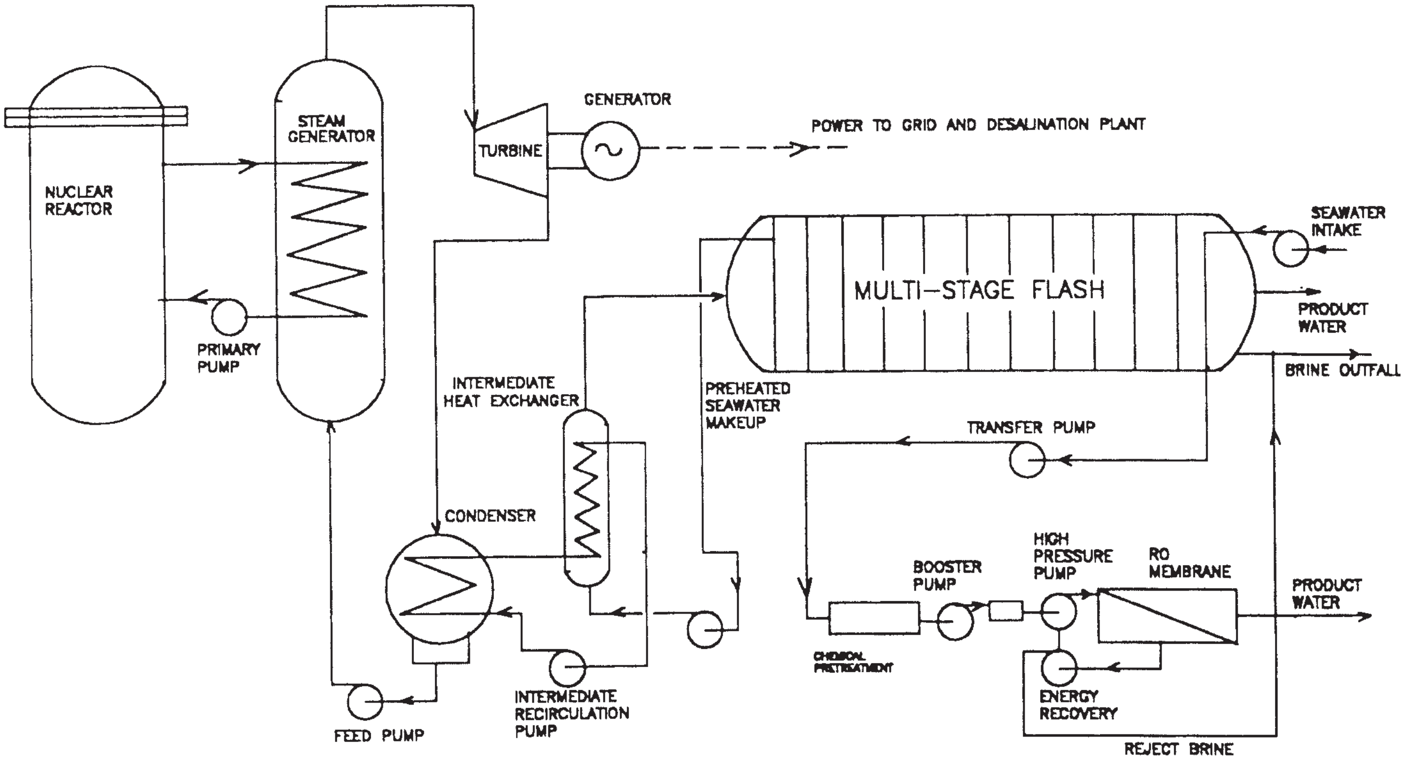

FIG. 5.6. Schematic diagram of a nuclear power reactor coupled to an MSF–RO plant.

5.3. DESIGN REQUIREMENTS FOR THE COUPLINGS

5.3.1. Safety

The safety of a nuclear desalination plant depends mainly on the safety of the nuclear reactor and the interface between the nuclear plant and the desalination system. It must be ensured that any load variation of steam consumption in the desalination plant would not cause a hazardous situation in the nuclear plant. There should be suitable provision for monitoring the radioactivity level in the isolation loop and desalination system. In case of a PHWR, the tritium level in the heating steam and product water must be checked regularly. Adequate safety measures must be introduced to ensure near zero radioactivity release to the product water. The risk should also be assessed for accidental radioactivity carry-over. Modern reactor designs have very good safety features. An agreement of all relevant parties on safety and quality standards and clear regulations are very important for nuclear desalination applications.

The basic requirement to prevent radioactive contamination of the desalination plant and/or the atmosphere is of utmost importance in thermal coupling. At least two mechanical barriers and pressure reversal between the reactor primary coolant and brine must be incorporated. In the case of a pressurized water reactor, the steam generator is the first barrier. The second barrier could be the condenser of a backpressure turbine. In the case of heat generation reactors, careful attention must be given to providing sufficient barriers to prevent radioactive contamination. The most suitable heat generation reactors for desalination coupling are those with a closed primary cooling circuit such as a low temperature PWR or PHWR. In this arrangement, heat is supplied through an interface with a steam generator or primary heat exchanger. This provides a barrier between the reactor coolant and the steam (or hot water) for desalination. Direct supply of steam from the reactor core to the desalination plant, such as in a BWR, is not suitable for desalination without an intermediate barrier.

5.3.2. Design life

The design life of the coupling system should be as high as the design life of the individual processes, i.e., the nuclear system and desalination system. The main components of the nuclear plant are designed for more than 40 years. During operation, the components may deteriorate as a result of wear, corrosion, irradiation, thermal and mechanical stress or obsolescence. Deteriorated components may be repaired or replaced after thorough technical and economic analyses. Current nuclear plant designs avoid early deterioration of key components by using appropriate and proven materials, avoiding excessive stress, corrosion and radiation damage, and maintaining the water quality and other operating parameters.

Desalination plants are designed for an economic life of around 25 years, although some MSF desalination plants have been operating even after 30 years. MED vessels and piping are similar to those of MSF. MED systems with aluminium tubes must anticipate retubing at around 15 year intervals. Titanium, cupronickel or stainless steel alloy tubes may last 25–30 years. In an RO plant, membranes and filters are shorter life components and must be replaced at regular intervals. Membranes with a life of more than five years are now available.

5.3.3. Operational flexibility

The water to power ratio in power station changes with daily and seasonal variations. As electricity cannot be stored, only the steam flow rate in the turbine has to be adjusted as per power demand. A certain degree of flexibility is required in the plant to match local conditions. The design of a co-generation plant must provide for a minimum degree of flexibility to avoid the breakdown of production units when either the turbine generator or the desalination plant production is reduced or shut down. Such provisions could take the form of a backup condenser and/or a backup heat source.

The coupling of an RO or MVC desalination plant to a power plant has a higher degree of flexibility because the main interface is the power coupling. The coupling of an MSF or MED plant to a power plant introduces a close interaction between the operation of both plants.

The transient behaviour including operational flexibility to meet varying power and water demands and methods of maintaining steam supply to MSF and MED plants at low electrical load must be analysed in detail for nuclear co-generation plants. The transients are normally caused by load variation. The extent of variation differs from location to location. The power demand variation is a critical factor in countries where the summer power demand is largely air conditioning, and the load in winter may be only 30% or less of summer demand.

The potential difficulty in the operation of a co-generation plant with thermal desalination is the dependence of steam flow on the electricity demand. A thermal desalination plant does not respond very well to sudden load changes. There is normally no difficulty in ensuring the stable operation of a thermal desalination plant between 70–110% of full rated capacity with slow change in load. A sudden large reduction of steam flow rate to the desalination plant may lead to difficulty in operation because the brine flow may decrease below the admissible limit. This difficulty may be partially overcome by adopting a system in which the desalination evaporators are connected in parallel and stopping some of the units to ensure stable operation. This takes care of transient behaviour due to daily and seasonal load variation.

5.3.4. Reliability/availability

The reliability requirements of the desalination system must be taken into account while designing a steam supply system using nuclear energy. Sudden interruption of power or water supply may have serious safety as well as economic consequences. The reliability requirements must be addressed in the design phase of a nuclear desalination system. These requirements may be met by different measures.

A nuclear co-generation desalination plant consists of three interacting systems: the nuclear steam supply system (NSSS), the turbine generator system and the desalination unit. If the coupling has a high availability factor, the thermal desalination system coupled to the turbine generator may give a high overall availability factor. The desalination plant needs a backup heat source for its operation during the shutdown of the reactors. If the desalination plant is closed, provision should be made for a backup condenser for the discharge of the steam from the power plant.

A hybrid thermal desalination and RO plant coupled to the NSSS appears to give a high availability factor. During the shutdown of the reactor, the thermal desalination plant must also be closed as a result of non-availability of steam. The RO plant, however, can continue to operate using power from the grid.

5.3.5. Design limitations

A nuclear power reactor as such can accommodate almost any size of desalination plant. The seawater intake and outfall system and the environmental limitations with respect to temperature and salinity of seawater discharge influence the coupling of a desalination plant to a nuclear power reactor. The temperature and pressure of steam or hot water produced in a heating reactor also have an effect on the type of desalination system to be used and its specifications including coupling arrangement.

5.4. OPERATING EXPERIENCE WITH NUCLEAR DESALINATION

5.4.1. Nuclear desalination systems at Aktau, Kazakhstan

The Aktau power and desalination plant complex is located in an arid zone in the Mangyshlak peninsula, on the East Coast of the Caspian Sea. The complex was constructed at a site situated 12 km from the city, next to several developed industrial enterprises. A separate potable water treatment station was built at a location closer to the town. The complex consists of a nuclear power station based on a BN-350 fast reactor and a fossil power plant, which together provide steam to a condensing turbine and three backpressure turbines. The exhaust steam (0.6 MPa) from the backpressure turbines is used as the heat source for the first stage evaporators of an MED desalination plant (Fig.5.7). If more steam from the power plant is available than is required for desalination, it is used to supply heat energy to the nearby industrial enterprises and settlements. A transit pipeline exists between the power stations and the heating network, which routes steam to the industrial district heating system [25].

The nuclear plant has been in operation since 1973 and has now completed 100 000 h of operation. The nuclear reactor is shut down for twenty days twice a year for refuelling and scheduled maintenance. During the shutdown periods, heat for the desalination plant is supplied by the thermal power station. Such switching between heat sources for the desalination plant has been carried out regularly for more than 20 years, and no problems have arisen.

There are two distillate lines from the desalination plant: drinking quality water (TDS up to 200 mg/L) and high quality water (TDS = 2 to 10 mg/L) for boiler feedwater and other industrial uses. Table 5.I gives key characteristics of the product water. The product water quality does not depend on the heat source used, i.e. nuclear or fossil.

FIG. 5.7. Evaporators for the nuclear desalination plant (LMFBR–MED) at Aktau, Kazakhstan.

TABLE 5.I. WATER PRODUCT CHARACTERISTICS OF AKTAU

Characteristics	WHO guideline values	Distillate «G»	Distillate «A»
Total dissolved solids (mg/L)	<1000	1.96	198.6
Temperature (ºC)	NG[a]	45	28
Color (TCU)	15	—	—
Turbidity (FTU)	5	—	—
Conductivity (μS/cm)	NG[a]	4.05	326.7
PH	6.5–8.5	8.46	8.07
Total hardness (mg/L) ($CaCO_3$)	500	0.78	66.0
Chloride (mg/L)	250	0.48	55.6
Sulphate (mg/L)	400	0.31	33.2
Calcium (mg/L)	NG	0.08	7.6
Magnesium (mg/L)	NG	0.09	8.2
Sodium (mg/L)	200	0.18	48.5
Aluminium (mg/L)	0.3	—	—
Copper (mg/L)	1.0	0.013	0.06
Iron (mg/L)	0.3	0.033	0.09
Zinc (mg/L)	5.0	—	—
Fluoride (mg/L)	1.5	—	—
Nitrate (mg/L)	10.0	—	0.27
α activity (Bq/L)	0.1	—	—
β activity (Bq/L)	1.0	—	—

[a] NG – no guideline value set.

An important advantage of the BN-350 reactor which is now programmed for decommissioning since April 1999 are low levels of radioactivity release to the environment. The average value of routine radioactive gas emission is 10–15 Ci/d compared to an allowable level of 500 Ci/d. The gas emissions include argon, xenon and krypton, which have short half-lives and do not present a health hazard to the population. Both the operating experience and the analysis of design basis and beyond design accidents involving the reactor have shown that the radiological consequences of all abnormal operating conditions have no effect on the desalinated water quality.

5.4.2. Nuclear desalination plants in Japan

Fifty-three nuclear power plants are being operated by the ten electric power companies in Japan as of December 1998. All of them are located at sea sites in order to use sea water as the ultimate heat sink. Some of these plants are equipped with seawater desalination plants in order to provide high quality make-up to the boiler feedwater and for in-situ potable water uses after appropriate treatment including addition of minerals.

The first Japanese nuclear power plant, a gas cooled reactor (GCR), came into operation in 1966. The first Japanese nuclear power and seawater desalination plant started operation in 1978 at the Ohi Nuclear Power Station. The plant was installed by Kansai Electric Power Company and consists of a 1175 MW(e) PWR coupled to an MSF distillation process with a capacity of 1300 m^3/d. As of 1998, nine additional nuclear seawater desalination plants were installed by Kansai, Shikoku and Kyushu Electric Power Companies. Eight of these plants are currently in operation. The desalination plant capacities are in the range of 1000 to 2600 m^3/d. The average salinity of intake seawater is 35 000 mg/L, and the average temperature is 17°C. Table 5.II gives the operating nuclear desalination plants in Japan [26]. Figure 5.8 shows the nuclear desalination plant (PWR-MSF) in Ohi, Japan.

Three kinds of desalination process are represented: MSF, MED and RO. MSF (unit capacity of 1300 m^3/d) was selected for the earlier plants. However, MED and/or RO processes with unit capacities in the range of 1000 to 2600 m^3/d were chosen for

FIG. 5.8. Nuclear desalination plant (PWR–MSF) at Ohi, Japan.

TABLE 5.II. OPERATING NUCLEAR DESALINATION PLANTS IN JAPAN

Plant name	Location	Application	Start of operation reactors / desal.		Net power (MW(e))	Water capacity (m^3/d)	Remarks
Ikata-1,2	Ehime	Electricity/ desalination	1977–82	1975	566	2000	PWR/MED, MSF
Ikata-3	Ehime	Electricity/ desalination	1994	1992	566	2000	PWR/MSF (2 × 1000 m^3/d)
Ohi-1,2	Fukui	Electricity/ desalination	1979	1973–76	1175	3900	PWR/MSF (3 × 1300 m^3/d)
Ohi-3,4	Fukui	Electricity/ desalination	1991–93	1990	1180	2600	PWR/RO (2 × 1300 m^3/d)
Genkai-4	Fukuoka	Electricity/ desalination	1997	1988	1180	1000	PWR/RO
Genkai-3,4	Fukuoka	Electricity/ desalination	1995–97	1992	1180	1000	PWR/MED
Takahama	Fukui	Electricity/ desalination	1985	1983	870	1000	PWR/RO

the later plants because of their higher efficiency compared to MSF. Among the eight operating nuclear desalination plants, two are based on MSF, three on MED and three on RO. Selected highlights from the operating experience of these plants include:

The seawater desalination plants have been in operation for more than 20 years. All these plants have operated successfully and have not experienced any serious anomalies so far. There has been no occurrence of leakage of radioactive substances into the product water. The desalination plants have become very important and effective facilities for supply of high quality make-up and potable water for the nuclear power stations.

The capacities of the desalination plants are small, but the operating data obtained to date are fully applicable to the expected operation of larger scale nuclear desalination plants. The data highly support the use of nuclear power for seawater desalination worldwide.

The seawater desalination plant designs for nuclear plant couplings are identical with those of fossil plant couplings. The only exception is for desalination plants based on RO, in which case the plastic casings of RO membranes have been covered with carbon steel.

5.4.3. Nuclear desalination projects in India

India has successfully operated a small experimental facility in Trombay using steam from a fossil source since 1984 and is planning to set up a 6300 m^3/d hybrid MSF-RO plant at its Kalpakkam PHWR in Tamil Nadu (Table 5.III).

5.5. OPERATING EXPERIENCE WITH NUCLEAR DISTRICT HEATING SYSTEMS

The technical viability of using nuclear heat for the supply of hot water and steam for district heating and other industrial processes has been demonstrated both in dedicated nuclear heating plants and in heat and power co-generation plants. Nuclear heat application systems have been in service for over 20 years without any serious problems. Tables 5.IV and 5.V are lists of operating nuclear heating plants and nuclear heating plant projects, respectively [27].

Dedicated nuclear heating systems were designed, built and operated in China and in the Russian Federation. The plant in China was for demonstration purposes, whereas the Russian plants supply heat to settlements in the northern parts of the country.

A 5 MW(th) test nuclear heating reactor (NHR-5) was commissioned in China and has been in operation since 1989, supplying heat to the INET Centre, near Beijing. The Russian Federation has operated an experimental 10 MW(th) heating reactor at Obninsk since 1954 and has developed the technology of the nuclear district heating reactor AST-500.

Most of the nuclear reactors supplying heat at present are co-generation plants, in which the main product is electricity and only a small fraction of the reactor power is used for nuclear heat applications. For thermodynamic reasons, the extraction of low temperature/low pressure steam from the turbine leads to a low heat cost to

TABLE 5.III. NUCLEAR DESALINATION PROJECT IN INDIA

Plant name	Location	Application	Start of operation reactor / desal.	Construc for coupling	Net Power (MW(e))	Water capacity (m^3/d)	Remarks
Kalpakkam 1,2	Tamil Nadu	Electricity/ desalination	Reactors:1984-86 RO:2000/2001 MSF: after 2001	Design of desalination system	2 × 170	6300	Hybrid MSF/ RO

TABLE 5.IV. OPERATING NUCLEAR HEATING PLANTS[a]

Country	Plant type or name	Location	Application	Phase	Start of operation reactors / heat	Net Power (MW(e))	Heat output capacity (MW(th))	Temperature (ºC) at interface (feed/return)	Remarks
Bulgaria	Kozloduy	Kozloduy	Electricity/ District heating	Commercial	1974–82 1990 1988–93	4 × 408 2 × 953	20	150/70	
China	NHR-5	Beijing	District heating	Experimental	1989 1989	—	5	90/60	
Hungary	PAKS 1-4	Paks	Electricity/ District heating	Commercial	1983–87[b]	3 × 433 1 × 430	30	130/70	4 × V-213 WWER
Russia		Obninsk	District heating	 Experimental	1954–[b]	—	10	130/70	
Russia	WWER-1000	Novovoronezh[c]	Electricity/ District heating	Commercial	1972–73 1981	2 × 385 1 × 950	230	130/70	
Russia	WWER-1000	Balakovo	Electricity/ District heating	Commercial	1986–93[b]	4 × 950	230	130/70	
Russia	WWER-1000	Kalinin	Electricity/ District heating	Commercial	1985–87[b]	2 × 950	230	130/70	
Russia	WWER-440	Kola	Electricity/ District heating	Commercial	1973–84[b]	4 × 411	55		
Russia	EGP-6	Bilibino	Electricity/ District heating	Commercial	1974–77[b]	4 × 11	133	150/70	
Russia	BN-600	Belojarsk	Electricity/ District heating	Commercial	1981[b]	2 × 560	220	130/70	
Russia	RBMK-1000	Petersburg	Electricity/ District heating	Commercial	1974–81[b]	4 × 925	~170	130/70	

TABLE 5.IV. (cont.)

Country	Plant type or name	Location	Application	Phase	Start of operation reactors / heat	Net Power (MW(e))	Heat output capacity (MW(th))	Temperature (ºC) at interface (feed/return)	Remarks
Russia	RBMK-1000	Kursk	Electricity/ District heating	Commercial	1977–86 [b]	4 × 925	~170	130/70	
Slovakia	Bohunice-3,4	Bohunice/Trnava	Electricity/ District heating	Commercial	1985 1987	2 × 408	240	150/70	2 × V213 WWER
Switzerland	Beznau 1,2	Beznau	Electricity/ District heating	Commercial	1969–71/1983–84	1 × 365 1 × 357	80	128/50 (water)	

[a] Data updated from PRIS-98.

[b] Not confirmed

[c] Unit 1 was taken out of operation in 1988, unit 2 in 1990.

TABLE 5.V. NUCLEAR HEATING PLANT PROJECTS

Country	Plant type or site	Location	Application	Phase	Start of operation (year)	Power (MW(e))	Heat output (MW(th))	Temperature (°C) at interface (feed/return)
Bulgaria	Belene	Belene	Electricity/ District heating	Design		2 × 1000	400	150/70
China	NHR-200	Daqing City	District heating	In construction	2000	—	200	90/~60
Japan	HTTR	O-arai	Process heat	Operation	1998		30	950/395
Russia	RUTA	Apatity	District heating/	Design		—	4 × 55	85/60
			Air conditioning	Design		—	4 × 55	85/60
Russia	ATEC-200		Electricity/ District heating	Design		50–180	70–40	150/70
Russia	VGM		Process Heat	Design		—	200	900/~500
Russia	KLT-40		Electricity/ District heating & Desalination	Design		35	110	
Russia	AST-500	Voronezh	District heating	Construction suspended		—	500	150/70
Russia	AST-500	Tomsk	District heating	Construction suspended		—	500	150/70

consumers, provided the cost of distribution is not a dominating factor. Nuclear co-generation plants for electricity and district heating were built and operated in Bulgaria, Hungary, the Russian Federation, Slovakia and Switzerland. Almost 500 reactor-years of quite satisfactory and encouraging operational experience have been accumulated. The plants have operated safely and reliably.

The Kozloduy NPP in Bulgaria has supplied heat to the town of Kozloduy since 1990. The Kozloduy NPP consists of four WWER reactors of 408 MW(e) and two WWER reactors of 953 MW(e). No relevant problems with district heating were reported.

The Paks Nuclear Power Plant (Hungary), consisting of four units of the Soviet design WWER-440 type V-230, is supplying heat to the town of Paks. The water pressure in the heat exchanger is kept higher than the steam pressure to prevent contamination of the hot water system.

The Bohunice Nuclear Power Plant in Slovakia produces electrical energy and low temperature heat for heating and industrial purposes. The heat supply from the nuclear power plant is used for the town of Trnava.

The district heat extraction from the Beznau NPP (Switzerland (2 × 360 MW(e) PWR) has been operated reliably and successfully since its commissioning in 1983/84. The peak heat load is about 80 MW(th), leading to about 10 MW(e) loss of electric power. The district heating system supplies about 2100 private, industrial and agricultural consumers through 35 km of main piping and 85 km of local distribution pipes. Since the consumers are spread over a relatively wide area, the heat cost to them is higher than with individual oil heating, which is, however, accepted as a contribution to protecting the environment.

The most extensive experience with district heat supply from nuclear co-generation plants has been gained in the Russian Federation. The NPPs of Bilibino, Belojarsk, Balakovo, Kalinin, Kola, Kursk and Petersburg are supplying heat from steam turbine bleeders through heat exchangers to district heating grids of towns with typically about 50 000 inhabitants, situated between 3 and 15 km from the NPP site. The heat output capacities range from about 50 to 230 MW(th).

The design precautions to prevent the transfer of radioactivity into the district heating grid network have proven to be effective in all these countries. These design features include one or more barriers to radioactive substances, e.g. in the form of a leaktight intermediate heat transfer loop at a pressure higher than that of the steam extracted from the turbine cycle of the nuclear plant. These loops are continuously monitored, and isolation devices are provided to separate potentially contaminated areas.

District heating systems require a backup heat source when the main heat source is unavailable. Therefore, at least two nuclear power units or a combination of nuclear and fossil fired units are used for district heating grids.

5.6. OPERATING EXPERIENCE WITH NUCLEAR PROCESS HEAT SYSTEMS

There are several nuclear process heat systems operating in different countries (Table 5.VI). In Canada, steam from the Bruce Nuclear Power Development (BNPD) was supplied to heavy water production plants and to an adjacent industrial park at the Bruce Energy Center (BEC). BNPD is the world's largest nuclear steam and electricity generating complex. It includes eight CANDU nuclear reactors with a total output of over 7200 MW(e), the world's largest heavy water plant (HWP), and the Bruce Bulk Steam System (BBSS). The BBSS, capable of producing 5350 MW(th) of medium pressure process heating steam, was built to supply the HWPs from the four 848 MW(e) units of the Bruce A complex. Each of the four 2400 MW(th) reactors can supply high pressure steam to a bank of 6 heat exchangers (24 in total), which produce medium pressure steam for the HWP and site services. The normal capacity is approximately 1680 kg/s of medium pressure steam from the reactors with 315 kg/s emergency backup available from oil fired boilers. In 1995, Unit 2 of the Bruce A NPP was laid up; the HWP and units 1, 3 and 4 of Bruce A were laid up in spring 1998.
The six private industries currently established at the park are:

(1) a plastic film manufacturer;
(2) a 30 000 m^2 (7.5 acres) greenhouse;
(3) a 12 million L/a ethanol plant;
(4) a 200 000 t/a alfalfa dehydration, cubing and pelletizing plant;
(5) an apple juice concentration plant; and
(6) an agricultural research facility.

In India, the RAPS II at Kota has been supplying 110 t/h of steam at 250°C temperature and 4 MPa pressure since 1980. The steam is reduced to 0.6 MPa and used in the nearby heavy water plant.

In Germany, the Stade NPP PWR, 1892 MW(th), 640 MW(e), has supplied steam for a salt refinery which is located at a distance of 1.5 km, since December 1983. The salt refinery requires 45 t/h process steam with 190°C at 1.05 MPa. This represents a thermal power of about 30 MW and is 1.6% of the thermal output of the NPP. Since 1983, the steam supply by NPP Stade has had very high availability, and the operating experience with process steam extraction is very good.

In Switzerland, the 970 MW(e) PWR of Gösgen has provided process steam for a nearby cardboard factory since 1979. The process steam (1.37 MPa, 220°C) is generated in a tertiary steam cycle by live steam from the PWR. It is then piped over a distance of 1750 m to the cardboard factory. After condensation, it returns as 100°C hot water to the PWR. A maximum process steam extraction of 22.2 kg/s is possible,

TABLE 5.VI. OPERATING NUCLEAR PROCESS HEAT PRODUCTION PLANTS

Country	Plant name	Location	Application	Start of operation reactors	Start of operation heat	Phase	Power (MW(e))	Heat delivery (MW(th))	Temperature (ºC) at interface (feed/return)	Remarks
Canada	Bruce-A[a]	Bruce	Process heat	1977–87	1981	Commercial	4 × 848	5350		D_2O production and six industrial heat customers
Germany	Stade	Stade	Electricity/ process heat	1983		Commercial	640	30	190/100	Salt refinery
Switzerland	Gösgen	Gösgen	Electricity/ process heat	1979	1979	Commercial	970	25	220/100	Cardboard factory
India	RAPS	Kota	Electricity/ process heat	1975/1980		Commercial	160	85	250	D_{2-}

[a] Unit 2 was taken out of service in 1995, units 1, 3 and 4 were to be taken out of service in spring 1998.

which represents a thermal output of about 54 MW or about 2% of the total thermal power of the PWR.

Information on the nuclear process heat production projects in China, Japan and the Russian Federation is summarized in Table 5.VII.

5.7. RELEVANT ISSUES OF NUCLEAR HEAT APPLICATIONS

Relevant issues based on nuclear heat application experience are:

- Positive experience has been gained in the use of nuclear heat for district heating and industrial process heat. The existing systems are economical and socially accepted.
- The technical and safety related experiences gained from nuclear district heating systems can be directly used for the development of nuclear desalination plants based on distillation processes.
- There are no major technical or safety problems with seawater desalination complexes using heat and/or electricity from nuclear power plants.
- To prevent radioactive contamination, one or more protective barriers are required between the nuclear plant heat transport circuit and the heat application grid circuit. The heat transport circuits must be monitored continuously, and adequate separation devices have to be incorporated in their design.
- If only a small fraction of the reactor power is used for nuclear heat applications, there is very little perturbation on the operation of the nuclear plant. However, if a major fraction of the reactor power is used for nuclear heat application, the effects of all transients anticipated in the application systems have to be considered in the design and safety assessment of the nuclear plant.

The following conditions are essential for future nuclear heat application systems:

- Public acceptance must be obtained and a nuclear infrastructure must be established.
- Access to technology and the cost of distribution grids must be considered in evaluations of the viability of nuclear heat applications.
- For a comprehensive comparative assessment of heat supply from a nuclear versus a fossil fuelled plant, the social costs related to the environmental impacts should be considered, including the emission of NO_x, SO_x and CO_2 from fossil power plants.

TABLE 5.VII. NUCLEAR PROCESS HEAT PRODUCTION PROJECTS

Country	Plant name	Location	Application	Start of operation reactors / heat	Phase	Heat delivery (MW(th))	Temperature (ºC) at interface (feed/return)	Remarks
China	HTGR-10	Beijing	Electricity/ process heat	Criticality 1999	Construction	10	700–950/25	Experiments for HTR technology development
	HTTR	O-arai	Process heat	Criticality 1998	Construction completed	30	950/395	Experiments for HTR technology development
Russia	VGM		Process heat		Design			

- Stringent safety precautions should be adopted for nuclear plants designed for district heating or seawater desalination since these plants would be built near populated areas to keep the cost of product distribution as low as possible.

PART II

SPECIAL ASPECTS AND CONSIDERATIONS RELEVANT TO THE INTRODUCTION OF NUCLEAR DESALINATION

Chapter 6

TECHNICAL ASPECTS

6.1. INTRODUCTION

The prospect of using nuclear energy for seawater desalination on a large scale remains very attractive since desalination is an energy intensive process that can utilize the low grade heat from a nuclear reactor and/or the electricity produced by such plants. It makes little difference to the desalination process how the energy is produced. However, the need to avoid radioactive contamination of the product water, and the need to co-ordinate the implementation and operation of major capital intensive power and water projects, are some of the important aspects that should be considered.

It is well known that nuclear reactors are most competitive for large electric plants if the conditions of low interest rates for capital and an available large national or regional power grid are both satisfied. Small and medium reactors, including heating reactors and barge mounted reactors that are suitable for dedicated desalination plant use, may be commercially available in the coming years and could be more attractive for regions with smaller grids. The availability, reliability, safety and security of nuclear fuel and the disposal of waste material are also important aspects requiring serious attention for the adoption of nuclear co-generation.

There are several technical aspects to be considered for selecting the nuclear desalination option as a means of solving the freshwater problem. Some of them have been identified in Part I. In this chapter, technical aspects specific for coupling nuclear reactors and desalination systems will be reviewed. Due consideration should be made of these aspects before decision making which should continue to be reviewed even after the decision has been made. These aspects are:

(1) Considerations for appropriate coupling,
(2) Technical protection against product water contamination, and
(3) Reliability and flexibility requirements.

These aspects primarily refer to land based nuclear desalination plants. However, some further technical considerations for floating nuclear desalination plants are also briefly outlined. Other specific aspects will be elaborated in later chapters in Part II, e.g., safety aspects (Chapter 7), economics (Chapter 8) and national requirements (Chapter 9).

6.2. DESIRABLE TECHNICAL FEATURES OF NUCLEAR DESALINATION PLANTS

It is a major challenge to select the optimum nuclear reactor and desalination plant technology. It requires an understanding of the processes, knowledge of the interaction effects and an approach to optimal integration. It should also take into account further improvements in both nuclear and desalination technologies.

6.2.1. Some aspects of decision making processes

Water and power supplies are both of prime importance for the economic development of a country on macro- and microscales. Commitment to produce a considerable part of both of these essential resources in one installation requires every possibility to be carefully reviewed and evaluated.

The most important aspect to be considered by the decision makers is obviously the amount of power and water needed in the particular region where a nuclear desalination/co-generation plant is to be built. The selection of nuclear and desalination plant types and sizes depends on these requirements, apart from the financial terms and conditions from the suppliers.

As discussed in Chapter 3, co-generation reactors of PWR, WWER and PHWR type, heating reactors and barge mounted reactors of appropriate sizes are known to be suitable for this purpose, and a number of new reactor types under development are likely to be available in the foreseeable future.

The selection of desalination plant partly depends on the type of reactor considered and the end use of product water, e.g. for drinking, industrial, commercial, etc., and hence the required quality of product water. Heating reactors are considered only for thermal desalination while co-generation reactors are suitable for both thermal and membrane desalination. Thermal desalination plants (MSF, MED) provide very pure water that is directly usable for process applications. RO plants provide drinking quality water as per WHO standards. For process water needs, a second stage will be necessary. A hybrid plant can provide for both needs.

Good specifications are not enough for designing the most appropriate plant. The contractor and the designer have to work together to achieve a thorough understanding of the local situation. If the national authorities have determined that a co-generation installation may advantageously satisfy the local power and water needs, they must first define the scope of a feasibility study to be undertaken including the main basic data necessary for a technical and economic evaluation. One of the most complex problems is the selection of the plant size. Initially the water and power demand must be determined at the moment when the installation can reasonably be expected to start up.

The schedule for completing a nuclear plant is around five to six years and for the desalination plant it may be two to three years [28]. This schedule may appear to be achievable for a highly industrialized country, but it is somewhat ambitious for a developing country. If a nuclear co-generation plant is contemplated, the water and power demands have to be established for a period of 10 to 20 years from the initial time.

6.2.2. Importance of power to water ratio in selecting co-generation plants

A number of large co-generation power and desalination plants using fossil fuels have been built in various parts of the world in recent years. Combined power and water production represents the largest use of the co-generation concept with over 25 000 MW(e) of installed capacity. Nuclear co-generation applications are a small fraction of this capacity. Only about 5 GW of thermal energy is currently reported to be used in nuclear co-generation applications for domestic and process heat supply and desalination. The demand for water versus power varies from country to country and also during seasons of the year. Therefore, the design of future plants requires a careful consideration of power to water ratio.

A review of large scale power desalting projects undertaken in recent years by Awerbuch [29] underlines the importance of the power/water ratio in selecting the appropriate technology (Table 6.I). The power to water ratio is defined as megawatt of power required per million gallons/day of fresh water produced. The values in the table are estimated with knowledge of the achievable GOR in desalination processes and the turbine efficiency in power plants. This information could be somewhat useful while considering the setting up of nuclear desalination plants.

The data in Table 6.I relate to a number of possibilities for energy utilization from the fossil fuelled power stations coupled to current commercial desalination processes. However, the power to water ratios roughly apply to nuclear co-generation/desalination plants because most coupling options are not unique to either fossil or nuclear. The steam utilization only need be considered therefore. This table gives a guideline for the selection of the nuclear reactor size for producing a selected amount of water for the different desalination processes and steam coupling arrangements. A backpressure steam coupling system requires half the power plant capacity compared to an extraction steam coupling system. An MSF plant would require 50% more power plant capacity than an MED desalination plant. Electrically driven desalination processes such as RO and VC clearly require minimum investment in the power plant. The desalination processes, however, should also be selected on the basis of the required water quantity and quality as well as on the basis of the available technology.

The optimum configuration for co-generation of power and water depends greatly on the power to water ratio at different periods of electricity and water

TABLE 6.I. TYPICAL POWER TO WATER RATIOS FOR DIFFERENT TECHNOLOGIES

Technology	Power to water ratio[a]
Steam turbine BTG-MED	3.5
Steam turbine BTG-MSF	5
Steam turbine EST-MED	7
Steam turbine EST-MSF	10
GT-HRSG-MED	6
GT-HRSG-MSF	8
Combined cycle BTG-MED	10
Combined cycle BTG-MSF	16
Combined cycle EST-MED	12
Combined cycle EST-MSF	19
RO	0.8–1.5
VC	1.4–1.6

[a] Power to water ratio = MW(e) required per 10^6 gal/d of water produced
BTG = backpressure turbine generator
EST = extraction steam turbine
GT = gas turbine
HRSG = heat recovery steam generator

demand. In winter, when the power demand is low and the water demand is continuously high, selection of a plant arrangement with a high power to water ratio will result in a significant amount of idle power. At the same time, electrically driven desalination technology can be an excellent choice for hybridization with more conventional co-generation plants. In this case the nuclear plants can be maintained on-line, and plants with high fuel cost can be taken off-line while maintaining constant water production. Also, a healthy mix of electrically driven desalination plants helps accommodate water demand fluctuations. The marginal cost of water would rise significantly if auxiliary boilers or bypass steam turbines had to be used by the pressure reducing station to keep the desalination plant at full capacity.

6.3. CONSIDERATIONS FOR COUPLING WITH NUCLEAR REACTORS

Various aspects of coupling nuclear co-generation and heating reactors with MSF, MED and hybrid desalination plants have been discussed in Chapter 5, particularly highlighting the safety considerations involving isolation loops/heat exchangers in the utilization of steam from nuclear reactors. This section primarily deals with basic modes of connecting the water plant with the power plant. The schemes depend on the requirements of water versus power at a particular location [28].

6.3.1. Backpressure and extraction schemes

Figures 6.1 and 6.2 show the backpressure and extraction schemes for a steam turbine. For a plant requiring higher power to water ratio, normally the backpressure scheme is recommended. On the other hand, the extraction scheme is preferred for satisfying low power to water requirements. In the backpressure scheme all the steam is expanded in the turbine to an elevated turbine backpressure depending on its design. Then low grade steam exiting the turbine is passed directly to the brine heater where it releases its latent heat of vaporization. The condensate is returned to the heat source. This scheme requires relatively low investment and has a good efficiency when operated at rated capacity. However, backpressure systems cannot vary their power to water ratio. In the case of coupling to MSF, the steam flow must remain relatively constant, and therefore the plant must be preferentially base loaded. Coupling to MED allows more flexible turndown ratios.

In the extraction scheme, the steam is expanded in a high pressure turbine to a selected pressure depending on the design. It is then distributed between two flows. In the first, it passes to the brine heater and in the second to a low pressure turbine where steam is expanded to a vacuum condenser. The extraction scheme enables the water plant to be permanently supplied with expanded steam, independently of power load.

The above two schemes can be considered to be based on the specific power and water requirements at a particular location in the country. Typical sizes of thermal power stations and the large size desalination plants set up in the Gulf States and in India in recent years are presented in Table 6.II. This gives a guideline that could be useful for nuclear co-generation plants, as well.

6.3.2. Other schemes

A nuclear desalination complex can be planned, designed and constructed as a single project. It can be also planned, designed and implemented as two schedule-wise separate projects. In the first approach, the nuclear system and the desalination system are planned and designed as a single package; hence, the total plant including the interface can be substantially optimized. This approach is both a straightforward and desirable procedure for design optimization and overall cost efficiency. However, there can be circumstances where a desalination plant can be planned and implemented after the nuclear plant is commissioned. In this second approach, some

TABLE 6.II. SOME RECENT LARGE SCALE DUAL PURPOSE PLANTS FOR DESALINATION AND ELECTRICITY

Location	Type of desalination plant		Desalination plant capacity (m^3/d)	Power plant capacity MW(e)	Year of operation
Jeddah (SWCC)[a]	SWRO	Phase I	56 800	924	1988
	SWRO	Phase II	56 800		1995
		MSF	227 100		1980
Yanbu-Medina[a]	Phase II	SWRO	128 000	150 (BTG)	1995
		MSF	144 000		1994
Al Khobar III[a]		MSF	280 000	475 (BTG)	1997
Shoiba II[a]		MSF	454 000	575 (BTG)	1997
Abu Dhabi[b]		MSF	273 000	732 (EST)	1996
Dubai[b]		MSF	273 000	450 (GT-CS)	—
Az Zour[c]		MSF	262 400	300 (EST)	1989
Jamnagar[d]		MED	48 000	350 (GT-CS)	1999

[a] Saudi Arabia
[b] UAE
[c] Kuwait
[d] India

BTG = backpressure turbine generator
EST = extraction steam turbine
GT-CS = gas turbine combined cycle

design modifications for coupling the desalination system to the existing nuclear plant would be required. The modifications depend on the interconnecting configuration. This approach may not be a best approach from the overall cost point of view, but it has some advantages such as short lead time for water production, lower investment requirement, higher potential participation of national industries, etc.

Some other types of schemes may be considered for obtaining steam from power plants for desalination as given below:

Low pressure steam can be supplied to a desalination plant from an existing low pressure turbine by operating at higher exhaust pressure, but in general this is limited to around 0.2 bar. The power loss is low in this case, resulting in low steam cost. However, the low steam pressure limits the top brine temperature, and thus a high GOR cannot be achieved.

The steam can be extracted from the crossover pipe to the low pressure turbine. This steam has a relatively high energy content compared to that required for low temperature heating purposes. This results in a higher relative power loss. On the other hand, a high GOR can be achieved in the desalination plant by incorporating a larger number of stages/effects subject to design limitations.

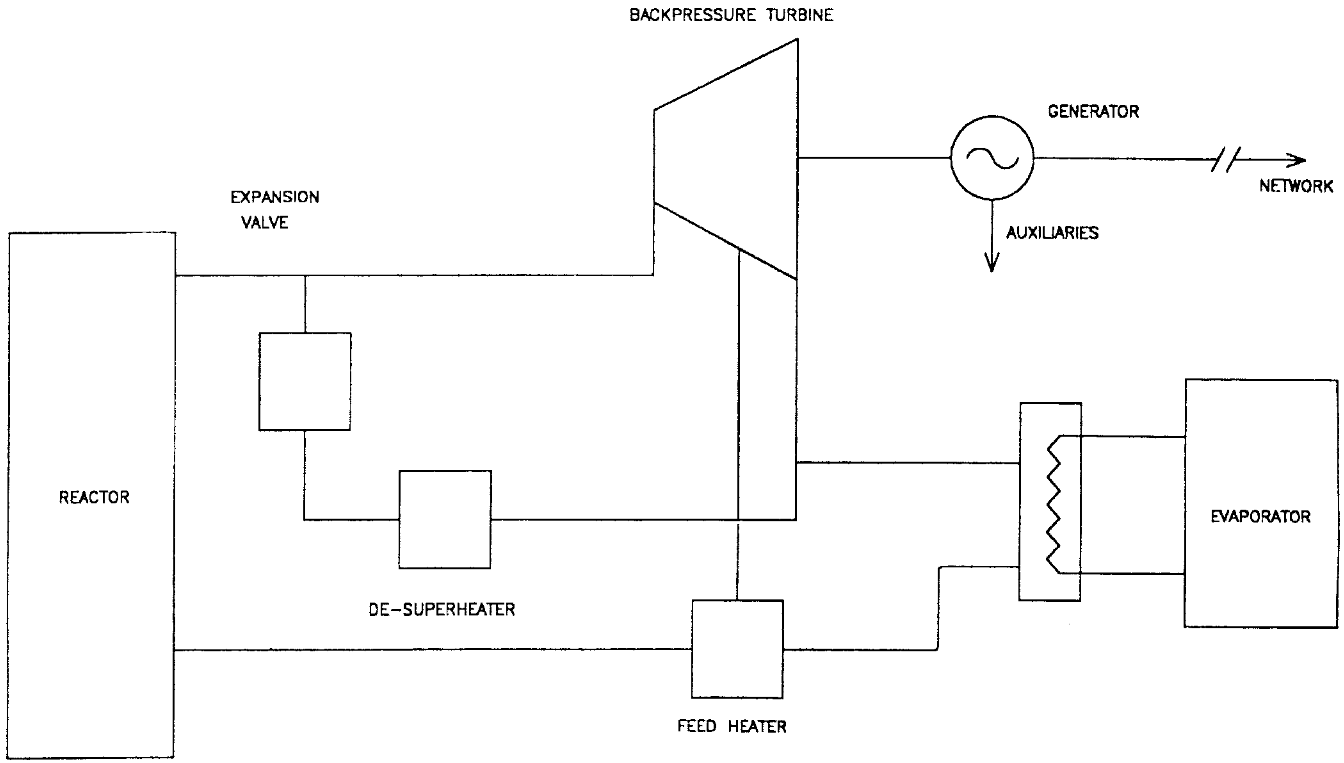

FIG. 6.1. Dual purpose plant backpressure cycle.

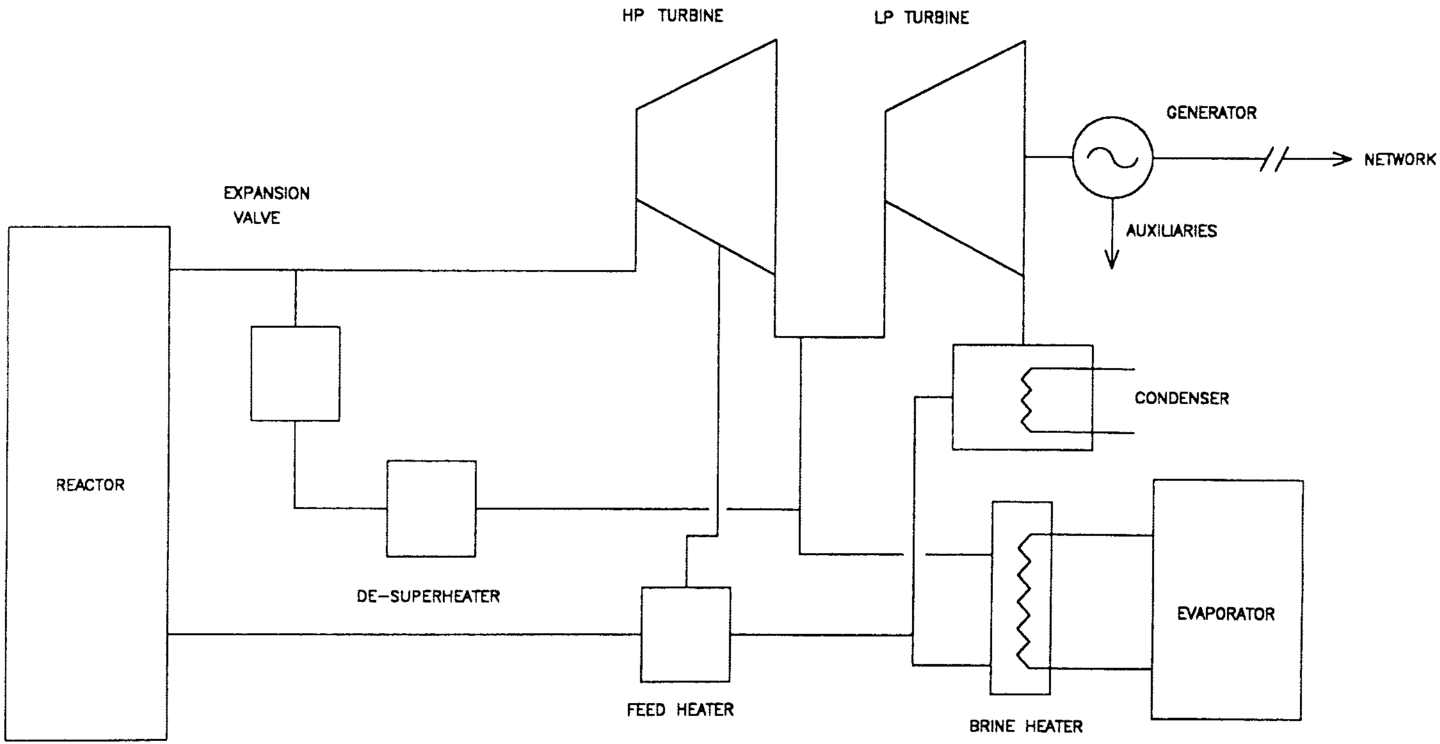

FIG. 6.2. Dual purpose plant extraction cycle.

Low pressure steam at the desired pressure could be taken from extraction ports of an extraction/condensing turbine. In this type of coupling arrangement, the full electrical output could come back on-line if the desalination plant is shut down. The turbine arrangement has a higher flexibility for the variable water production to power production ratio.

A backpressure turbine and a condensing turbine can be installed in parallel. The backpressure turbine steam exhaust at desired conditions would be coupled to the desalination plant. This arrangement enables the coupling of all types of thermal desalination plants with a nuclear power plant giving constant water output. However, it requires two different turbines leading to higher capital cost.

In nuclear desalination plants, the coupling of a nuclear reactor with a desalination plant has additional components that are not normally included in the scope of either the nuclear reactor or the desalination unit. The additional components to be considered are mainly the heat transport system and the backup heat source and heat sink systems. The heat is transported by brine recirculation, water circulation or steam. Each of these alternatives includes pumps, pipe and fittings (with valves, instruments, controls) and heat exchangers.

6.4. TECHNICAL PROTECTION MEASURES AGAINST PRODUCT WATER CONTAMINATION, INCLUDING MONITORING AND ISOLATION

When coupling a desalination plant with a nuclear plant, the risk of radioactive contamination of the product water must be kept as low as reasonably achievable. The desalination plant must produce water that meets well defined quality requirements as per end use. Design precautions must be taken to avoid product water contamination from radioactive materials during normal operation and accidents.

To achieve this, one or more protective barriers usually in the form of a leak-tight intermediate heat transfer loop are provided between the primary and desalination systems. The principle of pressure reversal is also used in which a higher pressure is maintained on the desalination plant side so that the direction of a potential leak is away from the desalination plant. The activity in the intermediate system and the desalination plant is continuously monitored. Condensate that is returned to the power plant from the desalination plant is also monitored for radioactivity. Apart from gross radioactivity, the presence of specific radioisotopes such as caesium, strontium, tritium etc. is monitored periodically.

When coupling an MSF plant with a nuclear power plant, the MSF brine heater serves as an additional barrier. Pressure reversal is achieved by maintaining the brine in the brine heater at a higher pressure than that of the heating media so that any potential leakage in the brine heater will be into the steam power cycle and not into the desalination plant. The control devices, which monitor the salinity of the steam power cycle, will signal the need to shut down the plant if a leak occurs. The combination of barriers and pressure reversal ensures that the probability of radioactive contamination is very low. Nevertheless, there should be protective instrumentation to monitor for radioactivity in an MSF plant, actuate systems to divert the effluents away from the main product streams and notify the operators to stop the process.

A more stringent provision is a ‘pressurized water isolation loop’ between the condenser of the backpressure turbine and the brine heater of the MSF plant. The pressure in this loop is kept lower than the brine pressure but higher than that of the backpressure steam. Thus, it acts as an additional barrier and an additional pressure reversal system.

The MED plants are coupled to a nuclear plant through open flash-loops. Backpressure turbine exhaust steam is condensed in the flash loop condensers. The latent heat is transferred to the saline water stream to heat it up by about 5^{o}C. A part of it flashes in the flash chamber, forming vapour for the first effect of the MED process. A part of the saline water is continuously drawn off as brine blowdown and condensate is pumped out as product water. Makeup saline water is added to maintain the salinity of the flashing brine.

For a contiguous RO system co-located with a nuclear power reactor, there is normally no risk of radioactive contamination reaching the desalination plant through the energy transfer connection. Even if the reactor is thermally coupled to the RO plant through the use of condenser cooling water as feedwater to the RO system, the physical interactions between the reactor and desalination plants are minimal. Since condenser cooling water is discharged from the nuclear plant before it is used in the desalination plant, there is little feedback from the desalination plant to the nuclear plant. In case of a hybrid desalination plant, the reject cooling sea water from MSF/MED can be used as feed for RO plant, thus having a rather loose coupling compared to a contiguous preheat RO plant.

When multiple nuclear desalination units produce potable water, the leakage of radioactivity from one of the units may contaminate the entire water inventory. Additional design precautions should be taken and implemented so that any accidental radioactivity release in one unit does not contaminate the water produced by the others.

6.5. RELIABILITY AND FLEXIBILITY REQUIREMENTS

6.5.1. Reliability, availability and quality assurance

The fact that potable water is essential to sustain life and health and to provide human comfort mandates that a reliable supply be assured under all conceivable conditions. Assurance of a reliable supply also applies to industrial use because, without water, production would come to a standstill. No industrial installation, whether desalination or power plant, can have 100% availability and reliability. There are always planned as well as unplanned outages. Therefore, alternate measures must be taken to provide for at least a minimum uninterrupted water supply at all times.

The availability requirements for a nuclear desalination plant must be established during the design stage. These requirements may be met by a number of strategies. Provision for sufficient water storage capacity and redundancy in both desalination units (trains) and energy sources are the measures that can be included in the design stage of the desalination plant. Adequate reliability can be ensured by designing, fabricating and testing all equipment as per applicable codes and standards and providing necessary instrumentation to monitor and maintain the operating parameters.

The availability of a nuclear desalination plant can be high for a contiguous RO or VC plant coupled to nuclear power plant using only electricity because the coupling has little influence on the operation of either the nuclear plant or the desalination plant. On the other hand, the overall availability of a thermal desalination plant coupled to a nuclear power plant can be high only if the coupling has a high availability factor.

To maintain high availability, it is recommended that the integrated plant be designed and coupled in such a way that the power and water plants can be disconnected from each other whenever it is necessary to continue the operation of either plant alone. The means for producing good quality water should also be considered in the design stage for the case when the nuclear reactor is not in operation but water must be produced. The design can incorporate diesel generators or gas turbines for the supply of power and heat in such cases. If two or more nuclear power sources are available at the site, both of them may be connected to the desalination plant in such a way that the plant receives heat from one nuclear unit while the other serves in standby. Design measures to enable switching between these two units should not be complicated. High availability can also be achieved by using an auxiliary boiler during shutdown of single nuclear reactor used for steam source.

A hybrid desalination plant, incorporating more than one desalination processes, such as MSF-RO, MED-RO, etc., coupled to a nuclear power plant can, in general, give a high availability factor. The electrically coupled RO or VC plant continues to produce water using grid power even when the thermal desalination plant is not working because of non-availability of steam from the nuclear power plant or for any other reason. However, the quality of product water from the plant is not the same. On the other hand, the thermal desalination plant can continue to work when RO is not on-line, if steam is available. The hybrid system can be an economical configuration with high availability if there is a definite demand for two types of water, very low TDS water for industrial process use and moderate TDS water for domestic use.

Other measures, which may enhance both availability and safety to a considerable extent, include providing a diesel generator (DG) set of suitable capacity for emergency lighting and operation of important motors/equipment. Electric power cables should be suitably designed and laid. To comply with safety standards, instrument cables and safety related cables should be laid separately and physically isolated from the power cables. Communication systems should include telephones, intercoms, cordless systems and a public address system to permit co-ordination between operators and supervisors during startup, shutdown and emergencies.

Reliability also includes assurance that the product water meets the quality requirements. The final product water quality should be assessed by on-line conductivity measurements and batch analysis. Safety features such as high/low alarms for process parameters, on-line process monitoring and controls, event sequence recording, etc. should be incorporated for reliability. For batch analysis, a self-contained chemical control laboratory should be established, with conductivity and pH measuring instruments for calibration of on-line instruments. Other laboratory instruments may include oxygen analysers, flame photometers and spectrophotometers for carrying out detailed chemical analyses. Chemical analysis of the product water along with the necessary certification from a competent authority may be required for releasing desalinated water for public consumption.

6.5.2. Flexibility

The power-to-water product ratio in a nuclear desalination plant may change with daily and seasonal demand variations. Appropriate design measures must be incorporated to accommodate these fluctuations in the plant. The flexibility of a co-generation plant can be defined as its ability to vary its output of water and power according to the demand for each. In a nuclear co-generation plant, the reactor and generator can be operated at varying load without much difficulty. However, the operational flexibility of a thermal desalination plant has been very limited in practice. The optimization of co-generation plant design would benefit from a better knowledge of both the capability of water plants for flexible operation and the economic effect of such operation on the water cost.

The present day distillation plants based on MSF and MED can operate with some degree of load flexibility known as the ‘turndown ratio’. For MSF plants it is around 110–70% of nominal capacity, while for MED plants a turndown ratio of 120–45% is possible. At a co-generating nuclear plant, it is not difficult to design the NSSS to meet these steam flow variation requirements if the amount of steam to the desalination plant is a small fraction of the total steam generated.

6.5.3. Transients

The design of a co-generation plant must provide a certain degree of flexibility to accommodate variations in operating parameters and to avoid breakdown of the production units in case of transients. Anticipated transients most often occur during startup and shutdown of the desalination plant. The procedures for startup and shutdown are more or less standardized for desalination plants. Some variation may exist due to auxiliaries which are rarely similar for any two plants, and the preferences of the operator also matter. There can also be some differences between the design and actual operating parameters. The steady state values can vary because they depend on the ambient temperature, seawater temperature, steam temperature and pressure including production rate desired, operating experience, etc. The variations in plant parameters from normal or design operating values should be dealt with on an individual component basis. Parameter variations, anticipated transients and upsets should be identified and considered in the design stage.

The unanticipated transients, such as malfunctioning of the rotating equipment including pumps and control valves, vacuum problems and steam supply variations etc., should be analysed case by case on the basis of local conditions. The results of this analysis should be reflected in the design and operational procedures. However, certain conditions can arise which may require emergency measures. The primary causes may be due to pump trip, power failure or lack of steam supply. A decrease in steam extraction pressure (at constant steam flow rate) will result in a transient reduction in desalination plant performance because the maximum brine temperature cannot be maintained.

In case of thermal desalination plants, a certain flexibility in accommodating these transients is achieved by arranging a steam bypass around the turbine with a pressure regulating valve and a desuperheater. The bypass valve is opened when the steam flow to the desalination plant is not sufficient for stable operation. In case of a sudden large reduction of steam flow rate, some of the parallel trains of the thermal desalination plant may also have to be switched off to continue stable operation.

6.5.4. Design basis events

The design of nuclear desalination plant should include protective measures against any extreme external events. The extreme external events include both natural external events and artificially induced external events. Natural external events are disastrous natural phenomena such as tornadoes, earthquakes, surges, floods etc. External artificial events are disastrous events produced by activities such as air crashes, chemical explosions etc. It is very difficult to evaluate these events in terms of design basis events. The knowledge and experience of experts must be taken into consideration. They require considerable expertise and engineering judgement.

It is essential to collect historical data on the severity of the external events and compare the selected design basis values with the historical data for correct evaluation. A practical approach to the problem is to evaluate two levels of severity corresponding to the expected events and the design limit events. The expected events are those events that are expected to occur at least once during the lifetime of the plant. They are also called ‘operating events’, and the plant is usually designed to withstand them and continue operation, e.g. the operating earthquake or the operating wind load. The design limit events represent either the physical limits of the phenomena or events of very low probability. The plant must be designed to withstand these events without large radioactive releases. For expected events, the plant structures, systems and components must remain operational, and normally allowed stresses should not be exceeded. For the design limit events, the structures, systems and components should perform only the intended safety function, and limiting stresses for extreme conditions should not be exceeded.

6.6. FLOATING NUCLEAR DESALINATION PLANTS

The design concept of a barge mounted floating nuclear desalination plant has been put forward as a possible option for coastal regions with small and medium range freshwater demands. This concept, which was derived from ship propulsion reactor experience, pursues the objective of complete in-shop fabrication of the nuclear desalination plant with subsequent transport to the site in an operation ready state. The design and operating experience gained from ship propulsion reactors is highly applicable to barge mounted nuclear desalination plants. The operating conditions for such plants, which typically would be located in natural or artificial lagoons, are less demanding than for nuclear vessels such as icebreakers. This creates confidence that the operation, reliability and safety characteristics of any floating nuclear desalination facility are more favourable.

There are three principal concepts for the arrangement of floating nuclear desalination plants:

- both the nuclear power plant and desalination plant are mounted on one barge,
- the nuclear power plant and desalination plant are mounted on different barges,
- the nuclear power plant is barge mounted and the desalination plant is based on coast land.

Each arrangement has certain advantages and disadvantages and should be evaluated with respect to the required water production capacity, desalination processes applied, site conditions, local participation requirements, etc.

The design and safety considerations of a floating nuclear desalination plant are different from those of a land based nuclear desalination plant [30]. The effect of roll and pitch has an influence on the design of process equipment. It may adversely affect the performance of heat exchangers or lead to cavitation problems in the pumps. Reliable operation must be ensured for static fluctuation on either side up to 15°, dynamic inclinations (rolling) at an amplitude of 45° and period of 7 to 14 s on a case to case basis.

A floating nuclear desalination plant operates in a very corrosive environment and with various external events that may differ from those for a land based installation. Space is one of the major constraints, hence the plant is designed for compactness. It should be lightweight and reliable. Other considerations accounted for in the design are easy dismantling, quick repair and assembly. Design measures should ensure complete removal of condensate/product water from the equipment even when inclined to either side.

Another inherent requirement for successfully implementing a floating plant is the availability of support services over the plant lifetime. These must be provided either by a central dispatch service for several plants or by the individual plant owner/operators.

6.7. COMPARISON OF FOSSIL AND NUCLEAR DESALINATION

One of the important differences between nuclear and conventional land based heat sources is the economics in the energy cost breakdown. As a rule, conventional boilers have low capital and high operating costs, and nuclear reactors have high capital and low operating costs. As a result, nuclear reactors benefit more than conventional boilers from increases in capacity, reductions in fixed charge rate and from a high load factor. The marginal operating cost of nuclear reactors is lower, justifying their being kept base loaded for a longer period than boilers. The nuclear fuel cost is lower; hence, a lower overall reactor efficiency is acceptable. With technical development and an increase in the capacity of the fuel industry, the nuclear fuel cycle cost should decrease during the life of a reactor.

It may also be noted that very often the major part of conventional fuel costs relates to their transportation. In the case of nuclear fuel, transportation is a small part of the fuel cycle cost, so that the cost of nuclear energy does not vary greatly according to the geographical location of reactors. Nuclear reactors reject no pollutants to the atmosphere, and this may be especially important in overindustrialized regions or recreational areas as well as for the countries listed in Annex A of the Kyoto protocol.

The main disadvantage of nuclear reactors is that they are competitive only when the base load is sufficiently high, and this precludes their utilization in many developing areas. Even in areas where fossil fuel costs are high, the economic minimum capacity of reactors is of the order of several hundred thermal megawatts. Another disadvantage is that the coupling of an evaporative desalination plant with a nuclear plant is more complex compared to coupling with a fossil fuelled plant. In a fossil plant, the required heat can be taken directly from the backpressure or extraction turbine to the MSF or MED plant.

The linking of a turbine generator and a water plant to the same heat source permits a larger steam capacity. This is of great benefit to nuclear reactors. The lower grade of steam from a nuclear heat source requires more steam to be passed through the turbine per kW·h(e). For the same power to water ratio, the steam temperature at the turbine outlet is lower for a nuclear installation, thus permitting a less expensive water plant. Nuclear power-only plants have lower thermal efficiencies, and more heat has to be rejected in the condenser.

Chapter 7

SAFETY AND ENVIRONMENTAL CONSIDERATIONS

7.1. INTRODUCTION

Desalination is a commercially mature technology and is extensively used in several parts of the world. The use of a nuclear power plant as an energy source for desalination plants has not been extensively exploited although it has been used on a limited scale. The safety, regulatory and environmental issues that must be addressed in the design, construction and operation of a nuclear desalination plant are primarily those related to the nuclear power plant itself. Nevertheless, some specific concerns related to the coupling between the power plant and the desalination plant must be taken into account.

Public acceptance and economic viability of nuclear desalination depend on the achievement of a high level of safety and environmental protection. The consequences of the Three Mile Island (TMI, 1979) and Chernobyl (1986) accidents have emphasized the need for evolving common safety principles for all types of nuclear installation. Nuclear power production results in the generation of significant quantities of radionuclides in the reactor core, and protection against radiation emitted from these radionuclides has been the focus of extensive study over a span of more than five decades. The achievement of an impressive safety record in the nuclear industry has been due to design innovations, quality assurance and human expertise, which are required to a lesser degree in fossil fuelled power plants.

The development and publication of standards, requirements and design guidelines for the safety of nuclear power plants is one of the activities of the IAEA. These documents are published as the Safety Standard Series (SSS) [31]. The SSS embodies an international consensus on objectives, concepts, principles, logic, methods and facts which are necessary to promote a common approach to ensuring safety in peaceful applications of nuclear energy. The SSS is written for use by organizations designing, manufacturing, constructing and operating nuclear power plants as well as by regulatory bodies. The SSS is organized into a hierarchy of three categories including:

- ***Safety Fundamentals:*** The Safety Fundamentals category is the primary category in the hierarchy. Publications in this category present basic objectives, concepts and principles to ensure safety in the development and application of nuclear energy for peaceful purposes.

- ***Safety Requirements:*** Publications in the Safety Requirements category specify basic requirements that must be satisfied to ensure safety for particular activities or application areas. These requirements are governed by the basic objectives, concepts and principles that are presented in the Safety Fundamentals. Requirements are expressed with 'shall' statements. Recommendations are expressed with 'should' statements.
- ***Safety Guides:*** Publications in the Safety Guides category supplement Safety Requirements by presenting recommendations, on the basis of international experience, of measures to ensure the observance of safety standards. 'Safety measure' means any action that might be taken, condition that might be applied, or procedure that might be followed to fulfil the basic requirement of Safety Requirements. Safety measures must be effective as a means of ensuring the observance of applicable safety standards.

The Safety Fundamentals "The Safety of Nuclear Installations (SS No. 110)" established three safety objectives for nuclear power plants. The first is very general in nature. The other two are complementary objectives that interpret the general objective, dealing with radiation protection and the technical aspects of safety, respectively. These objectives are:

- ***General safety objective:*** To protect individuals, society and the environment from harm by establishing and maintaining in nuclear installations effective defences against radiological hazards.
- ***Radiation protection objective:*** To ensure that, in all operational states, radiation exposure within the installation or due to any planned release of radioactive material from the installation is kept below prescribed limits and as low as reasonably achievable, and to ensure mitigation of the radiological consequences of any accidents.
- ***Technical safety objective:*** To take all reasonably practicable measures to prevent accidents in nuclear installations and to mitigate their consequences should they occur; to ensure with a high level of confidence that, for all possible accidents taken into account in the design of the installation, including those of very low probability, any radiological consequences would be minor and below prescribed limits; and to ensure that the likelihood of accidents with serious radiological consequences is extremely low.

Finally, in the implementation of these objectives, a defence in depth principle has been established:

- ***Defence in depth:*** To compensate for potential human and mechanical failures, a defence in depth concept is implemented, centred on several levels of protection including successive barriers for preventing the release of radioactive material to the environment. The concept includes protection of the barriers by averting damage to the plant and to the barriers themselves. It includes further measures to protect the public and the environment from harm in case these barriers are not fully effective.

7.2. RADIATION HAZARDS FROM NUCLEAR DESALINATION SYSTEMS

As for all nuclear plants, the safety concern with a nuclear desalination plant arises from the potential for the accidental release of radioactivity to the environment. A particular concern unique to nuclear desalination plants is the potential for release of radioactive materials into the product water as well as the environment with its consequent short and long term effects on the biosphere, especially on human health.

7.2.1. Radiation hazards under normal operation

During the normal operation of nuclear desalination plants, the possible sources of human exposure to radiation are:

- Exposure to the public due to radioactivity released in gaseous and liquid effluents including the product water, and
- exposure to plant personnel during operation, maintenance and trouble-shooting.

In a nuclear reactor, the sources of the radiological hazard are the fission products originating in the fuel and activated corrosion products originating in the primary coolant and moderator systems. Most fission product radioactivity remains in the fuel elements, although a small fraction can leak into the coolant and moderator through defects in fuel cladding. The existing radioactive waste management practices effectively remove fission and corrosion product radioactivity from coolant and moderator circuits. However, a very small part of it may eventually be released into the environment during normal operation. Experience has shown that the additional exposure from such radioactive releases to the public living in the vicinity of nuclear power plants is negligible and much smaller than the exposure from the natural background radiation.

Any potential detriment to human health that may arise from nuclear power generation (and hence nuclear desalination) is mainly due to abnormal occupational exposure of power plant personnel to radiation from fission and activation products. This can be avoided by effective implementation, at the design stage, of the ALARA (‘as low as reasonably achievable’) principle and by efficient monitoring and management control during operation. With adequate design provisions and an effective monitoring programme, the average annual radiation dose to the operating staff can be kept to within a few per cent of the annual exposure dose limit recommended by the International Commission of Radiological Protection (ICRP) for occupational exposure.

In a nuclear desalination plant it is also necessary to prevent transport of radioactivity into the product water. This can be effectively accomplished by suitable design features which make use of multiple barriers and pressure differentials to block transport of radioactive materials to the desalination plant, and with appropriate monitoring before distribution of the product water.

7.2.2. Radiation hazards from nuclear power plant accidents

The record of safety and environmental protection in the operation of nuclear power plants is outstanding. This is because, in accordance with the defence in depth principle, the nuclear plant uses highly reliable safety systems in conjunction with a series of multiple barriers designed to prevent radioactivity from reaching the environment and the public in the event of an accident. With the exception of the Chernobyl case, the various transients that could have led to serious nuclear accidents in commercial nuclear plants to date have shown that these safety systems and design features have performed their function and provided the required level of protection against the release of radioactive materials.

The plant should include a system capable of preventing water distribution, for example by means of isolation, if the level of radioactivity in the product water exceeds the pre-established level. There are continuing efforts to advance reactor technology and improve reactor safety even during severe accidents.

7.3. SAFETY ISSUES IN NUCLEAR DESALINATION

Approach to safety

Both public acceptance and the economic viability of nuclear desalination depend on the achievement of a high level of safety and environmental protection. As for all nuclear plants, the approach to safety in nuclear desalination is essentially a continuous quest for excellence in reducing the radiation risks to the public to the lowest practical level and is based on understanding the objectives and principles of safety. It consists of formulating adequate objectives and implementing reliable measures, consistent with the defence in depth principle, to protect individuals, society and the environment from radiological hazards. This ensures that in all normal operation and accident situations, radiation exposure within the plant and to the environment is kept below prescribed limits.

Safety principles for accident prevention, protection and mitigation

As was discussed in Section 7.1, the safety principles for accident prevention in a nuclear plant underscore the need to take practicable measures to prevent nuclear related accidents and to limit their potential consequences. All possible accidental situations including those with even a very low probability are taken into account during the plant design process. This approach is taken to ensure a high level of confidence that the likelihood of a serious accident is extremely low and that the radiological consequences of such an accident would be minor and within prescribed limits.

The safety of nuclear desalination plants depends on the safety of the nuclear plant and the nature of its coupling to the desalination system. The extent of interaction between the nuclear plant and the desalination system must be taken into account in determining the safety of the nuclear desalination system.

7.3.1. Nuclear reactor safety

7.3.1.1. Radioactive material inventory

The operation of nuclear power plants results in the formation of radioactive materials within the reactor system from the fission process in the fuel. Another source of radioactivity is the corrosion products such as chromium, cobalt and manganese and impurities in the coolant that become activated by neutron absorption. These quantities are small compared to fission products. In addition, neutron absorption by boron, commonly used for control of the fission process in PWRs, and by deuterium in heavy water cooled reactors leads to the formation of tritium. Radioisotopes of nitrogen, carbon and argon are also formed.

The potential release of these radionuclides must be taken into account during normal operation and accident situations. The specific inventory of radionuclides that must be considered during an accident will depend on both the nature of operation before the accident and the postulated accident scenario. Provisions must be included in the design to allow for monitoring and detection of radioactive materials that might be carried over from the reactor plant to the desalination plant and subsequently into the product water stream. Provisions may be required for the storage of product water until radionuclide levels are within allowed limits.

7.3.1.2. Accident types

More than 99.9% of the radioactivity generated by the fission process in a nuclear plant remains in the fuel as long as it is adequately cooled. The balance remains within the circulating coolant as long as the primary system is not breached. A major accidental release of radioactivity from the fuel could take place only in the eventuality of severe damage to the fuel and its cladding. The main types of nuclear power plant accidents that could potentially lead to such a release have been identified and accounted for in the design. A containment system is generally provided as the final barrier to avoid the release of radionuclides into the environment.

The nuclear fuel is a heat source and overheating of the fuel occurs only if the heat being generated in the fuel exceeds the rate at which it is being removed. This type of heat imbalance in the reactor fuel core can occur by loss of coolant or by transient events with inadequate loss of heat removal.

- ***Loss of coolant:*** The occurrence of loss of coolant in the reactor core could cause the fuel to overheat and eventually lead to core melting unless emergency cooling is supplied to the core. This type of accident is known as a loss of coolant accident (LOCA). Loss of coolant supply may arise due to a number of factors such as failure of pumps, rupture of coolant system etc.

- ***Transients:*** Overheating of the fuel can result from transient events, in which the reactor power increases beyond the heat removal capacity of the reactor coolant system. Alternatively, transient events may involve reduction of the heat removal capacity of the reactor coolant system below the core heat generation rate. All such transient events, which could occur alone or in combination, must be considered in the safety analysis. The principal areas of interest are increases in reactor core power and decreases in coolant flow.

7.3.1.3. Safety design features: implementation of defence in depth

The safety objectives for the nuclear power plant are to prevent accidents, to ensure their management and to mitigate their potential consequences. There are two aspects to implementation of defence in depth. One is to provide barriers that would have to be successively breached for radioactive material to escape outside the plant. The other is to prevent the barriers from being breached.

As stressed, the first aspect of defence in depth in the design is the provision of a series of physical barriers to confine the radioactive material at specified locations. The number of physical barriers required is a function of the potential internal and external hazards, and of the consequences of failures. Typically, during power operation, the barriers enclosing the fission products in water reactors are:

- The fuel matrix (first barrier)
- The fuel cladding (second barrier)
- The reactor coolant boundary circuit (third barrier)
- The containment or other housing structure (fourth barrier).

Slightly different configurations may be found in other reactor concepts (e.g. gas cooled reactors).

The integrity of these barriers is ensured by conservative design margins and by high quality in manufacture, inspection and maintenance. In the case of failure of one or more of these passive barriers, active engineered safety systems such as emergency core cooling, emergency coolant supply and containment sprays and filters are provided to ensure the integrity of the remaining barriers.

As mentioned above, the second aspect of the defence in depth strategy is to prevent the barriers from being breached. This is accomplished by the design of the plant operational systems. It is related to the way the plant is operated and to its time response under accident conditions. It consists of five levels of defence:

- The aim of the first level of defence is to prevent deviation from normal operation and to prevent system failures. This requires that the plant be soundly and conservatively designed, constructed, maintained and operated in accordance with appropriate quality levels and engineering practices, such as the use of redundancy, independence and diversity. To meet this objective, careful attention is paid to the selection of appropriate design codes and materials, and to the control of fabrication of components and of plant construction.
- The aim of the second level is to detect and intercept deviations from normal operating conditions in order to prevent anticipated operational occurrences from escalating into accident conditions. This level requires the provision of specific systems identified in the safety analysis and the definition of operating procedures to prevent or minimize damage from such postulated initiating events (PIEs).
- For the third level it is assumed that, although very unlikely, the escalation of certain anticipated operational occurrences or PIEs may not be arrested by the systems intended to do so, and a more serious event may develop. These unlikely events are addressed by the design basis accidents for the plant, and inherent safety features, fail–safe design, additional equipment and procedures are provided to control their consequences and to achieve stable and acceptable conditions following such accidents. This requires engineered safety features to be provided which are capable of leading the plant first to a controlled state and subsequently to a safe shutdown state, and maintaining or

restoring rapidly at least one barrier for the confinement of radioactive material. This may also include the application of accident management procedures.

- The aim of the fourth level is to address severe accidents in which the design basis may have been exceeded and to ensure that radioactive releases are kept as low as practicable. The most important objective of this level is the protection of the confinement function. This may be achieved by the application of best estimate approaches, complementary measures and procedures to prevent accident progression, and mitigation of the consequences of severe accidents, in addition to accident management procedures.
- The fifth, or final, level is aimed at mitigation of the radiological consequences of potential releases of radioactive materials that may result from accident conditions. This requires the provision of plans for the on-site and off-site emergency response.

7.3.1.4. Safety assessment

The objective of the safety assessment is to determine whether the nuclear power plant design has met the defined safety objectives and requirements. This assessment is carried out during the design process and is independently verified before granting of a license to operate. The safety analysis that is the most relevant part of the safety assessment takes into account various assumed postulated initiating events and the consequent events including operator actions that might arise during operation. A detailed quantitative analysis of the reactor and fuel behaviour during the sequence of events following the postulated initiating event is also included. The safety systems are assessed to develop the required confidence in the plant's ability to cope with a wide range of failure scenarios.

7.3.1.5. Safety implementation at different stages of a reactor project

Safety implementation at each stage of a nuclear reactor project is very important. Safety implementation is a managerial function and must be incorporated as an integral part of all activities of the project.

During the early project stage, the safety related activities are site survey and bid evaluation, including preliminary safety analysis. The process of siting studies involves site survey phase and site evaluation. During the site survey phase, suitable land areas are systematically investigated to identify the most suitable location with respect to geological faults, flooding, etc. During site evaluation, measurements and investigations are performed on the site and a final evaluation of the design basis is made. Geology, seismology, hydrology, meteorology, population distribution and artificial events are analysed with respect to the site.

During bid evaluation, a preliminary safety review is made with respect to the engineering and safety codes and criteria to be used for the plant design, including the capability and reliability of engineered safety features.

The reactor design stage involves conceptual, basic and final detailed design. The findings of the site characteristics form an important part of the design basis. All decisions relating to the safety of the design are carried out during this period. The ultimate safety of the reactor itself, the adequacy of its containment, engineered safety features and other structures are decided upon. It is essential that considerations of safety be given a vital role at this stage of a reactor project.

During the construction stage, it is necessary to ensure that the plant is constructed in accordance with the design. The execution of a good reactor design, if not properly carried out, can nullify the safety features. A rigorous quality assurance programme, inspection and testing methodologies have to be instituted and maintained at all times.

The operating organization has full responsibility for the safe operation of the nuclear power plant. Before commencement of reactor operation, emergency preparedness plans should be demonstrated. Operation of the plant is to be in accordance with licensing constraints to limit the operation to plant conditions shown to be safe. Maintenance must be in accordance with a written programme prepared in advance. A radiological programme must be developed for the protection of site personnel, the public and the environment. This includes management and control of radioactive waste.

7.3.2. Reactor safety considerations introduced by the addition of a desalination plant

The overall safety of an integrated nuclear desalination plant complex is mainly dependent on the safety of the nuclear reactor, the design impact of coupling the reactor plant to the desalination plant, and the transient interactions between the two. This interaction should be assessed under various coupling situations to determine its effect on the safety of the reactor and desalination systems, both in normal operation and accident situations. The safety issues related to the mutual interactions between the nuclear power plant and the desalination plant must be assessed as a part of the design of the integrated nuclear desalination system. It is of vital importance that the design, operation and performance of a nuclear desalination plant be such as to ensure the safety of the nuclear reactor and protection of the product water against radioactive contamination. Specific safety related considerations pertinent to nuclear desalination plants include the following.

7.3.2.1. Coupling considerations

In coupling a nuclear plant with a distillation process, such as MSF or MED, there is a direct transfer of thermal energy and hence a direct interaction between the power plant and the desalination plant. Operational transients in either the nuclear plant or the desalination plant could have a direct effect on the operation of the other system. Such transients could have safety implications, with need to be assessed. In the case of a nuclear co-generation plant for electricity and heat production, the thermal coupling could require additional considerations. The turbines in a dual purpose plant have to satisfy the requirements of both systems simultaneously. The power plant is the heat source for the desalination plant, and the desalination plant is the heat sink for the power plant. In this arrangement, the safety implications of balancing the operational and control needs of both plants must be assessed.

If thermal desalination plants are supplied steam directly or indirectly from a backpressure turbine, failures in the desalination plant can force shutdown of the power plant. In these cases, it is desirable to provide an alternate heat sink. Likewise, if desalted water is utilized in the nuclear plant for process make-up, a desalination plant malfunction directly affects the operational needs of the nuclear plant. Water storage or an alternate source of make-up must be provided.

If a contiguous (co-located) desalination plant uses an electrically driven process such as RO or VC, the desalination system may draw its electrical energy either from the grid or by direct connection to the nuclear plant with an auxiliary connection to the grid. In this case, there is only a very weak interaction between the reactor and the desalination plant. Shutdown of either power plant or desalination plant need not interrupt the functioning of the other unit, unless the desalination plant represents a large fraction of the load on the power plant. In this case the effect of a sudden shutdown of the desalination plant is not expected to be a serious concern, because a complete ‘loss of load’ is one of the accident scenarios that is normally to be evaluated in the safety analysis and provided for in the nuclear plant design.

If the RO desalination plant draws part or all of its feedwater from the condenser cooling water discharge of the nuclear plant, as in the RO preheat configuration, there is a ‘weak’ thermal coupling between the nuclear plant and the desalination plant. The possibility of interaction effects between the nuclear plant and the desalination plant are likely to be minimal in this case. This type of coupling should pose little or no safety concern for the nuclear plant or desalination plant.

7.3.2.2. Quality of product water

In thermal processes, the heat energy is mainly supplied in the form of low temperature steam or hot water. Coupling is accomplished via a heat transfer circuit between the nuclear and desalination plants. Since radioactivity can potentially exist in the nuclear plant's steam or hot water systems, there is some risk of radioactive contamination carry-over, which must be prevented. This can be accomplished by adding intermediate heat transport loops, using pressure reversal, monitoring and other methods as described in Chapter 4. Scenarios involving failure mechanisms in materials, systems or components, which could lead to carry-over of radioactive contamination to the product water, should be determined and provisions necessary to avoid such contamination must be assessed and implemented. The frequency and consequences of these scenarios need to be considered in the safety assessment for the integrated nuclear desalination plant.

Contiguous electrically driven desalination processes such as RO or VC, which use the nuclear plant's condenser cooling water for preheated feed, have a less direct coupling interaction and thus have a lesser safety concern with respect to product water quality. The possibility of radioactivity carry-over into preheated feed, while unlikely under condenser vacuum conditions, must nevertheless be evaluated.

7.3.2.3. Discharged water considerations

The limits for discharge of radioactivity to the environment are normally specified by national regulatory bodies and are often based on internationally agreed values. Brine discharges, cooling water discharges and product water must be evaluated in this respect. The specification is worked out for each location of the nuclear plant taking into account the food chain of the local population, the site conditions, etc. The annual limit of intake (ALI) values for each radionuclide is determined, and these form the guidelines for assessment of discharge levels from the nuclear desalination plant.

Discharge limits for a nuclear plant are normally based on open discharge into the sea, allowing for high levels of dilution before reaching the human population. The integrated nuclear desalination system poses an additional burden on the radiological assessment, and on the formulation of acceptable product water specifications, particularly with respect to product water radioactivity levels, since the potable water may be used directly by humans without dilution.

The product water may have different uses, such as process water or drinking water. The required product water quality may differ depending upon the end use. With reference to allowable total dissolved solids and composition, the information is well documented. The radiological contamination allowable in the product water may depend upon the usage of the water. The total exposure to an individual can be determined from a knowledge of the radionuclide concentration in the drinking water by carrying out a complete pathways analysis considering all possible routes by which the desalted water might eventually lead to a radiological impact on the individual.

Finally, care must be taken in the design of the intake and outfall structures for a nuclear desalination plant to ensure that water discharged from the plant cannot be circulated by local water currents back to the location of the intake structure. While this is an important consideration for nuclear power plants, it is particularly important for nuclear desalination plants. Discharge water from the nuclear plant, possibly containing radionuclides, must not be drawn back in to the intake structure and subsequently make its way to the desalination plant, leading to the possibility of radioactive materials being carried over into the desalted water.

7.3.2.4. Monitoring for radioactive contamination

The allowable radionuclide concentrations in the product water are so low that continuous monitoring of the product water may not be technically possible. In this case, a state-of-the-art continuous monitoring system should be used with supplemental periodic batch monitoring for radionuclides with low detectability thresholds. The monitoring of the product water is an important feedback for the operating personnel of the nuclear desalination plant, and the information flow needs to be rapid to enable shutdown of the process before significant quantities of radioactive contaminated product water have been released.

If the permissible radioactivity limits are low enough that batch monitoring is required, then the product water may need to be held in storage tanks or a reservoir before its release to the distribution system. The holdup time must be a sufficient period to enable completion of monitoring before certifying that the product water is safe for public distribution.

7.3.2.5. Siting and the impact of proximity of population centres

Proximity to population centres is an advantage for desalination plants from the point of view of water supply planning, whereas isolation from population centres is often preferable for a nuclear plant. Balancing these two competing factors is an essential element in the overall water and energy supply policy for a country. Where the nuclear desalination system is located in proximity to population centres, this must be taken into account in emergency planning. In addition, the safety aspects being enforced at every stage of the nuclear desalination project should be made apparent to the general public to ensure product acceptability.

7.4. REGULATORY AND LICENSING ASPECTS

7.4.1. Regulatory codes and standards

Safety codes, guides and standards play key roles in ensuring the safety of nuclear desalination plants. They primarily serve as the foundation of safety and environmental protection. They define performance requirements and certify good practice. They provide a basis for equipment standardization and inspection. They also provide a basis for public confidence and acceptability.

7.4.2. Licensing procedures and stages

Owners of the nuclear desalination systems must comply with national and local regulations governing the construction of both nuclear and desalination plants. They will be required to submit all documentary evidence to substantiate their compliance in order to obtain the license from the regulatory authorities. This is a well established process in countries with a developed nuclear infrastructure. It is less straightforward in countries embarking upon their first large nuclear project. There are several options in the latter case. The regulatory authorities in various major supplier countries have established safety codes and regulatory guides with respect to nuclear power plants and desalination systems. The regulatory authorities in the importing country may adopt the regulatory principles, including codes and standards, from the country exporting the system. Manufacturers are familiar with those standards and will be able to demonstrate compliance with regard to system construction. The owners will be responsible for site related considerations.

Licensing of nuclear power plants involves considerable interactions between the nuclear regulatory authority and many national authorities. In the case of nuclear desalination, this will involve additional authorities dealing with water supply and water quality regulations.

7.4.3. Inspection and enforcement

The regulatory body utilizes the process of regulatory inspection to ensure that the licensee is fulfilling the conditions set out in the license and regulations. The regulatory body should plan its regulatory inspection and enforcement programme to assure that the nuclear desalination plant is constructed and operated in conformity with the approved designs and that the nuclear desalination plant personnel are competent to operate the system safely. Regulatory inspection is a continuous activity, carried out throughout all stages of the project.

7.4.4. Decommissioning of nuclear desalination facilities

Decommissioning of a nuclear desalination facility consists of measures taken at the end of the facility’s lifetime to ensure protection of the public from the residual radioactivity and other potential hazards. Decommissioning of a nuclear desalination facility essentially involves extensive decontamination/decommissioning of the nuclear plant and disposal of the desalination plant as the latter is not supposed to be contaminated with radioactivity. Two basic approaches to decommissioning are immediate dismantling of the nuclear facility and safe storage with deferred dismantling. Methods of decommissioning nuclear desalination facilities could range from minimum removal and fixation of radioactivity with maintenance and surveillance, to extensive cleanup, decontamination and entombment. Each decommissioning method requires surveillance, and care during the holding period, which may vary from a few years to decades.

7.5. ENVIRONMENTAL EFFECTS OF NUCLEAR DESALINATION SYSTEMS

The generation of electricity and production of potable water by either nuclear or fossil energy has some environmental effects even when all performance standards are met. An important design objective for nuclear desalination plants is to minimize the impact of various releases from the plant to the surrounding environment. Sources of potentially hazardous releases from nuclear desalination plants include radiological gaseous and liquid effluents, heat discharges from the waste steam, brine and chemical discharges, and solid waste discharges from different units of the plant. Various plant releases are subject to strict controls, requiring either batch processing of effluents or continuous monitoring before discharge to the environment to ensure that the established permissible levels are not exceeded.

7.5.1. Non-nuclear environmental effects

7.5.1.1. Thermal discharges

Nuclear desalination plants, like fossil desalination plants, require large amounts of cooling water for the power plant and/or desalination plant condensers. The temperature of the cooling water discharge from the plant can have a significant environmental effect on aquatic life. Unfavourable temperatures may adversely affect reproduction, growth and survival of aquatic life. Regulatory agencies at various levels of government have established water temperature standards which are used to govern such discharges. One method for minimizing the impact of a thermal discharge on the marine environment involves the construction of outfall structures and distributors to safely disperse the warm discharge water into relatively deep seawater locations or far offshore. The outfall can also be designed for safe discharge of concentrated reject brine.

7.5.1.2. Chemical and brine discharges

Normal operation of nuclear desalination plant leads to discharge of certain chemicals from the turbine condenser cooling system and the radioactive waste system, and high salinity brine from the desalination plant and sanitary waste system. The chemical content of discharges, other than the reject brine of a desalination plant, may vary from plant to plant. For example, chlorine or some other biocide may be added intermittently to cooling water to remove accumulations of organic matter inside the condenser. Phosphate and zinc compounds may be used as corrosion inhibitors, sulphuric acid may be used to adjust the alkalinity of recirculating cooling waters and demineralizers may be regenerated periodically using acid and alkali. The brine discharged from the desalination plant may contain, in addition to its high dissolved salt load, scale inhibitors and coagulant aids. The maximum concentrations of some of these chemicals in the discharge system should not exceed levels that are toxic to aquatic life. If the temperature of the discharge is high, it may compound the risk by enhancing the metabolic rate of toxic substances.

7.5.1.3. Land requirements

The siting of nuclear power plants for electricity generation and desalination requires large land areas for its exclusive use. The use of large land areas may pose problems in the long run with respect to the growth of population near the nuclear plants. The availability of power, waste heat and good quality potable water may attract additional industries and their employees to the neighbourhood of the nuclear plant site, and allowance should be made to take account of such long-range population trends.

7.5.2. Nuclear environmental effects

A dominant concern in the nuclear industry is with radioactive releases and their effects on the biosphere, especially on human health. Owing to this concern, dose rate limits are established, protective measures desired and their application enforced. Radioactivity gets accumulated in different liquids, solids or gaseous streams with varying radiation levels. Inevitably, disposal is required. The technological aspects of the management and disposal of radioactive wastes are discussed in Chapter 3.

From the environmental viewpoint, the objective of radioactive waste management systems is to prevent the release of unacceptable amounts of radionuclides from the nuclear fuel cycle to the human environment. Waste disposal practices generally follow the fundamental principles recommended by the International Commission on Radiological Protection [32], i.e. all radiation exposures shall be kept as low as reasonably achievable, taking into account economic and social factors, and shall not exceed the appropriate dose limits now or in the future. In addition, it is generally accepted that radiation exposures to future generations should not be higher than those acceptable to present generations.

In accordance with the above principles, the practices followed in radioactive waste management and disposal allow some waste constituents to enter the human environment. Thus, gaseous and liquid effluents released routinely from nuclear power facilities contain very small controlled quantities of radionuclides. Underground disposal of conditioned wastes containing the balance of the waste radionuclides is regarded as allowing some of the radionuclides eventually to enter the human environment but with a time delay and dilution sufficient that their concentrations will be insignificant at any point of potential uptake by humans. On this basis, waste disposal carried out under appropriate control at suitable sites is not expected to give rise to any significant exposure of the public.

Chapter 8

ECONOMICS OF NUCLEAR DESALINATION

8.1. INTRODUCTION

The main role of economics of any engineering project, e.g. coupling a desalination plant with a nuclear power plant, is to assist in making decisions. These decisions may be technical, financial, managerial or administrative. They may refer to a near future project and/or long term programmes.

The benefit of economics to decision making stems from the reduction of the number and type of factors by which the project alternatives to be decided upon are measured. Instead of coping with many technical, physical, time, staff and other factors, economics enables the evaluation of project alternatives in terms of money (as a common denominator). Economic comparisons can be carried out on a per project/programme or per unit product basis, provided equivalency is established relative to time, place, quantity and quality of the products for each alternative.

The following economic criteria are commonly used as the ‘bottomline’ of economic analyses:

- ***Cost of product****:* This is the most important, ‘popular’ and useful economic criterion. It can be evaluated in terms of the cost per unit product for a given plant (or per a given programme for a fixed date).
- ***Percentage of local currency:*** A specific criterion related to the *cost of product* is the *percentage of local currency* in the product cost and the investment. It is expected that where two alternatives show practically (i.e. almost) the same cost, the preferred one will be that with the higher local currency.
- ***Investment:*** In principle, the *investment* is embedded within the *cost of product* criterion and, therefore, should not be presented as a separate, independent criterion. However, *investment* has parallel impacts on the financing problem and the risk policy of the owner. For example, if evaluation of two alternatives yields practically the same product cost, the one with the lower investment will probably be taken, because of lower risks and easier financing. Depending on the availability of financing or the risk aversion policy of the owner, a preferred project alternative may be one with a meaningfully lower investment even though the predicted product cost is slightly higher.

These considerations lead to the following associated criteria:

- ***Cash flow, payback period and rate of return****:* These are usually of concern to private investors more than to large public authorities (such as the government) as owners. These three criteria depend on the investment and the annual expenses. They depend also on the next criterion:
- ***The price of the product****:* The *price* differs from the *cost* by the profit (or subsidy). Whereas the cost constitutes the expenses for production, i.e. the producer's outgoing money, the price is what the customer pays back to the producer, i.e. incoming money. The price is determined by (among other factors) the next economic criterion:
- ***The value of the product to the customer:*** In the case of desalted water, there is an added value, as compared with many other water resources, due to the high degree of controllability of quantity, quality and availability of desalted water.

Cost, price and value are measured and expressed in the same units (currency per product unit). They often differ in magnitude, but in many cases the differences are fairly low.

The last two criteria, price and value of products, differ from the other criteria, as they are not affected by decisions made by the project owners/designers/managers. Rather, they result solely from the prevailing economic conditions. They have to be quantitatively evaluated (or determined, if it is difficult to evaluate objectively).

This chapter describes and discusses these criteria as well as related aspects such as financing, economy of scale, techno-economical optimization and scheduling. Specific economic criteria for 'economic evaluation of bids' are presented in Section 13.7. A short discussion on the economics of hybrid desalination plants is also included.

A comparison of the cost of nuclear versus other energy sources for power and water production requires a complex evaluation, which takes into account numerous site, size and time dependent factors. Large nuclear power plants becoming operational in the near future can in many cases produce electricity more economically than fossil plants, particularly if transportation of fossil fuels is an important cost factor. The passage of time will probably increase the economic advantage of nuclear energy. The key economic factor for fossil generated electricity is the cost of fuel delivered to the power station. Increase in fossil fuel prices due to eventual scarcity may have a large effect on both power and desalinated water cost. In addition, several countries are considering a special tax for fossil fuel combustion because of the release of harmful gases (CO_x, HC, SO_x and NO_x) to the environment. This would increase their capital and operational costs.

For a nuclear power plant the key factor is the total capital cost. The nuclear fuel cycle cost is a much smaller component of the total cost and is likely to remain more stable than fossil fuel cost in the future. Thus, nuclear energy will become an increasingly attractive option for both power and water production in the future.

8.2 PRODUCT WATER COST AND ITS COMPONENTS

There are several possible objectives for which product water cost is evaluated:

- Comparing alternatives for the production (including the reference ‘no-go’ alternative, i.e. to avoid desalination). Design optimization is a special case of such comparisons;
- Preparing for financing by forecasting cash flow;
- Pricing;
- Outlook on the country’s economy (in particular, for a nuclear desalination programme rather than a specific project);
- Information for future projects.

The specific objective for which product water cost is evaluated will determine the degree of accuracy, details and caution at which this task is effected. Also, the specific objective determines the time at which the cost is evaluated (e.g. for pricing the time should be close to commissioning, whereas for comparing alternatives it is towards decision making — well before conceptual design).

The product water cost is most commonly evaluated by summing all cost components for desalted water, which include:

- the capital cost of the desalination plant including interest during construction,
- the cost of energy (or energies for distillation processes) for the desalination plant,
- O&M cost.

The contribution of individual cost components to the overall water cost depends on many factors such as production capacity, type of desalination process, site characteristics, type of energy source, etc. However, the common experience from most seawater desalination plants shows capital cost to be 30–50% of the total product water cost, energy cost 50–30% and O&M cost 15–25%.

The cost of water storage, transportation and distribution has to be added to the production cost in order to determine the water cost at the user site, because these costs are normally not included in the production cost of desalted water. Such facilities and costs are sometimes shared with other water resources. These costs are highly site dependent and can only be analysed on a case by case basis.

The cost of energy is the cost of heat, steam and/or electricity supplied to the desalination plant. For a single purpose plant with a dedicated heat source (e.g. nuclear heat reactor or fossil boiler), the energy cost is the total cost of constructing and operating the energy source divided by the total energy output in any given period of time. For a dual purpose or co-generation plant, the calculation of the energy cost is more complicated because the power plant produces two products, electricity and heat.

The main economic factors of a dual purpose nuclear power and desalination plant are given in Table 8.I.

Interest and insurance rates have a very large effect on a nuclear desalination plant's product water cost and, therefore, an accurate determination of the appropriate rates is essential. The load (or utilization) factor is also a large influencing factor because of the relatively higher contribution of the capital cost for a nuclear desalination plant. The contribution of energy cost to the overall product water cost is directly related to the actual generation cost of the nuclear plant. The annual cost for desalination maintenance services, chemicals and replacements must be included as factors in O&M cost. Operating labour cost constitutes another factor in the desalted water cost and is important for small capacity plants.

8.2.1. Main factors influencing overall product water cost

The discussion of the main factors influencing the overall product water cost parallels the approach for the cost of electricity for a nuclear plant. Further detail is given in Ref. [13].

TABLE 8.I. MAIN FACTORS OF NUCLEAR DESALINATION PLANT ECONOMICS

Capital investment cost
Fuel cost
Operation and maintenance cost
Infrastructure development cost
Plant construction duration
Plant load factor
Plant net electric power rating and desalting capacity
Plant economic life
Interest rate (foreign and local)
Escalation factor (foreign and local)
Discount rate
Currency exchange rates
Contractual conditions including financing and payment schedule
Insurance rates

8.2.1.1. Capital cost component

The capital cost component of the product water includes all investments associated with the desalination plant itself. A portion of the capital cost of a nuclear plant may also be allocated to the desalination plant. However, depending on the evaluation methodology, the nuclear plant capital cost portion may be included either in the desalination plant capital cost component or in the energy cost component. The latter is the more common method. The various methodologies are discussed in Section 8.3.

In most cases capital cost (C_c) is the largest cost component. It is usually calculated, per unit product, by

$$C_c = I\ (CRF)/P$$

where I = total capitalized investment, CRF = capital recovery factor (at the year end), P = average annual production (in units of product).

This calculation is often referred to as ‘levelizing the capital cost’.

Capital investment

The capital investment cost, I, of a nuclear desalination plant includes the cost of site, nuclear steam/power system, coupling arrangements, including, for evaporative desalination, intermediate heat exchanger, bypass lines and desalination plant. The capital investment cost of a nuclear desalination plant also includes all expenditures incurred in the design, licensing, construction, fabrication, installation and commissioning of the plant. The total capital investment is the sum of direct and indirect costs, including contingencies, interest during construction and escalation. Table 8.II gives different contributions to capital investment cost of a nuclear desalination plant and defines the common terms used in invest cost calculations.

Capitalization of the investment is done for a certain date. The most convenient is the date of plant commissioning, D. Thus, I becomes

$$I = \Sigma I_m\ (1 + d)^{D-D_m}$$

where

where	Σ	=	the summation of all direct and indirect expenditures to complete plant installation, including decommissioning,
	I_m	=	a specific expenditure,
	d	=	annual discount or interest rate (see below),
	D	=	reference date for capitalization (expressed in years),
	D_m	=	date of this expenditure (expressed in years).

TABLE 8.II. MAIN CONTRIBUTIONS TO A NUCLEAR DESALINATION PLANT CAPITAL COST

Cost	Contribution
Direct cost	Plant site and structure
	Nuclear reactor system (PWR, PHWR, etc.)
	Steam generation system
	Turbine system (for co-generation) & balance of plant
	Coupling system including intermediate loops
	Electric plant equipment
	Desalination plant
	Miscellaneous plant equipment
Indirect cost	Construction management, equipment and services
	Home office engineering and services
	Field office engineering and services
Base cost	= Direct cost + Indirect cost
	+ Owner’s costs
	+ Spare parts
	+ Contingency
Total cost	= Base cost (or ‘Overnight cost’)
	+ Escalation
	+ Interest during construction

Typical values of I for efficient single purpose plants are at present: US $800–1000 per unit capacity (i.e. m^3/d) for large SWRO and for low temperature MED plants, slightly higher for MSF and high temperature MED. The investment cost for the power plant is roughly US $600–1500 per installed kW(e) for fossil fuel and US $1500–3000 per installed kW(e) for nuclear power. These values result from experience and from feasibility studies. The exact value of I depends on plant capacity, site economical and physical conditions, specific technology and other factors.

If the evaluation methodology used is based on allocating a portion of the nuclear plant investment cost to the desalination plant investment cost, then I must include that portion. Typical values of I for dual-purpose plants per m^3/d of desalted water capacity (when part of the power plant investment is allocated to desalination) could be, therefore, of the order of US $900 per m^3/d. This is based on US $800 per

m^3/d for SWRO consuming 4 kW·h(e) per m^3 and US \$600 per installed kW(e) for fossil fuel, the lowest desalination and power investments. The sum is:

US \$800/(m^3/d) + US \$600/ kW(e) × (4 kW1·h(e) per m^3)/(24 h/d) = US \$900/(m^3/d).

Similarly, for high temperature MED at US \$900 per m^3/d consuming 6 kW·h(e) per m^3 and US \$2800 per installed nuclear kW(e), the total specific investment allocated to desalination could be of the order of US \$1600 per m^3/d if this cost allocation methodology is used.

Infrastructure development costs constitute a special part of the investment component, a portion of which relates to specific plants while the remaining portion relates to the entire national desalination and energy programme. Infrastructure development costs include costs incurred on planning studies, R&D activities in support of nuclear desalination, staff teaching and training, national infrastructure development, national participation promotion, technology transfer and regulatory and licensing costs. These costs are difficult to evaluate. It should be considered that they could produce benefits by promoting the country's overall development. Theoretically, they should be included in I as a separate, identified item, but practically this is complicated. Constituting, however, a relatively very small part of I, they can be included in the 'miscellaneous' item of I.

Capital recovery factor

The capital recovery factor, CRF, is usually calculated (based on end-of-year-recovery) by

$$CRF = d/[1 - (1 + d)^{-n}],$$

where d = annual discount or interest rate (see below), and n = years of economic lifetime of plant.

The economic lifetime of the plant is, according to the last formula, the basis for determining depreciation and, therefore, influences the water production cost: the longer the plant life, the lower is the product capital cost component. An economic lifetime of about 25 years is generally assumed for desalination plants, and 30 or more years is assumed for power plants. It is important to note that the physical life of plants may be longer than the economical life. This is done in an economic evaluation because of the possibility that emerging new technologies, higher maintenance expenses in the late plant years and other reasons may render the plant obsolete.

Annual average production

The average annual production, P, is factually known only at the end of the plant life. At the earlier stages of a project it can be only estimated. This is done by multiplying the nominal production rate — usually given in units per day (or per hour) — by 365 days (or 8760 hours) and by the anticipated load factor,

$$P = 365\ P_N \times LF$$

where P_N = the nominal production rate and LF = the load factor.

LF is associated with the plant's actual production. It represents the fact that the plant or the unit produces annually less than its theoretical potential at full time and full nominal production rate. Typical LF values are 0.90–0.92 for RO and 0.7–0.8 for MED and MSF. The latter can be raised up to 0.9 by adding a backup heat source to accommodate power plant outages. Hybrid desalination plants have LF values between those of RO and MED/MSF.

Power stations are operated to meet the fluctuations in demand due to daily and seasonal variations. Load fluctuations are not favourable to plant economics and, in particular, not to nuclear and desalination systems because they have a significant fixed cost due to their high capital cost. There are various means to minimize the effect of these fluctuations on the load factor. One is to designate dual-purpose plants for base load operation. Also, depending on the type of desalination process, the coupling of a desalination system to a power plant can improve the utilization of the latter and thereby decrease power and water costs.

8.2.1.2. Interest and discount rates

The interest rate is the annual cost of money required for the investment. Similarly, the discount rate is the annual value of this money to the owner of the plant. In principle, both the interest and discount rates may be equal, especially if the total investment is financed by loans having the same interest rates and a payback period identical to the lifetime of the project. If the project is financed by loan(s) having shorter (or longer) payback periods and/or when several sources of different interest rates are financing the project, the discount rate d may differ from the interest rate of the single loan or from the mean value of interest rates of several financing sources. Then d is used in the above given formula for I to calculate the capitalized values of the payback sums of these loans. Frequently, for feasibility or preproject studies, there is no reference to loans and the interest rate is taken equal to the discount rate; their identical value is used as d in the above formulas to calculate I and CRF.

The exact value of the discount rate is often determined by the government (sometimes even arbitrarily) according to high level economical and financial considerations. For example, a government that has large previous debts may decide upon a value of the discount rate to be higher than the interest rate even if the total investment is financed by a single loan that does have a payback period identical to the lifetime of the project.

Usually the value of the discount rate is determined within the range of 5–10% per year, related to 'constant currency' at a given date, thus bypassing inflation. More representative values at the time of this publication are 7 or 8%.

The interest and discount rates are the major non-technological factors that strongly influence the product cost. According to the method described above, they have a double effect on the capital cost of a product unit – first in the capitalization of I, then in levelizing the capital cost. Thus, intensive negotiations may take place towards determining their exact values.

8.2.1.3. Energy and fuel cost

Depending on the evaluation methodology, the energy cost to the desalination plant may be the cost of energy delivered or the fuel cost. The former is the more common method. In this case, the energy component of the product water cost is equal to the cost of building and operating a nuclear plant to supply the energy. For a dual-purpose plant, a portion of the nuclear plant cost may be allocated to the desalination plant as the 'energy cost'. Section 8.3 discusses the various methodologies for determining the amount of allocation.

Energy consumption for desalination

SWRO needs mainly mechanical energy, which it is convenient to supply by electric motors. Typical values for large, efficient units (~10000 m^3/d or higher) are about 4 kW·h(e) (±10%) per m^3 desalted water, not including pumping of desalted water from the plant.

MED and MSF need mainly thermal energy, which it is convenient to supply by low or medium pressure steam (subatmospheric or below 3 bars, respectively). They need also secondary and tertiary mechanical energy for pumping and maintaining vacuum, which is conveniently supplied by electricity (and possibly, for gas pumping, by high or medium pressure steam). The economic value of the consumed steam(s) is slightly less than the cost of the net electricity, which could have been generated by the steam. In efficient MED plants, it is equivalent to about 4.5 kW·h(e) (±15%) per m^3; for MSF it is roughly 80% higher. The additional secondary and tertiary mechanical and electrical energies are equivalent to 1–2 kW·h(e) per m^3 for MED and 2.5–4.5 kW·h(e) per m^3 for MSF.

Costs of energy units from various sources

The cost of energy supplied to the desalination plant by a nuclear plant versus a fossil plant is directly related to the cost of electricity generated by a nuclear plant versus a fossil plant. In this regard, the lower nuclear fuel cycle cost as compared with fossil fuel cost is the key factor in the economics of nuclear desalination. It totals up to about 0.5–1.0 cents per kW·h(e), with the gross electricity cost at the power plant ranging between 3.5 to about 6 cents per kW·h(e). Higher values are valid for small plants, remote places, poor technologies and/or poor implementation, and for power from the grid.

The cost of fossil fuel, such as coal, includes the cost of transportation from the pit to the plant site, thus depending on the location of the site and increasing with the distance. It is usually two to four times higher than nuclear fuel cost per kW·h(e). However, most — sometimes all — of this relative advantage of nuclear fuel cost is eroded by the higher capital cost of nuclear installations, as given above in Section 8.2.1.1. Thus, the costs of electricity (at a given capacity and site) differ only a little — a fraction of a cent per kW·h(e) — according to whether nuclear or fossil fuel is burned to generate this electricity. For large scale SWRO this small difference in electricity cost adds up to about ±2 cents per m^3, sometimes in favour of the fossil plant.

For MED and MSF, having higher energy consumption than RO, the difference in desalted water cost also increases in principle. However, since many evaporative desalination systems need more complex thermal coupling if connected to a nuclear heat source, the potential of nuclear fuel is further eroded.

The energy and fuel cost component

From the above given data it is possible to have the range of the energy cost per m^3 desalted water — 13 to 27 cents at the exit of efficient contiguous SWRO plants, 17 to 43 cents for MED and over 40 cents with MSF. These values include all the costs associated with energy supply to the desalination. The wide range is explained by variations in prevailing conditions and input data due to size, location and other differences. Exceptions still may be found. The actual fuel component is roughly 15–50% of these values, depending on the contribution of fuel to the overall power cost.

8.2.1.4. Operation and maintenance costs

The contributions to the O&M cost component are shown in Table 8.III. Some of the O&M costs, such as wages and salaries, insurance and other fees, are fixed costs, i.e. they do not depend on the number of annual operating hours and on the load

TABLE 8.III. COMPONENTS OF A NUCLEAR DESALINATION PLANT O&M COST

Cost category	Description
O&M materials and equipment, repair costs, etc.	Maintenance materials and equipment required for repair or replacement, consumables including pretreatment chemicals, etc.
Wages and salaries	Plant and administrative staff of a nuclear desalination plant, special workers for intermittent short periods of maintenance activities.
Insurance	Insurance fees
Inspection	Routine inspection fees
Other costs	All other relevant O&M costs

factor. The variable costs, such as consumables, maintenance materials and repair costs, depend on the load and number of operating hours. Other costs, such as chemicals, membrane replacement and spares, have both fixed and variable components.

8.2.2. Design and planning parameters

There are two kinds of (nuclear or other) desalination system design parameters: those that influence the economics, mainly the external parameters, and those that are influenced by the economics, i.e. determined by economic considerations via optimization.

The first kind includes the quality and the production rate of the desalted water, timing and location of the project (the latter determines the seawater properties – salinity, analysis and temperatures — as well as other environmental, geographical and infrastructure characteristics), the type of plant (contiguous or standalone) and the desalination process. These parameters may include user requirements or input data, expressing the owner’s preference and possible constraints. Initially, they seem to have a one way effect on the economics. When methodically examined, however, almost all of them have mutual feedback effects to some extent with economic considerations. Thus, for example, the user may compromise on higher product water salinity — say, 400 instead of 250 ppm initial required value — to reduce the water cost by a few per cent.

Parameters of the second kind are internal plant specifications. For thermal desalination plants, the product water cost is influenced by the number of effects or stages, top brine temperature and GOR; and for RO plants, it is influenced by membrane configuration and type, flux, recovery ratio and rejection rate, operating temperature and pressure. These parameters have a strong effect on water cost and, thus, their values should be determined by applicable optimization techniques and sound engineering judgement.

The usual goal of optimization is to identify the parameters with which the best results — in most cases lowest product cost — are obtained. The output of optimization is a set of qualitative choices and quantitative values according to which a desired project is implemented. In the optimization procedure, the relevant options are examined by weighing (to the extent possible) their advantages and disadvantages. Eventually the product cost is calculated for all the promising candidate options, and the best is found by discrete comparison or by the minimum derivative.

One problem with optimization is the sensitivity of the results to variations in the input values; small changes in these data may yield large quantitative and qualitative differences with the output results. Thus, input data should be cautiously and accurately determined. This might be difficult as some of the input data are not known accurately at the optimisation stage of the project.

Another problem may occur in case of a dual-purpose plant, where water cost can be traded off against power cost. If the lowest water cost is found, through optimization, for an option (i.e. one of a few possible sets of parameters) in which the power is generated at a higher cost than with another option or other options, then a method should be elaborated to identify the best option.

8.2.2.1. Production rate

The production rate, namely plant capacity, is economically associated with the economy of scale. The advantage of large capacities manifests itself in four aspects. In percentage cost reduction the first one is the personnel expense — e.g. a plant of 400 000 m^3/d employs roughly only four times as many the workers as a plant of 12 000 m^3/d. Second is the investment, which increases less than proportionally with the capacity — e.g. the investment in an SWRO plant of 400 000 m^3/d is roughly only 20–23 times as much as in a plant of 12 000 m^3/d, reducing the capital cost component of 1 m^3 desalted water by 30–40%. The relationship between the investment I (US $) in an SWRO dual-purpose plant and the nominal production rate P_N (m^3 per year) in the above range of capacities is very roughly:

$$I = 30P_N^{0.865}$$

The third aspect of product cost reduction due to the economy of scale is the energy, as the energetic efficiencies of equipment items usually increase with their size. The last aspect is the benefit of secondary improvements, which also increase with the plant size.

8.2.2.2. *Salinity of the product water*

The salinity of the product water is indicative of the 'desalination effort' – the lower the salinity, the higher the salt separation effort in terms of energy and equipment. In the range of 600–50 PPM, it may add roughly 2 cents/m^3 per 100 PPM salinity reduction.

8.2.2.3. *Higher recovery ratio*

Higher recovery ratio decreases the seawater feed requirement for a given plant output and, hence, the pumping power, intake and outfall equipment size (including feed pumps and, in the case of RO, the pressure recovery device) and the pretreatment equipment and chemicals consumption. These economic savings, however, bear some penalties. Higher recovery ratio means higher salt concentrations in the main desalination system and, in particular, towards the brine outlet. Consequently, it increases the energy in the main desalination system as well as the probability of scaling in the brine outlet zone of the main desalination system and, especially in the case of RO, adversely affects the product water quality.

8.2.2.4. *Hybrid desalination system parameters*

A special qualitative design parameter is the possible concept of 'hybrid' desalination plant where more than one desalination method is used, such as RO with MED. The philosophy of this concept is to combine the specific advantages of each method. In practice, this possibility shows economical benefit only seldom, under quite unique circumstances. Naturally, if one desalination method is economically superior over the other under the prevailing conditions, adding less competitive systems is economically wrong. Moreover, for a given capacity, a single system has the best economy of scale. Finally, it is easier to install, operate, control and maintain a single desalting technology than several ones. For nuclear desalination there seem to be only two cases where hybrid plants may be economically justified – both, if it is found that MED shows better economy than RO. One case is where the economics of RO using the cooling water from the MED is still better than both 'MED alone' and 'RO alone' possibilities. Such a case seems unlikely to be encountered. The second is where large power load fluctuations are expected and, hence, the practical performance of the coupled MED can be damaged. Coupling additional RO units — provided the additional desalination is needed — will improve the power load factor and render the MED economical.

8.3. COST EVALUATION METHODOLOGY

8.3.1. Single purpose plants

A single purpose nuclear desalination plant consists mainly of a heat or power source (i.e. nuclear reactor) solely for a desalination plant. The unit cost of the desalted water in such a case is obtained by dividing the total project cost by the entire lifetime output of desalted water. This is equivalent to dividing the annual average levelized project cost by the annual average output of desalted water.

The unit water cost of a desalination plant of a given capacity is calculated on the basis of the investment and operating costs for particular interest and inflation rates.

When comparing a single purpose desalination plant with alternative water production schemes, the unit production cost of desalted water is not sufficient. More information is necessary with respect to the following:

- Location of the delivery point, which will generally be close to the centre of consumption for the case of a desalination plant;
- Continuity and reliability of the supply;
- Quantity and quality of the desalted water produced.

It may also be considered that desalination creates additional freshwater resources whereas other means of supplying water consist in making existing resources available.

8.3.2. Co-generation plants

A co-generation plant, which produces both electricity and good quality water, is often called a dual-purpose plant, which has the following economic advantages over single purpose plants [7]:

- ***Lower financial investment due to sharing of facilities*** — Seawater supply and brine outfall, land requirement and site preparation costs are less, and some ancillary equipment such as pumps, compressors, lighting, transformers as well as administrative buildings can be used in common. For evaporative desalination there is saving in steam generators and final condensers.
- ***Less fuel consumption*** — The total fuel consumption is less, since some main components are larger in dual-purpose plants, thus having higher efficiencies. Also, energy is saved in shared facilities and common subsystems as well as by short distance energy transport.
- ***Less personnel requirement*** — A dual-purpose plant requires fewer staff than the two single purpose plants because of joint operation of common facilities.

However, a dual-purpose plant also has disadvantages, some of which are as follows:

- ***Less overall flexibility*** — Its operation may not be as flexible as a single purpose plant. There is economic pressure to maximize the combined production of water and power. In particular, it is desirable to operate a nuclear power station near base load to be most economic. The same is true in most cases for desalination. However, such design and operation may reduce the plant flexibility and cause some indirect penalties. Certain designs provide, indeed, for variation in the water to electricity ratio, but in some cases this may be at the cost of efficiency or extra investment.
- ***Slightly lower availability factor*** — Any incident interrupting the output of one of the two products may lead to a disturbance or stoppage in the production of the other, thus increasing the cost per unit product. It is possible to improve the plant availability as a whole and reduce this cost increase by connecting SWRO to the grid or adding devices such as bypass steam lines so that steam can be directed to the evaporative desalination plant if the turbogenerator is out of operation. Likewise, addition of an auxiliary condenser enables the power plant to be operated if the desalination plant is shut down. However, these devices involve extra investment.
- ***Off-optimum site and timing*** — The optimal location and/or commissioning date of the desalination plant, from the aspects of water conveyance, distribution and supply, may not coincide with those of the power plant, bearing another penalty.

The economic comparison of dual-purpose and single purpose plants involves more than a balance of their respective investment and operating cost, as the environment in which they are located should also be taken into account.

It is important to note that while the economic weight of the above dual-purpose plant advantages is fully expressed in the quantitative cost calculations, it is difficult to economically quantify the above disadvantages, because of their smaller scope, complex nature and indirect role. Thus, they are only partly taken into consideration in the cost calculation.

With dual-purpose plants there is a question of the true cost calculation for each product, especially in view of the above given advantages and disadvantages. The total production cost of the combined two products (desalted water and electricity) within the plant boundaries of a co-generation plant can be obtained by evaluating the fixed and variable costs of the co-generation plant. However, when seeking to establish a separate cost for each product, the difficulty arises because of sharing of common cost items such as staff, land, site development, offices, seawater intake and outfall systems, laboratory and other common auxiliaries. The main difficulty involves placing an economic value on the energy delivered to the desalination plant.

There are several techniques of allocating costs to the two final products of a dual-purpose plant, water and electricity, or to an intermediate product such as steam delivered to the desalination plant.

8.3.2.1. The power credit method

The power credit method is the most commonly used method. It is based on the comparison between the proposed dual purpose plant and an imaginary reference single purpose power plant using an identical NSSS (or alternative primary heat source). The amount of net energy generated by the reference single purpose plant (E) and total expenses incurred (C) are calculated first, from which the cost per saleable kW·h ($C_{kw·h}$) is derived ($C_{kw·h} = C/E$). Then the amounts of both the desalted water (W) and the (lesser) net saleable power (E_2) produced by the proposed dual-purpose plant, as well as its total expenses (C_2), are calculated. $E_2 < E$ because of the energy needed for desalination in the dual-purpose plant. Obviously, $C_2 > C$, because of the extra desalination expenses. The desalted water is then charged by these expenses and afterwards credited by the net saleable power cost: $C_2 – E_2 \times C_{kw·h}$.

The cost of the desalted water is thus derived:

$$C_{water} = (C_2 – E_2 \times C_{kw·h})/W$$

while the cost of the saleable power is the same as with the said reference single purpose power plant, $C_{kw·h}$. If W, C, E, C_2 and E_2 are annual quantities of m^3, US \$ and kW·h as appropriate, then C_{water} is obtained in US \$/ m^3.

8.3.2.2. The marginal water cost method

This costing method differs from the previous one by the basis of comparison between the proposed dual-purpose and the imaginary reference plants. Whereas in the ‘power credit method’ this basis consists of the identical primary heat source, the ‘marginal water cost method’ assumes identical net saleable power and energy (E_2 = E). Accordingly, the primary heat source of the proposed dual-purpose plant is larger than for the imaginary reference plant. Consequently, lower water costs (C_{water}) are derived owing to the economy of scale, with all the advantages of enlarged size and resource sharing allocated to the desalted water. This costing method has been used only a few times in past feasibility studies.

This method might be practically questionable if the required quantities of power and water lead to single- and dual-purpose plants with two different primary heat sources, one for the reference plant and the other for the proposed dual-purpose plant, that are not available in the market.

8.3.2.3. Cost allocation method based on exergy prorating

The exergy of a system is a measure of the value of energy. It is the upper limit of the share of energy that is transferable to mechanical work in bringing a system from its present thermodynamic state to a stable equilibrium with the environment. The exergy of mechanical and electric energy is higher than the exergy of heat, and the exergy of heat coming from high temperature steam is higher than the exergy of heat coming from low temperature steam.

Although thermodynamic analysis has been traditionally based on energy and the first law of thermodynamics, a system's performance can more appropriately be evaluated using the exergy approach. Energy can be neither produced nor destroyed, therefore it is non-depletable. An exergy analysis describes how the potential of a system to produce mechanical work is used and where the losses of that potential occur.

In the exergetic cost allocation method [11], the overall expenditures, C_2, of the co-generation plant are divided into the following cost components:

(1) Direct electricity generation expenditures, C_{Ee}, allocated exclusively to the generation of electricity;
(2) Direct steam production expenditures for providing heat to the desalination plant, C_{Se}, allocated exclusively to the production of potable water;
(3) Common electricity and steam production expenditures, C_{com};
(4) Remaining water production expenditures, C_{w*}:

$$C_2 = C_{Ee} + C_{Se} + C_{com} + C_{w*} \quad \text{(in US \$/a)}$$

The method of calculating each of the above components according to the plant exergy flows is described in Ref. [2]. The principle is that C_{com} , which is a large component of C_2, is divided between the power and the water in proportion to the exergy which each of them consumes.

It seems that according to the exergy prorating method, all the advantages of size and resource sharing are allocated equally (and 'equivalently') between the power and the desalted water, while in the power credit method the water gets relatively *more* benefit and in the marginal water method the water gets *most* of the benefit.

8.3.3. IAEA Desalination Economic Evaluation Programme (DEEP)

The DEEP programme calculates the cost of water (and power) for single as well as dual-purpose plants. The latter is evaluated using the principle of the power credit method.

During 1991 and 1992, a generic investigation was conducted by the IAEA on the technical approach and the comparative cost for utilizing nuclear energy with various state-of-the-art desalination technologies. A key outcome of the investigation was the development of a convenient methodology for rapidly calculating performance and costs of power and water production for various power and desalination plant couplings. DEEP is the IAEA's software package for the economic comparison of seawater desalination plants, including nuclear options. It has been validated with reference cases. On the basis of the validated version, a user friendly version has been prepared along with a manual with information on how to use DEEP [10]. The methodology is incorporated in an EXCEL spreadsheet routine, which is available from the Nuclear Power Technology Development Section of IAEA.

The methodology is suitable for economic evaluations and screening analyses of various desalination and energy source options. The methodology is embedded in a spreadsheet routine containing simplified sizing and cost algorithms which are easy to implement and are generally applicable to a wide variety of equipment and representative state-of-the-art technologies. The spreadsheet methodology was substantially improved to include the capability to model many types of nuclear/fossil electric power and heat sources of varying sizes, depending on site specific demands. It embodies the basic technical and economic principles of power and desalination plant performance and can be adapted to any site conditions. Current cost and performance data are incorporated so that the spreadsheet can be quickly adapted to analyse a large variety of options with very little new input data required.

The output includes the levelized cost of water and power, breakdowns of cost components, energy consumption and net saleable power for each selected option. Specific power plants are modelled by adjustment of input data including design power, power cycle parameters and costs. The desalination systems are modelled to meet the World Health Organization (WHO) drinking water standards. However, modifications and changes can easily be incorporated on the basis of description in the manual.

The spreadsheet serves three important objectives:

(1) It enables side-by-side comparison of a large number of design alternatives on a consistent basis with common assumptions.
(2) It enables quick identification of the lowest cost options for providing a specified quantity of desalted water and/or power at a given location.
(3) It gives an approximate cost of desalted water and power as a function of quantity and site specific parameters including temperatures and salinity.

For planning an actual project, final assessment of project costs should be done more accurately on the basis of more substantive information including project design and specific vendor data.

The use of the spreadsheet methodology is limited to the types of the power or heating plants, desalination processes and coupling models described in the manual. The spreadsheet models the common commercial processes for large scale seawater desalination as given in Table 8.IV. The MED process is assumed either to be a low temperature, horizontal tube system or a high temperature, vertical tube evaporator (modification to horizontal tube evaporator is possible). Heat is supplied in the form of low-grade dry-saturated steam, and maximum brine temperature is assumed to be limited to 70°C and 125°C for low and high temperature MED, respectively. MSF is modelled as a oncethrough process. Heat is supplied in the form of hot water or low grade saturated steam and maximum brine temperature is limited to 135°C.

Standalone assumes that the RO plant is only electrically coupled to the power plant. Contiguous RO assumes that the RO plant shares a common seawater intake and outfall with the power plant cooling system and may take the advantage of the power plant reject heat for the feedwater preheating. In addition, there are two membrane options available, hollow fibre membranes and spiral wound membranes.

In the hybrid concept, the thermal desalination and the membrane plants together provide the desired water quality and demand. Feed to RO is taken from the condenser reject water of the thermal desalination plant or power plant condenser.

The spreadsheet includes different types of nuclear reactor (Table 8.V). Some of them can provide both electricity and heat and are capable of being coupled with any of the desalination plant concepts such as thermal desalination or membrane process or both. Some of the energy sources are 'heat only' systems and are coupled only with thermal desalination systems using hot water or low pressure steam. Some of the energy sources are considered as 'power only' systems and are only to be coupled with membrane process using electricity. The input data in the spreadsheet can be adjusted to enable the model to approximate any type of nuclear steam power plant including liquid metal systems.

TABLE 8.IV. DESALINATION PROCESSES CONTAINED IN THE SPREADSHEET

Process	Description
Distillation	Multi-effect distillation
(thermal desalination)	Multi-stage flash
Membrane	Stand-alone reverse osmosis
Contiguous reverse osmosis	
Hybrid	Multi-effect distillation with reverse osmosis
	Multi-stage flash with reverse osmosis

TABLE 8.V. ENERGY SOURCES CONTAINED IN THE SPREADSHEET

Energy source	Abbreviation	Description	Plant type
Nuclear	PWR	Pressurized (light) water reactor	Co-generation
Nuclear	PHWR	Pressurized heavy water reactor	Co-generation
Nuclear	SPWR	Small pressurized water reactor	Co-generation
Nuclear	HR	Heat reactor (steam or hot water)	Heat only

In case of water cooled nuclear reactors, the spreadsheet considers the specification of an intermediate loop for either steam or hot water supply to the desalination system to prevent the possibility of radioactive contamination of the product water. The model also includes a backup boiler for ensuring energy supply to the thermal desalination plant if the main energy source is not operating.

DEEP can be used for comparative calculations, in order to determine under which conditions nuclear desalination is economically competitive. The water cost for a sample case is presented in Table 8.VI.

8.3.4. Other international methods

The US Office of Saline Water (OSW) included a cost format in the 1972 edition of the Desalting Handbook for Planners [33]. It includes a tabulation of all direct capital costs and indirect costs (interest during construction, working capital, and contingency expenditure). It also includes a tabulation of annual operating costs including annual cost for depreciating capital. The total cost for production of desalted water is then worked out as the total of annual costs divided by the annual production.

TABLE 8.VI. IAEA DESALINATION ECONOMIC EVALUATION PROGRAMME (DEEP) — SAMPLE CASE — AP 600 PWR

Item	RO	MED	Hybrid (MED-RO)
Plant capacity (m^3/d)	500 000	500 000	500 000
Energy source	Nuclear	Nuclear	Nuclear
Seawater TDS (ppm)	38 500	38 500	38 500
Interest rate (%)	8	8	8
Levelized power cost	0.047	0.047	0.047
Water cost (US $/$m^3$)	0.72	1.06	0.87

An adaptation of this format was used in the cost updates prepared for the US Office of Water Research and Technology and is recognized by the International Desalination Association (IDA). A software package for calculation of costs for seawater desalination, following this format, is now available through IDA. It is designed to calculate cost for three commercial processes (MSF, MED and RO) for seawater desalination. The desalted water cost does not include product water storage, distribution or administrative costs. The sample cost figures for RO, MED and MSF based on the IDA seawater desalting cost programme is presented in Table 8.VII.

8.4. RELIABILITY OF COST ESTIMATES

Cost estimates should be made for a particular country and site, accounting for all relevant factors and conditions including local infrastructure, current market trends, site characteristics, etc. A distinction should be made between cost estimates intended for economic comparisons and cost estimates needed for cash flow studies, pricing or future project evaluations. It is relevant to include inflationary effects on payment schedules when estimating the future financial needs.

The economics of nuclear desalination is strongly dependent on local factors, the prevailing market price of electricity and water, and a series of institutional factors which may influence the economic assessment of the project.

As the degree of sophistication, complexity and size of dual-purpose power plants increases, several economic estimates may be needed for evaluating the economics of these plants. Different types of estimation may be employed for the same project, and each has a purpose. Some examples are as follows:

TABLE 8.VII. IDA SEAWATER DESALTING COST — SAMPLE CASE

Item	RO	MED	MSF
Plant capacity (m^3/d)	20 000	20 000	20 000
Seawater TDS (ppm)	37 000	37 000	37 000
Plant load factor (%)	90	90	90
Interest rate (%)	8	8	8
Electricity rate (US $/kWh)	0.08	0.08	0.08
Total capital cost (US $ million)	25.61	44.72	44.31
Cost of water (US $/$m^3$)	1.26	1.37	1.71

Costs at time of estimate

This is the most common procedure used in the water desalination literature for reporting capital and operating costs of desalination plants. It has value for feasibility studies, project screening and for the evaluation of the bid. Its value is diminished in later project stages, when real rather than presumed capital and operating costs over the life of the plant are considered.

Costs at later times, towards project completion

This upgrades the cost estimating procedure to the next level of accuracy by input of more factual data and by using an estimated inflation rate till completion of the project. This costing procedure is of particular importance when the project requires several years from the time of bid to startup, and/or when the procurement documents allow for progress payments and an extra charge for inflation.

Levelized cost in terms of ‘constant’ dollars

Inflation complicates these estimates and contributes to fuzzy results. Using ‘constant’ currency with a known fixed value at the time of the estimate is the common practice of bypassing this problem.

The levelized unit cost may be determined in either ‘constant’ dollars, where the costs are expressed in terms of the purchasing power of the dollar in some reference year, or terms of the ‘current’ or ‘as spent dollars’. The constant dollar costs increased by the rate of inflation give the current dollars.

Regardless of which methodology is used, only the total cost of the product water is determined, not the selling price.

8.5. ECONOMIC COMPARISON WITH FOSSIL FUEL BASED DESALINATION

The right source of primary energy for seawater desalination has a large effect on the economics of the desalination system. Nuclear energy becomes increasingly competitive in large installations compared to fossil fuel based desalination plants because fuel cycle costs are considerably lower for nuclear power plants than for fossil fuel plants. The ratio of fuel to total cost in a fossil plant is significantly higher than in a nuclear plant. This is likely to further increase as the inventory of fossil fuel is gradually depleted. An alternative competitor is grid electricity for SWRO.

Nuclear plants have some advantages in a dual-purpose arrangement. Improving the load factor for single and dual-purpose plants benefits the nuclear plant more than the fossil plant because of the higher capital cost component for nuclear plants. Thus, the optimal load factor at which nuclear dual-purpose plants will be operated is expected to be higher than that at conventional plants. A high load factor benefits the desalination process economics, reducing the capital and O&M expenses per m^3. Hence, the coupling with nuclear plants may be better for evaporative desalination even if the energy cost for this option is not lower than the alternatives.

Also, in most nuclear power plants the amount of useful exhaust heat per unit electricity generated is considerably higher than in the alternative ones. Thus, for evaporative desalination the amount of desalted water can be much larger, leading to a lower cost due to the economy of scale.

Finally, in case of turbine generator outage — with the steam generator or boiler functioning —, working with a bypass line is less expensive in the case of an evaporative desalination nuclear plant because of lower initial quality of the steam. The exergy lost with single purpose steam instead of dual-purpose is lower under the NSSS thermodynamic conditions than under fossil fuel boiler conditions.

Nuclear plant economics do not vary to any great extent with geographical location (except for highly seismic regions). This factor is important for the regions having low availability of fossil fuels. Nuclear desalination offers an additional degree of freedom in securing local energy requirements.

These factors favour the cost of desalted water in a nuclear co-generation/desalination plant. On the other hand, this involves some penalties even where the energy generated in a single purpose nuclear power plant costs less than in a fossil fuel plant. First, in most nuclear evaporative desalination cases, an additional coupling system is needed to safely transport the heat from the power steam cycle to the distillation system. This involves additional equipment, pumping energy and exergy loss of the transported heat. Such coupling systems are not always needed in fossil fuel dual-purpose plants, and even if they are used the requirements are less stringent, hence less expensive.

Second, the special siting requirements for nuclear plants may result in higher costs for water transportation from the plant to the users. Transportation costs for large volumes of water have been found to be of the order of US $0.001–0.002 per m^3 per kilometre.

In comparing the alternatives of nuclear, grid electricity and fossil fuel energy supply sources for desalination, it is important to know the proportion of local to foreign currency in the product cost. This seems to be meaningful for developing and other countries that are short in foreign currency.

In countries which import fossil fuel the foreign currency component in the energy cost becomes relatively high. Therefore the nuclear option might be preferred even if the total product cost for this option is not lower than the alternatives. Also, in many cases the civil engineering cost component in the nuclear installation is relatively higher. This expense is usually local currency, giving additional motivation to prefer the nuclear option.

8.6. COST AND PRICE OF WATER

8.6.1. Value of desalted water

The ‘value’ is the worth of the desalted water to the consumer. It depends on many factors such as water scarcity, specific applications, desalted water quantity and salinity, additional and alternative water sources qualities and costs, etc. Thus, for example, the value of water for luxurious hotels or military bases may be quite high, whereas for large scale agricultural irrigation it is usually expected to be low.

In many cases it is difficult to assess the value of the desalted water. However, it is reasonable to assume that, because of the relatively high availability and reliability of the desalted water and the controlled quantity and quality, the real value of desalted water may be higher than that of alternative water. In particular, this is the case where the alternative water has lower quality, such as high salinity or hardness.

In principle, it is justified to use desalted water if the real value of such marginal desalted water (considering availability, quality and quantity) is higher than its cost, provided that there is no better water source. The potential consumer of desalted water should consider this in the decision making on paying for desalted water. Similarly, a government should consider this aspect while determining its desalination policy and desalination programme.

8.6.2. Prices of water and power

Price is the money paid to the supplier by the consumer. It differs from the ‘cost’, which the supplier expended to produce the water or the energy, by the net profit. Under normal conditions the price level is between the ‘cost’ and the above mentioned ‘value’ of the product. Thus, both the supplier and the consumer benefit. If the consumer produces water for himself, the price equals the cost. On the other hand, if the authorities intervene by taxing or by subsidizing (having economical, social or political motives), the price to the supplier is different from that to the consumer.

The situation may become more complex for dual-purpose plants. Even under normal market conditions one product may be sold at a price which leaves a relatively modest profit while the other product yields a high profit. It is also possible to have an overall positive net profit due to a ‘good’ price of one product, e.g. electricity, even if the other — e.g. the desalted water — is sold for a price lower than its cost. In such a case, the latter is practically subsidized by the former. This might sometimes give a misleading impression (as some people mix the notions of ‘cost’ and ‘price’) that the cost of desalination is quite low, with a risk that wrong decisions may follow.

Additional aspects of this issue are covered in Section 9.5.2.

8.6.3. Cash flow, payback period and rate of return

These three criteria are strongly interrelated. They concern mainly private investors and owners, but to a lower extent they may be of interest to the customers and the government. Each of them constitutes a special criterion regarding the attractiveness of the investment:

- ***Cash flow*** provides two dimensional information on the financial balance and timetable at which investment components and other expenses — given by amounts of money — are paid, and at which payments for the products are received.
- ***Payback period*** is the time difference between the date of the net cash flow turning zero from previously negative and the (representative) date of the investment.
- ***Rate of return*** is the equivalent compounded interest at which the investment is recovered by the revenues from product sales.

These criteria, as well as others (such as the net-profit-to-investment ratio) depend strongly on the products’ price, investment, plant factor and plant lifetime. They are significant in price determination and mainly in financing the investments.

It may be interesting to indicate that these criteria can be bypassed from the plant owner’s point of view if the plant will be leased to him, so that his net expenses are continuous and annual and are linked to the sales revenues rather than to a preliminary large investment. Such an arrangement has not taken place yet in the desalination market.

It may also be interesting and important to note that when a long term, multiplant programme is initiated, investment takes place through many years. A single investor in such a programme will have to endure a very long payback period, especially if the production and/or generation capabilities are expanding, because the cash flow of the programme in later years consists of revenues from water/power sales (incomes) and progressing investment (expenditures).

8.7. FINANCING

The overall gross investments in large seawater desalination plants are in the range of $1000 per unit capacity of m^3/d. Similarly, they are around US $1000 per installed power unit capacity (kW(e)) for fossil fuel plants and roughly 50% to 200% more for nuclear power plants (see Section 8.2.1.1).

The problems of financing nuclear desalination projects are quite similar to those of nuclear power.

The major issues of financing high capacity plants are raising large capital funds under the optimal combination of the following conditions: low interest rate, long payback periods and maximum local currency. One of the difficulties is the long period of time between the investment date and the start of the payback period.

More aspects of financing are discussed in Sections 9.5.3 and 13.4.

Chapter 9

NATIONAL REQUIREMENTS

9.1. INTRODUCTION

The introduction of nuclear desalination in a country involves many activities that are specific to either nuclear energy or desalination. These activities create new requirements on the country's infrastructure, and require national commitments on a long term basis involving substantial efforts. In particular, the requirement for the government to make large financial commitments through long term financial and economical plans is a consequence of the fact that nuclear desalination is capital intensive. A country embarking upon nuclear desalination should critically and realistically assess its organizational, industrial and governmental capabilities and determine the requirements for implementing nuclear desalination.

In this chapter, the special aspects relevant to the national requirements for a country to introduce nuclear desalination will be identified and briefly discussed. These include review of the organizational requirements, infrastructure requirements, project requirement, public awareness and acceptance, and the international agreements and commitments on liability, safety and safeguards for nuclear reactors. The main focus will be on those requirements that are related to the integration of the nuclear energy source with seawater desalination processes. If the introduction of nuclear desalination involves the first introduction of nuclear energy to a country, more detailed and comprehensive reference can be made to other IAEA documents [13, 34–38].

9.2. ORGANIZATIONAL REQUIREMENTS

The initiation, formulation and implementation of a nuclear desalination programme need organizational structures for managing required activities at the governmental level as well as within the utilities, industry, research and development, and educational institutes involved. As for any long range programme, a nuclear desalination project requires early, extensive and intensive planning. Nuclear desalination projects need to comply both with nuclear regulatory and safety standards and with water quality standards. Special organizational structures are needed to take care of each of these aspects.

If the nuclear desalination project constitutes a country's initial introduction to nuclear energy, the first task to be performed is to set up a national organization for planning and co-ordinating the nuclear energy programme, including all related activities. The nuclear energy programme activities are usually performed by several national organizations together with national and foreign consulting and architect engineering firms, suppliers and contracting companies. The distribution of tasks, functions and responsibilities among the involved organizations follows patterns similar to those for conventional power or industrial plants but with the addition of a nuclear regulatory body. The function of this organization will be to regulate and control all nuclear facilities and ensure that their design, manufacture, construction, commissioning and operation comply with the safety requirements and quality standards stipulated in the regulations.

There is no universally applicable organizational framework that is equally applicable to every country and in every situation. It should also be recognized that the formation of the organizational structures is a continuous and gradual process. As the nuclear desalination programme develops, appropriate changes are gradually introduced according to the needs and available resources.

9.3. BASIC REQUIREMENTS

The total infrastructure of a nation can be viewed as a set of organizations that interact with each other to various degrees [36]. They are directly or indirectly under the influence of government policy.

Developing the industrial infrastructure involves the development of a number of industries in the country, whether for services, materials supply and fabrication or construction, so that optimum participation is achieved by these industries. There must be a general infrastructure to support the successful operation of national industries. For example, the industrial sector cannot develop if there are insufficient qualified personnel to staff the necessary functions both in the workshops and engineering offices. Thus, an educational infrastructure must be established to provide the relevant knowledge and training. Similarly, the industry cannot operate without a legal regime setting up regulatory directives with respect to the applicable codes and standards and licensing and quality assurance (QA) enforcement. In addition, communication and transportation are vital to industry, as are the R&D infrastructure and a legal system that regulates the mercantile sector.

9.3.1. Staff development

Like any other development programme, nuclear desalination involves staff for planning, project implementation, construction, operation, maintenance and management. To implement the staff development programme, the industrial methods and facilities to fulfil the staff requirements for nuclear desalination plants must first be identified. A significant number of personnel trained at the graduate engineering level may be required for the construction and operation phases. A limited number of specialized personnel may also be required to deal with very specific problems related to the application and future expansion.

To fulfil these requirements, the country's educational, scientific, technical and industrial organizations should make special efforts to closely co-operate with the organizations responsible for implementing the staff development programmes for nuclear energy, the government, and the water utility/plant owner.

A complete long term plan should be designed to meet the human resources needs of the specific organization that implements each step of the nuclear desalination programme. This begins with preliminary review and planning the preliminary design of the nuclear desalination units and ends with the full capacity operation of these units. The staff development programme should address the required disciplines, amount of staff, schedule, method of securing, plan for education and training, etc. It would be helpful to prepare an organizational chart of the nuclear desalination programme that shows the number of employees, the duties, the functions allocated to superintendents and managers in the main work areas of the plant (e.g., administration, operation, maintenance and technical support).

For a developing country, foreign vendors with different languages would most likely supply the first nuclear plant. In this circumstance, the problem of multilanguage translations of technical documents could arise. Experience shows that the higher the language skills of the professionals and technicians of the developing country, the better it will be able to meet the challenge of collaborating with foreign vendors, absorbing the technology, and achieving the national participation goals.

9.3.2. Industries

There are no firm rules regarding the industrial infrastructure requirements of a country starting on a nuclear energy and/or nuclear desalination programme. Basically, the plant has to be built, the equipment and components have to be installed and tested, and the plant has to be operated and maintained within the country. As long as the country has the goal to become self-reliant in implementing its nuclear desalination programme, it should provide at least a minimum of supporting infrastructure. Basic requirements include competent firms to carry out construction and erection and to support plant operations and maintenance. It should also include a basic programme to address the quality assurance and quality control requirements of the nuclear programme.

The available industrial infrastructure will probably not have all the technology, know-how, level of quality, or the expertise necessary for a nuclear desalination plant but, as shown by experience, these can be acquired. Regarding engineering and industrial capabilities, this becomes a basic requirement if a non-turnkey approach is adopted, or if there is a policy for increased national participation. However, even when a turnkey approach is adopted, a minimal engineering capability is essential for the effective implementation of the programme.

The national engineering, manufacturing, construction and erection capabilities play an essential role in the promotion and development of the nuclear desalination programme. This industrial infrastructure should be closely associated with the nuclear desalination programme, as they will provide a pool for the necessary skills and human resources.

9.3.3. Technical information and services

Before design and construction of a nuclear desalination plant, the utility should provide the necessary data and technical information with regard to the site infrastructure, the electrical grid, the site conditions, the site access, the power supply, the existing water distribution network, the existing water reservoirs, facilities and other relevant infrastructures. Throughout the nuclear desalination project implementation process, the utility may be required to frequently provide services and expertise in such areas as:

- Pre-project activities,
- Project management of the nuclear and desalination units,
- Public information and public relations,
- Supervision of suppliers,
- Site preparation,
- Personnel training,
- Preliminary and detailed design engineering,
- Design reviews and approval,
- Procurement and manufacturing of components from local industries,
- Construction and civil works,
- In-plant assembly and acceptance of main equipment;
- On-site assembly,
- On-site non-destructive inspection of welds,
- Systems and subsystems commissioning,
- Full capacity commissioning of the nuclear desalination plant,
- Nuclear desalination plant acceptance testing.

Once the plant is completed, its operation and maintenance and the supporting activities fully become a national responsibility, and hence they are classified as ‘essential’ for national participation. A country should assign first priority to the performance and supply of these ‘essential’ activities, which include:

- Plant operation and maintenance,
- Quality assurance and quality control,
- In-service inspections,
- Training and retraining,
- Radiological protection and environmental surveillance,
- Safeguards and physical protection,
- Fuel and fuel cycle services procurement,
- Fuel management at power plant,
- Waste management and disposal,
- Licensing and regulatory surveillance,
- Public information and public relations,
- Record keeping,
- Emergency preparedness.

9.3.4. Licensing and regulations

Before the implementation of a nuclear desalination programme, the framework for the nuclear plant licensing process should be established in accordance with adopted nuclear and health regulations in the user country. The existence of a fixed regulatory frame is a precondition for the bidding process. If the project is the first nuclear facility in the country, the nuclear licensing and regulation framework may not be in place. In this case it may be necessary to follow the supplier’s regulations at the beginning and then gradually establish relevant regulations. A reasonable objective for the establishment of such a framework is to harmonize the national regulations with regulations and norms in those countries where the nuclear desalination plant is designed. The main aim is to ensure that the nuclear desalination plant is licensable in the customer's country and thus to minimize changes in the design.

The national regulatory authorities have the responsibility for ensuring the health and safety of the general public, nuclear workers and the environment against possible adverse effects arising from the activities associated with nuclear energy. Thus, the regulatory authority establishes regulatory standards, codes and criteria. It reviews and evaluates the safety analysis documentation and environmental monitoring reports submitted by the utility/owner and issues licenses or authorizations for activities and facilities. It certifies qualified staff and conducts a comprehensive programme of inspections to ensure that everything conforms to the established rules and regulations. The regulatory authority may also provide liaison with regulatory agencies of other nations and pertinent international organizations.

9.4. PROJECT MANAGEMENT REQUIREMENTS

The function of project management can be defined as the overall direction and co-ordination of project implementation tasks; it is considered to be the most important activity for ensuring successful project implementation. Project management activities start with the decision to go ahead with the project (following planning, feasibility and siting studies) and end with turning over the plant to the organization which will be responsible for its operation and maintenance.

This is a very complex responsibility. For this reason, it is advisable for an inexperienced owner of the first nuclear desalination project to delegate the project management function to an experienced main contractor under a turnkey approach, or to an experienced architect–engineer under a split-package approach. However, the utility cannot delegate direct responsibility for control and supervision of the project and should therefore be prepared to fulfil this commitment in the most efficient way.

The success of the project depends entirely on how project management is implemented during the execution phase. Additional information on project management for a nuclear desalination project is given in Chapter 15, and a complete description of key activity areas during this phase for a nuclear desalination project can be found in Ref. [36]. This description will be helpful in organizing the project management of the nuclear desalination project.

9.5. PUBLIC ACCEPTANCE

In many countries, a nuclear desalination programme is a national undertaking, and hence its introduction and implementation within the country, including the acceptance by the population in general, is a matter to be handled primarily by national (and regional) governmental organizations and authorities. The utility, while providing a public service, also has an important role to play.

It is often recognized and pointed out that lack of public support could constrain the introduction of new nuclear facilities, whether it is electricity generating or co-generating. However, nuclear desalination may have more favourable acceptance in water scarce areas.

On the basis of previous experiences with regard to public interfacing that were shared among participants at various IAEA meetings, the response of the public to the nuclear programme is generally not very favourable in many nuclear experienced countries. On the other hand, the public's response is either favourable or neutral in countries that are newly planning to introduce nuclear programmes.

A public information programme aimed at both the general public and the inhabitants around the site of the nuclear desalination project should be carefully planned and implemented and started as early as possible.

In some countries where public support is not very strong, the general trend of actions for improvement seems to be increased interaction with the public. The form of interaction varies depending on the situation. Forms widely practiced include: public hearings in the planning stage, public hearings in the licensing procedure, arrangement of seminars or open meetings for the public, broader disclosure of information including publications, and/or arrangement of exhibit tours for the public to the nuclear facilities.

Environmental and health protection is a major public concern. The national and regional governmental organizations should take an initiative to inform the public through various publicity media (publications, seminars, exhibitions, etc.). The information should include the potential advantages and disadvantages of different energy sources. The information should also discuss desalination processes in terms of chemical, thermal and radioactive effluents.

There may be some concerns related to the lack of knowledge of the public. Continuous education of the public by the involved authority/personnel would be necessary so that the public properly understands the balance of risks versus benefits. The IAEA can assist the Member States, upon request, to arrange public information meetings in the form of workshops, seminars, publications, internet, etc. In the past, several workshops or seminars have been successfully arranged every year on a regional and/or national basis in co-operation with the local authorities in order to provide properly informed personnel in the decision making process. It is recommended that, even if no strong public concerns are ever experienced or foreseen in the country or region, the government and utilities should be aware of the practice and experience in other countries that have experienced issues related to public concerns. It is also recommended that the programme for public acceptance be introduced early in the project to help ensure smooth implementation of the project.

9.6. INTERNATIONAL AGREEMENTS AND COMMITMENTS

When a country decides to start a nuclear desalination programme, the responsibility for the development of all the necessary structures to create, regulate and maintain a nuclear desalination programme rests with the government and various national organizations and institutions. There are legal requirements at the national and the international level that will be entailed in the establishment of a nuclear desalination programme. Table 9.I identifies selected international agreements and conventions which IAEA Member States should observe.

9.6.1. Non-proliferation agreements and commitments

When countries begin to trade in nuclear materials and equipment for peaceful purposes, it has become the practice (and is today the invariable practice) for

TABLE 9.I. INTERNATIONAL CONVENTIONS

Convention	Relevant date
Convention on Nuclear Safety	In force since 1996
Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management	Opened for signature on 29 September 1997
Convention on Early Notification of a Nuclear Accident	In force since 1986
Convention on Assistance in the Case of a Nuclear Accident or Radiological Emergency	In force since 1987
Convention on the Physical Protection of Nuclear Material	In force since 1987
Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter	In force since 1975

international agreements dealing with the use of nuclear energy to specify a set of 'safeguards' to verify systematically that the State or States concerned will not use the relevant nuclear materials or equipment for purposes or in a manner proscribed by the agreement.

Treaty on the Non-Proliferation of Nuclear Weapons (NPT)

The Treaty on the Non-Proliferation of Nuclear Weapons (NPT) [39, 40] is an international collaboration, which came into force in 1970 for this purpose. Each non-nuclear weapon state that becomes party to the NPT binds itself not to acquire nuclear weapons or other nuclear explosives (Article II). It also binds itself to conclude an agreement with the IAEA for the application of safeguards to all its peaceful nuclear activities with a view to verifying the fulfillment of its obligations under the treaty (Article III). In return, the treaty recognizes the right of all parties to participate in the fullest possible exchange of equipment, materials, and scientific and technological information for the peaceful uses of nuclear energy; in other words, all parties are guaranteed full access to peaceful technology (Article IV). The parties also undertake to pursue negotiations in good faith towards nuclear disarmament (Article VI) and reaffirm their determination to achieve the discontinuance of all nuclear weapons tests (Preamble). These commitments obviously apply principally to the nuclear weapon States themselves, who alone, under the treaty, may develop and test nuclear weapons.

The NPT requires the application of IAEA safeguards to verify that the parties are using nuclear energy only for permitted purposes. As of 1996, 131 Member States had signed full scope safeguard agreements with the IAEA, and, as of June 1999, 187

Member States including five nuclear weapons States had signed partial safeguards agreements.

Safeguards have gone through three major phases. The first began in the late 1950s and the 1960s as nations started to trade in nuclear plants and fuel. The safeguards of that time were designed chiefly to ensure that this trade did not lead to the spread of nuclear weapons. The second phase reflected a growing perception that, pending nuclear disarmament, world security is better served with fewer rather than more nuclear weapons and nuclear weapon States. This found expression in the NPT which ".. shut the doors of the nuclear club" by confining nuclear weapons to the five nations that possessed them at that time. The tools to be used for this purpose was to apply safeguards on all the nuclear material in the States that had not acquired nuclear weapons and to keep a rigorous account of such material. The safeguards system to be applied by the IAEA was approved by the IAEA's Board of Governors in 1971. The States that had already acquired nuclear weapons undertook, in the NPT, to pursue in good faith the goal of eliminating them in due course without, however, setting any timetable for this process.

The third and most recent phase has consisted of a far reaching review designed to remedy shortcomings that had come to light in the 1971 system. The review began in 1991, and its results culminated in 1997 in the approval of a significantly expanded legal basis for IAEA safeguards. The review was directed, in part, at making IAEA safeguards more cost effective, and took account of recent advances in safeguards technology.

9.6.2. Safety agreements and commitments

Similarly, there may be several (regional or bilateral) agreements on safety, but at least the following should be considered.

Convention on Nuclear Safety [41]

This convention obliges parties to follow fundamental safety principles for land based civil nuclear power plants and to report on the implementation of safety measures to a conference to be held periodically. It has been in force since 1996. As of 8 May 1999, 51 Member States are party to the convention.

The Convention on Nuclear Safety was opened for signature in 1994 with the following three objectives:

(1) to achieve and maintain a high level of nuclear safety worldwide through the enhancement of national measures and international co-operation, including, where appropriate, safety related technical co-operation;

(2) to establish and maintain effective defences in nuclear installations against potential radiological hazards in order to protect individuals, society and the

environment from harmful effects of ionizing radiation from such installations;

(3) to prevent accidents with radiological consequences and to mitigate such consequences should they occur.

To this end, the convention obliges each contracting party to take, within the framework of its national law, the legislative, regulatory and administrative measures and other steps necessary for implementing its obligations under this convention, and to submit for review, a report on the measures it has taken to implement each of the obligations of this convention.

The convention also specifies obligations of contracting parties on “Legislation and regulation”, “General safety considerations” and “Safety of installations”.

Joint Convention on the Safety of Spent Fuel Management and the Safety of Radioactive Waste Management [42]

This convention obliges parties to take the appropriate steps to ensure that, at all stages of spent fuel management and radioactive waste management, individuals, society and the environment are adequately protected against radiological and other hazards, at existing facilities, siting of proposed facilities, design and construction of facilities, operation of facilities and disposal of spent fuel.

This convention shall apply to the safety of spent fuel management and radioactive waste management when the spent fuel/the radioactive waste results from the operation of civilian nuclear reactors.

The convention was opened for signature in 1997 with the following objectives:

(1) to achieve and maintain a high level of safety worldwide in spent fuel and radioactive waste management, through the enhancement of national measures and international co-operation.

(2) to ensure that during all stages of spent fuel and radioactive waste management there are effective defenses against potential hazards so that individuals, society and the environment are protected from harmful effects of ionizing radiation, now and in the future.

(3) to prevent accidents with radiological consequences and to mitigate their consequences, should they occur, during any stage of spent fuel or radioactive waste management.

As of July 1999, 39 Member States have signed the instrument including ten contracting States.

9.6.3. Other agreements involving the IAEA

Convention on Early Notification of a Nuclear Accident [43]

The Convention on Early Notification of a Nuclear Accident sets up the organizational and communications links with the IAEA and neighboring countries that would be needed in the event of a nuclear accident. It has been in force since 1986. As of April 1999, 84 States are party to the convention.

This convention shall apply in the event of any accident involving facilities or activities from which a release of radioactive material occurs or is likely to occur and which has resulted or may result in an international transboundary release that could be of radiological safety significance for another State.

In the event of an accident specified, the State party shall:

(a) notify directly, or through the IAEA, those States that are, or may be, physically affected by the nuclear accident, and the IAEA, of the nature of the accident, its time of occurrence and its exact location, where appropriate; and

(b) promptly provide the States referred to in subparagraph (a), directly or through the IAEA, with such available information relevant to minimizing the radiological consequences in those States.

Convention on Assistance in the Case of a Nuclear Accident or Radiological Emergency [***43]***

The Convention on Assistance in the Case of a Nuclear Accident or Radiological Emergency, which sets up co-operation links between countries for assistance in the case of an accident, has been in force since 1987. As of April 1999, 79 States are party to the convention.

The States parties shall co-operate between themselves and with the IAEA, in accordance with the provisions of this convention, to facilitate prompt assistance in the event of a nuclear accident or radiological emergency to minimize its consequences and to protect life, property and the environment from the effects of radioactive releases.

If a State party needs assistance in the event of a nuclear accident or radiological emergency, whether or not such accident or emergency originates within its territory, jurisdiction or control, it may call for such assistance from any other State party, directly or through the IAEA, and from the IAEA, or, where appropriate, from other international intergovernmental organizations.

The convention identifies the responsibility of the requesting State and the claimability of the assisting party. It also describes the functions of the IAEA in facilitating the necessary assistance.

Convention on the Physical Protection of Nuclear Material [44]

This convention obliges parties to make arrangements and follow defined standards for physical protection of nuclear material for peaceful purposes while in international nuclear transport as well as in domestic use, storage and transport. It has been in force since 1987.

States parties shall identify and make known to each other directly, or through the IAEA, their central authority and point of contact having responsibility for physical protection of nuclear material and for co-ordinating recovery and response operations in the event of any unauthorized removal, use or alteration of nuclear material or in the event of credible threat thereof.

The convention has been in force since 1987. As of April 1999, 64 parties had deposited the instrument of accession.

Joint Protocol Relating to the Application of the Vienna Convention on Civil Liability for Nuclear Damage of 1963 and the Paris Convention on Third Party Liability in the Field of Nuclear Energy of 1960 [45]

The Vienna Convention on Civil Liability for Nuclear Damage came into force in 1977 and established minimum standards to provide financial protection against damage resulting from certain peaceful uses of nuclear energy, in order to contribute to the development of friendly relations among nations, irrespective of their differing constitutions and systems. As of April 1999, 32 parties had deposited the instrument of accession.

The Paris Convention on Third Party Liability in the Field of Nuclear Energy was similar to the Vienna Convention in substance and came into force in 1968.

Considering that no State was a party to both conventions, the IAEA and the OECD jointly convened a conference on the relationship between the two conventions. The conference adopted the joint protocol relating to the application of the two conventions. It entered into force in 1992. Twenty States are parties to the Joint Protocol as of December 1996.

Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (London Dumping Convention)

This convention obliges the contracting parties to promote the effective control of all sources of pollution of the marine environment and to pledge themselves to take all practicable steps to prevent the pollution of the sea by dumping of waste and other matter. It came into force in 1975.

With respect to radioactive materials, the convention entrusts the IAEA with two specific responsibilities:

(1) to define “high-level radioactive wastes or other matter” as unsuitable for dumping at sea on public health, biological or other grounds, and
(2) to provide recommendations to be taken into full account by the contracting parties in the issue of permits for the dumping of “radioactive wastes or other radioactive matter not included in (1) above.”

The IAEA transferred “the definition and recommendations concerning radioactive wastes and other radioactive matter [46]” referred to in the convention to the Inter-Governmental Maritime Consultative Organization (IMCO), which performs secretariat duties in relation to the convention.

There may be other international agreements that may be relevant for a nuclear desalination project, especially for barge mounted plants. Examples include:

- International Convention for the Safety of Life at Sea, and
- Convention Relating to Civil Liability in the Field of Maritime Carriage of Nuclear Materials.

There may be other specific agreements, either regional or bilateral, for which a comprehensive list is beyond the scope of this guide.

PART III

STEPS TO INTRODUCE NUCLEAR DESALINATION

Chapter 10

POLICY ISSUES

10.1. INTRODUCTION

Water policy becomes one of the most important and critical public issues when water shortage directly affects the quality of living in a country. Among various solutions, seawater desalination offers a realistic alternative to cope with water shortage problems. Seawater desalination is an energy intensive technology. Therefore, priority should be given to full exploitation of other solutions for fulfilling potable water needs. Steps should be taken such as conservation of water, recycling of used water and development of existing water resources before deciding on seawater desalination (nuclear or otherwise).

After less expensive options have been exhausted and the policy need for seawater desalination is established, the option for nuclear desalination plants, in comparison with other energy options, should be developed. Potential reasons for selecting the nuclear option include:

- Economic advantage,
- Lowest adverse environmental and public health impact, especially compared to acid rain and greenhouse gas emissions,
- Improved energy resource self-sufficiency and long term fuel supply,
- Saving remaining fossil fuels, which are needed as vital raw materials in chemical industries and for which there is no other practical substitute,
- Reduced energy supply infrastructure requirements such as fuel transportation.

As a general observation, nuclear desalination constitutes a very important peaceful use of atomic energy in alleviating human miseries due to water scarcity. It can also expedite industrialization of developing countries with limited fossil energy resources.

It is likely that governments will have established policies related to such issues as national development (including goals and priorities), energy development (including supply) and international relations. These policies are usually of a long term nature and, likewise, are usually established by a national consensus on necessity. International relations may also largely influence the national policies including nuclear energy development. Although the policies of energy development and overall national development are closely interconnected, special attention should be focused on the energy development policy since it is a crucial factor for national development. Introduction of nuclear energy in a country is thus decided on the basis of energy policy. For the same reason, nuclear desalination should be addressed within the context of the national policies on energy, technology and water resource development.

In this chapter, the special aspects relevant to the policy issues for a country to introduce nuclear desalination will be identified and briefly discussed. This will include a review of the national energy and water policy, the national development policy and the policies concerning international and regional relations. The chapter will focus on the policy issues for integrating a nuclear energy source with a seawater desalination process. If the introduction of nuclear desalination involves the first introduction of nuclear power programme to a country, it is advisable to consult Ref. [42] for a more detailed and comprehensive discussion of policy issues.

10.2. OVERVIEW OF RELEVANT NATIONAL POLICIES

10.2.1. National development policy

Most countries have a national plan for sustainable development, which is periodically updated. This plan sets priorities for development and targets for economics, education and health, and achievements in other sectors. The plan should recognize energy resources and production as primary factors for sustained development. It should provide the essential background for the development of energy and water production and for any nuclear programme, and it should give priorities for investments. Water and power supplies are part of the basic infrastructure of a nation. The plan should forecast gaps between supply and demand and identify means for correcting the shortfall.

When energy and water self-sustainability is given high priority in a country, but has not been fully achieved at the time of decision, the means for meeting this goal must be planned and, if necessary, implemented with foreign support and participation of industrialized countries. As this development is a gradual process, the development plan should take into account the aspects to be discussed in the following paragraphs.

Level of national participation

Each country should decide on the level and extent of national participation desired at each stage in its nuclear desalination programme. National participation in the nuclear programme is a major development step and requires careful consideration and preparation. A range of participation levels is possible. In the event that the government considers that only expedient availability of electricity and water is important, a minimum level of national participation would involve a build-own-operate (BOO) type contract, in which a public consortium would take over all responsibility for the design, construction and operation of the plant. However, a common approach is to gradually increase the level of national participation. For example, the first plant may be ordered under a turnkey contract, and steady progress is then made with subsequent plant orders towards split package and multiple package contracts, each step placing increasing demands on the national infrastructures. With a corresponding expansion in the capabilities of the owner organization, it can take over the overall responsibility for the design of new plants and acquire even a capability to export plants.

Development of national infrastructure

A nuclear programme has often been seen as an opportunity for the development of a national infrastructure. A realistic and well formulated plan for a nuclear programme and for the development of infrastructures can stimulate a country's long term industrial development. The country should seek an optimum level of participation that would produce a positive industrial spin-off without jeopardizing the execution of a project. In no case should national participation affect quality.

When setting targets for national participation, policy makers should consider how the level of participation evolves together with of the overall nuclear programme. In this context, a policy of commitment to a long term nuclear programme involving several plants will give local suppliers confidence in achieving an adequate return on their investments in nuclear technology.

Development of human resources

Qualified human resources are a critical factor for the success of the nuclear desalination programme, especially for the nuclear portion of the plant. When the policy for nuclear desalination is firmly established, a plan for developing human resoures must also be established at the earliest stage because of the long lead times involved in developing highly qualified human resources.

10.2.2. National energy and water policy

A country considering a nuclear desalination programme should have a national energy and water policy specifying the objectives for the national energy and water plans. Key aspects to be addressed by the national energy and water policy include:

- Development of indigenous energy and water resources, and their infrastructure and distribution,
- Optimum management of energy and water supply,
- Stable and secure energy and water supply,
- Energy and water demand projections,
- Pricing of energy and water,
- Environmental protection,
- National standards for energy.

Policy making is not an easy task, not only with respect to technical aspects but also to national development programme goals. Where energy and water are concerned, the policy must be directed towards providing practical and effective solutions on a long term basis.

10.2.3. Policy concerning international relations

For a nuclear programme the dependence of a country on the international market or a bilateral partner for supplies is likely to last for many years. This will be facilitated by long term bilateral co-operation agreements between supplier and recipient governments, as well as between owner and other organizations and their counterparts abroad. The national policies must support such agreements. For successful implementation of a nuclear energy programme with support from abroad, it is prerequisite that the national policy support numerous and diverse international agreements and commitments related to the peaceful use of nuclear energy and its safeguards. There are also a number of international conventions, accession to which would facilitate the introduction of a nuclear programme as described in Section 8.6.

10.2.4. Regional co-operation

International relations, in general, and regional ones, in particular, have increasing importance, as shown by the number of regional associations and alliances being formed for various purposes. This applies also in the case of nuclear and desalination regional programmes as there are many topics in which regional co-operation could yield direct benefits.

It is not necessary that all parties to a regional co-operation agreement share an interest in nuclear power and its development. For example, there are some agreements involving countries that have sharply divergent views on nuclear power. An important feature of close regional co-operation is the long history of co-operative associations between these member countries, such as Euratom or ATRA.

Electric grid integration

Integration of the regional electricity grid directly benefits participating countries by increasing the security of electricity supply, improving its reliability and improving the economics of operation. Grid integration will demand co-operative planning of expansion of generation, but planning will be facilitated as a result of the wider experience available. Integration may also permit unit sizes that are larger than what any national grid could accept, and this could be very important for nuclear power development as commercially available nuclear plants tend to be large in size.

Nuclear safety

Close co-operation in nuclear safety matters between countries in a region can help to provide added assurance of the safety of plant operation. An important example is the provision for immediate access to information on incidents and accidents and co-ordination of emergency plans. Close co-operation can also give access to specialists and R&D capabilities in other countries to solve safety problems.

Environmental issues

Transboundary effects of discharge of radioactive effluents and brine can affect the region. Closer co-operation between countries can help in efforts to protect the aquatic environment. Through co-operation, human and technical resources can be shared between the countries in the region, which includes monitoring stations, analyses, and the benefit of protected environment.

Sharing of plant services

If more than one country in a region have nuclear plants there are obvious advantages in trying to share plant services, such as for plant maintenance, repair and spare parts, where feasible.

General R&D and human resource development

At a more basic level, if countries of a region combined their R&D capabilities and human resource development programmes, they could each gain tangible benefits and savings in infrastructure development.

Nuclear fuel cycle

Regional co-operation could not only bring economic benefits but could also provide added assurance of non-proliferation and safety in both operation and waste disposal. This could initially take the form of a joint storage facility for spent fuel. Later, this could be expanded to reprocessing, as needed, and disposal operations.

Non-proliferation assurances

Regional agreements can provide added non-proliferation assurance. Examples are the Tlatelolco and Rarotonga Treaties, and the Argentina–Brazil agreement. The Bangkok Treaty, creating a nuclear weapon free zone among the countries belonging to the Association of Southeast Asian Nations (ASEAN), and the Pelindaba Treaty, creating a similar zone in Africa, were opened for signature in 1995 and 1996, respectively. Work is proceeding on an equivalent treaty for the Middle East.

Water resources development

The problem of adequate potable water can also be tackled on a regional basis. There are numerous established precedents for water availability and its exploitation to be shared and practised among regional member countries, i.e. international rivers, lakes and groundwater. Water resources can also be interconnected like electricity grids in the region.

The Middle East is another region where mutual co-operation is practised in an effort to solve freshwater problems. Within the framework of the Multilateral Middle East Peace Process, the Middle East Desalination Research Centre was established in 1996 to conduct, facilitate, co-ordinate and support programmes and information exchange in desalination and related technologies, with specified emphasis on the needs of the Middle East region.

10.3. SPECIFIC POLICY ISSUES CONCERNING NUCLEAR ENERGY [42]

The responsibility for the development of all the necessary structures to create, regulate and maintain a nuclear programme rests with the government with support from different national organizations and institutions. The establishment of a nuclear programme will entail legal requirements at the national and international levels, as described in the following sections.

10.3.1. Regulatory issues

The responsibilities for the safety of nuclear installations and for radiation protection must be clearly defined in law. These responsibilities are assigned to the nuclear power plant operator and to the regulatory authority (or authorities where radiation protection and nuclear safety have been allotted to separate regulatory bodies). The regulatory authorities are responsible for establishing regulations, licensing and enforcement of regulations. IAEA standards require that the regulatory authority be clearly separated from the operating organizations. In many countries both functions have been vested with the atomic energy authority, but even in these cases there is now a clear trend towards ensuring that the functions are effectively separate.

The safety of nuclear facilities is ensured by strict application of safety rules, guides and regulations. Therefore, special emphasis must be put on establishing a national policy for safety regulations. Three examples of approaches that may be adopted in the development of a policy on safety regulations are as follows:

(1) In the past, several countries used the regulations and standards of the supplier country when importing their first plant. The basic criterion was that the plant be ‘licensable in the supplier country’.
(2) Another approach would be to adopt the IAEA NUSS Codes and the NUSS Safety Guides as a basis for regulations and standards to the extent practicable.
(3) Some countries may choose a more comprehensive system of their own. This system should be at least as strict as that laid down in the IAEA NUSS Codes.

10.3.2. Environmental protection

As established in the Kyoto Protocol [47], national energy policy should encompass the target of reducing the emission of greenhouse gases on a long term schedule. In addition the issue of limiting the radioactive effluents to the environment should be addressed in the policy. The relevant requirements include the Recommendations of the International Commission on Radiological Protection [48] and the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (London Dumping Convention) [46].

10.3.3. National participation in plant design, construction and operation

Basic industrial, technical, human resource and educational infrastructure are essential for implementing a nuclear desalination programme. In a country without nuclear industry, technology is usually acquired from countries with nuclear expertise that are able and willing to transfer it. However, for a successful technology transfer, the recipient country must be capable of absorbing the technology. The availability of qualified human resources is an essential requirement for technology transfer.

Experience shows that qualified human resources can effectively be developed by participation in the design, construction and operation of similar technical projects conducted by the technology supplying countries. When a decision is taken to launch a nuclear desalination programme in a country, the first nuclear power plant as well as the first nuclear desalination plant would most likely be supplied by foreign vendors. National participation in each stage of the programme including plant design, construction and operation as well as project management should be planned and implemented on a long term basis.

Each country has overall responsibility for planning and implementing its own national nuclear desalination programme. National participation is essential for fulfilling this responsibility. The extent of such participation will significantly depend on the existing industrial capabilities and on the availability of local resources for design, engineering, supply of necessary materials, services, equipment and qualified personnel.

10.3.4. The nuclear fuel cycle

The nuclear fuel cycle consists of a number of distinct industrial activities which can be separated into two sections: the front end comprising the steps before fuel irradiation in the nuclear reactors; and the back end, including the activities concerning the spent fuel. The national policy should address both parts of the cycle. Regarding the back end of the fuel cycle, there are three policy options for management of the spent fuel:

(1) Reprocessing for fabrication of MOX fuel to be recycled;
(2) Storage for 30 to 50 years and subsequent disposal as high level waste; and
(3) Deferral of the decision on whether to reprocess or dispose of the spent fuel.

10.3.5. Waste management and decommissioning

Waste management

Waste management involves the application of technology and resources to safely limit public and worker exposure to ionizing radiation and to protect the environment from radioactivity releases in accordance with national regulations and internationally established standards.

Operational radioactive waste from nuclear power plants is often treated to reduce its volume and/or conditioned, i.e. immobilized by converting it to a mechanically stable, insoluble form, and then packaged before its disposal. Methods for immobilization are different for low level waste (LLW) and high level waste (HLW). The technology for disposal of LLW and intermediate level waste (ILW) from nuclear plant operations is well established. For HLW, there is currently no final repository in operation, but the technology of multilayered natural and engineered barriers for the final repository is well studied [42].

Decommissioning

There are basically two options for the process of decommissioning a nuclear facility:

(1) The plant is dismantled soon after it has been removed from service.
(2) The fuel is discharged to a separate storage facility, but the remaining radioactive parts are mothballed for some period before dismantling.

In order to decommission a nuclear facility, three prerequisites must be satisfied:

(1) Well trained personnel with appropriate technical skills;
(2) A licensed storage or disposal facility to accommodate all decommissioned wastes;
(3) A regulatory basis for implementing a given decommissioning project.

The IAEA has published general decommissioning guidelines [49] for research reactors and small nuclear facilities but they can, to a great extent, also be applied to larger facilities. IAEA safety standards are currently being developed to provide more specific guidance on decommissioning regulations.

10.4. SPECIFIC POLICY ISSUES CONCERNING WATER MANAGEMENT

10.4.1. Water management policy

Elements of a water management policy include:

- making water available to increase food production,
- increasing access to drinking water and supply of water for sanitation needs,
- reducing water pollution to protect human health and the environment,
- recycling and reusing water,
- promoting regional co-operation for use of transboundary waters,
- improving human and institutional capacities to solve water problems,

- developing pricing mechanisms for water supply based on the end user and quality.

Water resource management must be based on rational policies and strategies, including trade-offs between water quantity and quality when considering demands for different public, industrial and agricultural uses. Water reuse and wastewater reclamation will be important tools for extending the water supply, particularly where marginal quality waters are adequate. Desalination of sea water or brackish groundwater can extend the supply of high quality water for potable use or specific industrial uses. Beyond these measures to boost supplies, however, only rigorous demand management could avert a looming water crisis.

As the pressure to provide adequate water supplies increases, so will the number of problems that countries must solve. In order for a country not to move to a position of higher water stress possibly with serious economic implications, certain actions must be taken, and most of them are urgent if the country is not to suffer a decline in its human, economic and environmental health.

There are some positive steps that can be taken at the national level relative to water management policy. Governments must reduce fragmentation of institutional responsibilities on water issues. It is crucial for water resources to be given high priority in planning, and water resources must be included in a country's economic studies and projections. A critical element in planning is accurate information on the state of the water resources. Over recent decades, the ability of many countries to assess water resources has actually declined because measurement networks and staffing levels have been reduced.

10.4.2. Market mechanism

Water has economic value and should be considered an economic as well as a social good. At the same time, it is essential that water planning satisfy basic human and environmental needs for water. There are inevitable controversial issues within each country that must be settled, but the direction should be towards recognizing water as an economic commodity while also stressing that provision for human consumption must be given top priority.

There is a need in many countries to begin or continue shifting the provision of water services from the government to the private sector. The government should assume the role of creator and regulator of an environment that allows involvement of communities, the private sector and non-governmental organizations in providing water and sanitation services as well as in developing and utilizing water in other sectors of the community.

The introduction of water marketing and pricing mechanisms can encourage the private sector to play an increasingly important role in providing the necessary financial resources and management skills needed for the successful development and utilization of the resources. Governments need to establish laws and regulations for the fair and efficient operation of water markets. Wherever subsidies or income transfers are deemed necessary for social or other national considerations, the objectives of such subsidies or transfers should be well defined, and the burden of the subsidy should not fall on the public or private utilities providing the service.

10.4.3. Capability building

The building of human and institutional capabilities is an essential step in preparing sustainable water strategies. It includes education, public awareness and the creation of a legal framework, institutions and an environment that enables people to take well informed decisions for the long term benefit of their society. Women, youth, non-governmental organizations and indigenous people need to be brought into capability building strategies, as they are essential in building a sustainable water future.

Important action recommendations on global water issues have been formulated at various international conferences[1]. Findings at these conferences dramatize the importance of putting into practice the concept of holistic management of fresh water as a finite and vulnerable resource, and the integration of regional water plans and programmes within the framework of national economic and social policy. Governments should incorporate these important principles in their social, economic and environmental planning.

10.4.4. Environmental protection

When implementing a nuclear desalination plant project, measures should be taken to protect the environment from the adverse effects of the desalination system. These are in addition to the normal measures taken to render the reactor system safe to the environment. In particular, the reject brine should be safely disposed of in such a way as to minimize its impact on the surrounding environment.

[1] For example, the United Nations Water Conference (Mar del Plata, 1977), the Global Consultation on Safe Water and Sanitation for the 1990s (New Delhi, 1990), the International Conference on Water and Environment (Dublin, 1992), the United Nations Conference on Water and Environment (1992), the Ministerial Conference on Drinking Water and Environmental Sanitation (Noordwijk, 1994) and the Commission on Sustainable Development (1994).

10.5. POLICY ISSUES IN FINANCING

10.5.1. Investment requirements

Nuclear plants have high initial investment costs but low fuel costs. The initial investment can be reduced to a certain extent by choosing a smaller unit. Seawater desalination plants and their accompanying facilities such as water storage, transport and distribution systems are also capital intensive installations.

It is estimated [50] that, for a medium size reactor of 500 MW(e), combined with a desalination system to produce 50 000 m^3/d of potable water, the initial investment can reach the order of US $1300 million. The desalination component would be of the order of US $50 million, i.e. less than 5% of the total plant cost. On the other hand, a nuclear desalination plant with a nuclear reactor of about 200 MW(th) producing 160 000 m^3/d desalted water would cost about US $300 million. The desalination component in this case would be of the order of about 60% [9].

The commitment of the government to a nuclear and water programme is of crucial importance in order to reduce the uncertainties and associated risks and improve the overall climate for financing. The government should prepare long term plans for nuclear energy and water development, as well as the associated financial and economic plans.

10.5.2. Electricity and water prices

National policy should be established so as to protect the owner from the effects of fluctuations in local and international currencies. If a plant is constructed on the basis of foreign financing arrangements, as is most likely in developing countries, electricity and water pricing should be adjusted to compensate for the fluctuations in currencies used for financing the project. This will minimize the effects of fluctuations in the market prices. For example, the fuel price is mainly based on international currencies, while other operational costs, such as labour costs, repair costs and other O&M costs, are to be escalated according to fluctuations in local price indices.

10.5.3. Basic financing and contracting approaches

The magnitude of the investment and the constraints to financing underscore the need to explore financing for a nuclear desalination project from all possible sources, both local and foreign. Examples of international financing sources include:

- public sector export credits;

- suppliers’ credits and financing arrangements through commercial banks guaranteed by export credit guarantee agencies and by multilateral development and financing institutions;
- bilateral financing sources; and
- private international markets for commercial loans and international bonds.

The financing of local costs is one of the most difficult problems for power projects in many countries. Domestic funds should be used to finance as much as possible of the total project costs, but in any event the local portion of these costs. Difficulties in financing local costs arise from shortages of utility and government funds and constraints in local capital markets. A well functioning domestic capital market is particularly important for organizing local financing.

In view of the increasing need for foreign exchange in most developing countries as regards meeting the financing requirements of a nuclear project, additional and complementary mechanisms are being sought. An approach most likely to be viable will be a build-operate-transfer (BOT) approach as described in Section 13.3.

Chapter 11

NUCLEAR DESALINATION PLANNING

11.1. INTRODUCTION

Implementation of a nuclear desalination plant project requires a programme of long term development strategy planning. The programme plan should consider several activities such as siting, design, construction, commissioning, plant operation, disposal of reject brine commensurate with statutory and regulatory guidelines, and development of supporting infrastructure and services.

The nuclear desalination programme is essentially integrated into the nuclear power programme. It is a major undertaking involving several organizations and constitutes a substantial effort on the national level. The programme planning is a continuous activity requiring constant updating due to the changing technological, demographic and social developments within the country concerned.

In order to implement a nuclear desalination project, the first task to be performed is a nuclear desalination programme planning study (NDPPS). The objectives of such a planning study are to:

- Assess the need, demand and economic viability of nuclear desalination, considering alternative water and energy sources;
- Determine the siting requirements; and
- Prepare the overall schedule for the programme that might be required.

The NDPPS should examine the long term needs and include a comparison of alternative water (and power) supply options as well as alternative technologies. This comparison helps to determine the role that nuclear desalination could play in the long term water and energy programme.

The planning tasks require a small but highly qualified professional team with ample experience covering a wide range of subjects. It may be difficult to find professionals who satisfy the technical qualifications, especially in a country that is just starting to plan its nuclear desalination programme. In such cases, foreign advisors or consultants as needed could complement the national team.

11.2. NATIONAL WATER PLANNING

The supply of water is essential for any economic and industrial activity as well as for maintaining the health and hygiene of humanity. In order to meet this need, water planning should be carried out on a national level and kept under constant review. This involves an analysis of past trends and present situations in the water market, survey of water resources and forecasts of water demand and supply. National water planning is essential for formulating policies and strategies for the water sector in the country concerned.

11.2.1. National water structure

The inclusion of a nuclear desalination programme into the national water supply plan is performed only after a careful analysis of the overall water structure of the country. The national water structure requires studying the overall water balance. If a national water balance is not available, it should be performed as an integral part of the nuclear desalination planning study.

The analysis of the water structure includes the following aspects:

- Water consumption by different sectors;
- Water production, availability and source potential; and
- Cost structure of the fresh water produced or treated and supplied.

The objective of such an analysis is to determine the trends in the composition of consumption of water, water resources and costs.

11.2.2. Availability of water resources

In order to develop a national water policy, a survey is needed to provide a reasonable knowledge of the country’s available and potential water resources. The survey should consider fulfilment of national water requirements from natural resources and water reclamation. In principle, the use of natural resources should have the first priority for any country. However, there might be situations wherein water reclamation is preferred because of economic reasons, even if there are available municipal resources.

The relevant existing and prospective water resources to be surveyed are:

- Rainfall and its collection systems,
- Surface water (rivers, lakes, dams),
- Underground water resources,
- Reclaimed water from domestic and industrial effluents,
- Desalination.

In general, the survey of water resources should be as complete as possible, taking into account the following main aspects:

- Quantity of resources: proven, probable, possible, speculative, etc.;
- Quality in terms of composition and characteristics of these resources;
- Costs in terms of development into its effective use, including environmental protection measures;
- Technical feasibility of development and use.

While a survey of the country's water resources may be readily available, its periodic review constitutes an important part of the nuclear desalination planning phase so that alternate possibilities of augmenting water resources can be correctly considered.

11.2.3. Water demand forecast

The water demand forecast is carried out under a frame of reference which includes the time period to be covered, the purpose of the study and the forecasting methodology. The data used, the criteria applied, and the methodology adopted will decide the results obtained. Such forecasts are usually classified according to the time period they cover. Typical classifications for water resource planning are:

- Short term (up to 5 years),
- Medium term (up to 15 years),
- Long term (20 years and longer).

Short term forecasts are intended to predict the water demand in the immediate future. They are based on an evaluation of prevailing conditions and of programmes under development. Medium term forecasts are intended for planning the actions that have to be taken in the near future in order to ensure an adequate water supply. Such forecasts are usually project oriented and provide information needed for investment decisions. The methods used for forecasting are based on extrapolating the population growth over the forecast period as covered by the forecast, taking into account the prevailing conditions and programmes under development. Water demand forecast in the long term based on the development of scenarios provides the basis for supply policy and strategy decisions. Past and prevailing trends in water demand are extrapolated by applying correlations between economic growth rates, economic development programmes and water consumption. For developing countries, the forecast methodology should pay great attention to the growth rates of the urban and the industrial sectors.

The approach for carrying out a water demand forecast involves the following steps:

(1) Identification of major factors determining water demand, population growth, irrigation and industry;

(2) Evaluation of the influence of changes in the evolution of these factors on the water demand;
(3) Determination of water demand growth resulting from the development of various sectors of society;
(4) A systematic analysis of the changing social, economic and technological factors contributing to the long term water demand evolution.

11.2.4. Water supply planning

Water supply planning is focused on the development of additional water resources to meet the demand forecast. The planning activity should take into account the major factors that could affect the development of new water supplies. These include:

- Availability of natural water resources;
- Availability of technology to convert or reclaim water from domestic and industrial effluents, and desalination;
- Current and estimated demand based on population growth, economic and industrial development;
- Current and estimated future costs of water;
- Investment and financial requirements for water supply, installation of water reclamation and desalting plants;
- Conservation of resources.

During the past three decades, awareness of the necessity to conserve the natural water resources has spread among major policy makers, and the concept of water reclamation and reuse has become a desirable option for meeting water demands. The 'water conscience' is an emerging theme in the basic philosophy of judicious use of natural water resources and of renewable water and desalination to promote a sustainable water supply to the country.

11.3. NATIONAL ENERGY PLANNING

Energy production is essential for progress and is closely correlated to a country's level of economic development. An adequate supply of energy is essential for promoting industrial activity and improving the quality of life of humanity.

An energy market analysis should be performed and periodically reviewed in any country. Methodologies ranging from simple to very sophisticated have been developed and are widely available for such an analysis. The energy market analysis considers the prevailing energy situation including the forecasts of energy demand and supply and a survey of energy resources.

11.3.1. National energy structure

National energy structure analysis is intended to provide a baseline for how energy is consumed and supplied in the current condition within the country. This involves obtaining data on:

- Energy consumption by industrial sector and by energy form,
- Energy imports and production by energy form,
- Energy cost structure.

A key consideration is that portion of the energy structure that is filled by electricity production, because this is the primary justification for embarking upon a nuclear power programme. To a lesser extent, nuclear heat production can occupy part of the national energy structure.

11.3.2. Availability of energy resources

A survey of available and potential energy sources is needed to formulate a national energy plan. A periodic review of these resources is an important activity towards establishing a national energy plan including nuclear power planning. The most relevant energy resources to be surveyed are uranium, hydropower, coal reserves, oil and natural gas. Renewable sources such as geothermal, wind, biomass, tidal and solar should also be surveyed. The survey should specify the availability of domestic energy resources and the dependence on imported energy. The survey of energy resources should be as complete as possible, taking into account the quantity, quality, costs of development and use, environmental protection measures and technical feasibility of development and use [13].

It may be difficult to evaluate the availability of energy resources for long term planning. In such cases, extrapolation of the known data on proven reserves, technical feasibility and cost of recovery may be necessary. Such extrapolations should be regarded as indicators of magnitude and need to be classified according to the degree of confidence in their accuracy.

11.3.3. Energy demand forecast

Energy demand forecasts are usually classified according to the period they cover, namely short term, medium term and long term. Short term demands typically cover a period of up to five years and are intended to predict the energy demand in the immediate future. They are based on existing conditions and programmes under development. Medium term forecasts typically cover a period of 10 to 15 years and are intended to support planning actions that need to be taken in the near future to ensure adequate energy supply. They are carried out by extrapolating the energy demand over the forecast period, taking into account the planned national development programmes. Water demand in the long term is of a scenario nature in terms of some assumptions on economic growth rates and energy consumption characteristics and policies adopted in the future.

The IAEA has developed the Model for Analysis of Energy Demand (MAED) to provide assistance to Member States in evaluating the future energy demands [13]. The MAED simulation model provides a flexible framework for incorporating the influence of social, economic, technological and policy changes into the long term evolution of energy demand.

11.3.4. Energy supply planning

The energy supply plan should be based on the country's energy structure and energy demand forecasts, and it should account for any major constraints that could limit the development of the energy supply. Some of these are as follows:

- Availability of national energy resources and assurance of energy supply from the international market;
- Technical capability for energy source development;
- Availability in some of the developing countries of conversion techniques from primary energy source to final form;
- Current and estimated future costs of energy development, investment and financing;
- Conservation of resources for sustained energy;
- Environmental impact from expanded exploitation.

11.4. SPECIFIC ELEMENTS OF NUCLEAR DESALINATION PLANNING

When the national plan identifies nuclear desalination as a way for fulfilling the country's energy and water needs, several factors must be addressed in the detailed development of the plan.

11.4.1. Plant capacity

An important consideration in selecting the capacity of the nuclear desalination plant is whether the plant will be single purpose or dual-purpose. In single purpose plants, where the energy produced in the nuclear reactor is exclusively used for desalination, the following advantages are inherent: siting of single purpose plants is more flexible than siting of dual-purpose plants. Smaller single purpose nuclear plants are likely to have improved safety characteristics, simple organizational requirements, reduced investment and shorter construction and commissioning periods.

In dual-purpose, plants where the reactor is designed to provide electricity as well as desalted water, the following advantages are inherent: the economy of dual-purpose plants is better because electricity as well as water can be sold. A larger nuclear power reactor can be chosen, thus taking advantage of the economy of scale. However, the plant should not constitute too large a fraction of the electricity and water supply.

The respective capacities of the nuclear power and desalination facilities must be taken into account when considering a combination of these two technologies. Whether a heat driven process or an electricity driven desalination process is chosen, the energy requirement may be small, and thus the small size of the nuclear power plant will better match the energy requirement. The mismatch in scale is significant even for the few very large desalination plants that have been deployed or are being discussed. If there is a large market for electricity in a region with an integrated electrical grid, this mismatch in size may be relatively unimportant. If this is the case, the size of the desalination plant can be optimized, independently of the power plant because all the excess electricity can be consumed through the grid.

In the case of single purpose nuclear desalination plants, the need for very small nuclear reactors would be indicated. Such plants would be suitable for areas without well developed electrical grids. Large nuclear reactors for electricity generation are available on a commercial basis, but experience with modern small nuclear reactors for single purpose desalination plants is limited.

11.4.2. Type of energy

Commercial desalination plants need energy either as heat or as electricity. Nuclear power plants can supply either or both, and therefore a comparative study needs to be carried out on the preferred combination of nuclear plant and desalination process. Nuclear power reactors can generate steam, hot water or a hot thermal fluid for use as a heat source directly to drive distillation based desalination plants such as MSF and MED. Nuclear power reactors can also supply electrical energy to drive RO, ED, MVC and membrane distillation. The relative merits of these processes are discussed in Chapter 3. The selection of the optimum combination will be based on economics, site factors, reliability, available technical expertise and prior experience.

11.4.3. Programme schedule

The schedule for completing acquisition, licensing, construction and commissioning of a nuclear plant and desalination plant needs to be carefully integrated. In the case of a nuclear plant, this time could be as short as five years after award of contract in an ideal project environment but is more likely to be around 6 to 8 years. By contrast, the same activities for the desalination plant may take only two to three years. Thus, the optimum time for installation of the desalination plant during the nuclear plant construction must be determined. It could be constructed early if an alternate source of energy is available, and if the potable water produced could be used during the nuclear plant construction or to generate early revenues from the water sales [51].

Alternatively, the desalination plant could be constructed late in the schedule to minimize capital investment during the period of reactor construction. Other factors favouring late desalination plant construction are the potential for improvements in desalination technology during the period of reactor construction and potential new requirements for additional water production capacity. Addition of extra facilities during initial construction in anticipation of increase in desalination capacity would require extra investment and result in unnecessary high product costs prior to the requirement of additional capacity.

11.4.4. Financing

The allocation of financial resources to any project to meet electricity and water demands should recognize the fact that water and electricity constitute a basic human necessity. Financing is a major constraint to nuclear desalination deployment because of the large initial investment. Some countries will be able to pay for their own needs, in addition to providing some financial help for others. Still, a substantial amount of financial resources will have to be found for many other countries needing fresh water. Because of the critical nature of the problem, ways must be found to overcome the financial problems.

A multisource financing approach may be developed for nuclear desalination. This may involve the following:

- International organizations;
- Public or government bodies;
- Private enterprises;
- The international banking community.

A long term, continuously sustained financial programme is necessary to support those countries where the need for water is a question of life.

11.4.5. National infrastructure and participation

Successful implementation of a nuclear desalination programme requires sound national infrastructure, availability of technical staff, financial resources and regulatory guidelines. The available industrial infrastructure within the country should be closely associated with the programme. Some competent construction and erection companies should be included in this infrastructure. The indigenous infrastructure may not have all the technology, know-how, level of quality, competence and expertise necessary for nuclear systems, but these capabilities can be acquired through technology transfer [37].

The infrastructure should include a robust electrical grid with at least a modest user capacity. Except in the case of a heat-only reactor, the nuclear desalination plant will normally generate a surplus of electricity. The electrical grid must have an adequate interconnected capacity corresponding to the size of the power reactor chosen.

Each country has the overall responsibility for the planning and implementation of its own national nuclear desalination programme. National participation is very essential for assuming this responsibility. The extent of such participation will significantly depend on the existing industrial capabilities and the availability of local resources for the supply of necessary technologies, materials, services, equipment and qualified personnel.

11.4.6. Availability of relevant personnel resources and training programme

Availability of skilled human resources and educational infrastructures are essential ingredients in any country embarking upon a sustained nuclear desalination programme. In a country without a nuclear industry, technology is usually acquired from a country with nuclear expertise. However, for successful transfer of technology, the country must be capable of absorbing the technology. The essential element is the availability of qualified human resources. A lack of qualified human resources and educational programmes will constitute principal constraints to the implementation of a nuclear desalination programme. Considerable effort and time must be spent in providing training programmes for development of skilled human resources. Countries with established nuclear programmes including educational institutions can assist in this regard.

11.4.7. Siting considerations

Siting considerations for a nuclear desalination plant are almost identical to those of a nuclear power plant. The identification, selection, evaluation and authorization of suitable sites for nuclear desalination plants require extensive studies and consideration of a large number of factors. Safety requirements associated with siting either a nuclear power plant or nuclear desalination plant dictate an isolation distance from population centres (where the water is consumed). This requirement will increase the distance for transporting the product water to the distribution system, thus adding to the overall water cost. The site should also have provisions for system expansion. Since the power plant needs cooling water and desalination plant needs feedwater, proximity of the nuclear desalination plant to the seacoast is mandatory. The environmental impact of brine disposal is a serious matter, which may favour coast locations that are more adaptable to economic brine dispersal. If the economic incentive for co-siting the desalination plant with the nuclear plant is marginal, the selection of an electricity using process such as RO may be more appropriate, because it would allow separate siting of the nuclear and desalination plants.

11.4.8. Licensing considerations

The licensing and regulatory framework has a major impact on the design, construction and operation of a nuclear desalination plant. This framework needs to be established and co-ordinated among the following classes of authorities:

- Regulators of nuclear facilities;
- Regulators of water production facilities;
- Public health officials;
- Regulators of electricity production and distribution;
- Siting and environmental regulators.

Because of the large number of authorities involved, licensing and operation of an integrated nuclear desalination facility may be more difficult than for separate power production and desalination plants. In order to implement a nuclear desalination programme in a timely manner, it is necessary to address the legislative aspects for establishing a legal framework for the project at the earliest. Licensing considerations should incorporate radiological protection, nuclear safety, environmental protection, radioactive waste management and control of nuclear materials.

Regulatory actions and licensing of nuclear desalination facilities constitute a national responsibility, which cannot be transferred elsewhere nor shared internationally. Each country must have its own regulatory and licensing authority with its own structure, rules, guides and procedures.

11.4.9. Public acceptance

Public acceptance is vital for the implementation of a nuclear programme and for nuclear facilities. It is even more important for a nuclear desalination plant as the water produced is to be used for human consumption. In many countries, a majority of the public is concerned about the risk of a serious reactor accident and the nuclear waste issue. In some countries, public opposition has even halted or prevented nuclear projects.

It is essential to inform the public early through a carefully designed long term information and education programme, based on correct and objective information. The public should be informed on the precise nature of the planned facility, experience with this kind of facility elsewhere, its costs, safety concept, environmental impact and potential benefits for the local community. The information must be complete and correct and should be presented early and in a well understandable fashion. In particular, the safety aspects such as continuous monitoring and isolation devices need be highlighted. Public participation in the early stages of the strategic planning and decision making process can be an effective mechanism for identifying and resolving public concerns regarding all aspects of the project.

11.4.10. Project management

A nuclear desalination project combines two activities that are normally carried out by separate entities. The management of a nuclear power project is usually done by an organization that is experienced in the generation and distribution of electricity, steam and heat. The management of desalination project generally is the responsibility of the utility that is specialized in the treatment and distribution of potable water. A nuclear desalination plant is a joint enterprise wherein equitable working arrangements must be developed among the participating parties for ownership, financing and management during construction and operation of the plant throughout its useful lifetime.

In nuclear desalination project management, detailed consideration should be given to various ownership options that may be practical. The entire plant may be owned by water utilities with surplus electricity sold to electric utilities in the region, or the entire plant may be owned by the electric utility with water sold to water utilities in the region. Alternatively, the plant could be owned jointly by water and electric utilities with negotiated allocation of costs to water and electricity. Also, a third party could own the plant and sell water and electricity to utilities at competitive rates.

Whether plant ownership is based on single or multiparty participation, the project management team should have representatives from water and electricity utilities. The responsibilities and authority of the respective parties need to be defined for the construction phase as well as the operational phase of the plant. Priorities must be developed for allocating available energy between the desalination plant and electricity supply during load fluctuations and partial outages of the nuclear reactor. The responsibilities and liabilities of the parties for the production of their respective products must be carefully defined in advance and contingencies must be developed for problems that may be expected to arise. A nuclear related project will require strong government involvement because it is a long term national project, investment intensive and energy related [36].

11.4.11. Expected benefits and constraints

Several economic benefits can accrue from the simultaneous generation of electricity and water. These include:

- Common use of the seawater intake/outfall system,
- Sharing of common facilities, services and staff,
- Feedwater preheating for the case of RO.

A nuclear desalination plant can utilize a common seawater intake/outfall system for providing feedwater and brine discharge for the desalination plant and cooling water for the power plant. The common seawater intake/outfall facility contributes to a reduction in the water cost.

Co-location of a nuclear power plant and a desalination plant makes it possible to share the infrastructure, maintenance facilities and service systems. Harbour, road and rail access, shipping and receiving facilities, maintenance shops and storage facilities, personnel accommodation and administration premises could be common to both plants. The operation and maintenance functions of the nuclear plant and the desalination plant must be closely co-ordinated. For this reason, it is desirable to have a single operating organization to run the entire complex.

A negative cost impact is associated with the isolation of the nuclear power reactor from the population centre due to radiological safety considerations. The costs incurred in potable water transport and distribution to the user may be higher, because of increased pumping power requirements and water losses en route.

11.4.12. International/bilateral co-operation

Sound and consistent international relation policies are important to the implementation of a nuclear desalination project since the international community has a wealth of technical experience and expertise, which it can make available through co-operation agreements and commercial contracts. Also, the project management will make use of the international market for nuclear and desalination equipment and technology transfer. National policies aimed at good international relations can do much to support nuclear technology development. Long term bilateral co-operation agreements between the supplier and recipient governments will facilitate launching an extensive nuclear desalination programme.

11.5. LONG TERM NUCLEAR DESALINATION EXPANSION PLANNING

The prime objective of long term nuclear desalination expansion planning is to provide a reliable and sustained supply of electricity and water using nuclear energy at the lowest possible cost with attention to public safety and environmental protection.

11.5.1. Expansion planning of a nuclear desalination programme

Long term expansion planning of a nuclear desalination programme involves consideration of several important aspects such as:

- Long term national energy and water policies;
- Reliable forecast for energy and water supply demand;
- Relative economic competitiveness of the nuclear powered and fossil fuelled desalination units of a given size;
- Choice of optimum power and desalination plant size;
- Siting of the plants;
- Available raw material resources of the country;
- Possible international relations affecting the supply of power and desalination equipment.

11.5.2. Considerations of expansion parameters and constraints

The use of mathematical models and computer programs for nuclear desalination expansion planning permits consideration of large number of relevant factors. It also saves time and reduces error. However, the accuracy of this approach depends on the quality of the input data. Preparation of the input database requires a lot of time and effort by highly qualified and experienced professionals who are familiar with the national energy and water supply system. The required data can be grouped as follows:

- Technical and economic data on the existing electricity and water supply system;
- Technical and economic data on the committed expansion of the system;
- Characteristics of alternate expansion options;
- Demand forecast;
- System operation experience and reliability criteria; and
- Economic ground rules and constraints.

11.5.3. Admissible unit size

Economy of scale plays a major role in reducing the specific cost of installed capacity, and this is particularly so for nuclear desalination. However, increasing the unit size of nuclear desalination systems has associated penalties such as upgrading the transmission network, supply disturbance in case of plant outage, etc. There exists an economically optimum unit size for each site, which accounts for the demand increase, system reliability, transmission network and economy of scale.

11.5.4. Economic optimization

The aim of economic optimization of nuclear desalination expansion planning is to determine the least cost pattern of system expansion to meet the electricity and water demand over a given period. Various models can be used for the economic optimization process. Simulation models formulate the system expansion on the basis of a predetermined investment strategy, minimum discounted costs and maximum rate of return. This involves analysis of all the benefits and costs, both direct and indirect, for various alternate system expansion patterns. It also involves determining the expansion pattern yielding maximum total net benefits. In working out the benefit analysis, the value of acquiring a pool of skilled personnel, upgrading of local industry and the overall impact on the balance of payment situation of the country need to be considered. The external costs incurred in combating environmental pollution also need to be taken into account.

Chapter 12

SITING OF NUCLEAR DESALINATION PLANTS

12.1. INTRODUCTION

The selection of a desalination plant site within a country or region is primarily governed by current or projected shortages of local water resources for the local population, industries and agriculture. The non-availability of a suitable energy source in the location could support adoption of nuclear desalination. When a nuclear reactor is selected as an energy source for desalination, special attention has to be given to the safety and environmental effects on the potential plant sites. This requires, among other things, detailed site qualification studies because locations adequate for siting conventional desalination plants may not satisfy the requirements for siting nuclear desalination plants. Also, site related factors can have a substantial impact on the cost of the nuclear desalination plant.

The selection of a suitable site is an important stage in the implementation of a nuclear desalination project. The objective of site selection study is to minimize cost, environmental impact and risk to the population. The study will also establish the site related inputs to design of the plant.

A large nuclear desalination plant could have an impact on the environment through its rejected heat and its brine and may affect the environment through radioactivity releases. However, with careful site selection and a good plant design, this impact can be reduced below regulation limits. The large amount of rejected heat should have no significant adverse effects on the species present in the aquatic environment into which the heat is discharged. It is also necessary to preclude the potential release of radioactive contaminants into the product water or reject brine streams.

A site is considered acceptable from the safety point of view if:

- There are no destructive phenomena against which protection through the design is impracticable;
- The probability of occurrence of severe destructive phenomena against which the plant can be protected (at reasonable additional cost) is small;
- The site characteristics (population distribution, meteorology, hydrology, etc.) are such that the consequences of potential accidents would be within acceptable limits.

The main activities related to siting of a nuclear desalination project can be divided into the following two stages:

(1) ***Site survey:*** The purpose of the site survey is to identify one or more suitable sites. This involves general studies and investigations of a large region to eliminate unacceptable areas. This is followed by systematic analysis and comparison of the remaining areas to define potential sites and to finally select the preferred candidate sites.

(2) ***Site evaluation:*** This stage might also be called candidate site qualification. Its purpose is to demonstrate that the preferred site(s) is (are) acceptable from all aspects, particularly public safety, and to prepare the required documentation for review and approval by the regulatory body. On-site measurements of seismic, meteorological and hydrological characteristics are to be involved at this stage. This information is used to prepare site related design specifications to be used in plant design and construction.

After the start of construction and before the start of plant operation, additional site studies are performed to complete and refine the assessment of site characteristics, as needed for plant operation. These studies also support the development of emergency plans for the case of potential accidents.

The safety criteria for siting small scale nuclear desalination plants, using dedicated heating reactors, can be more flexible than those for large scale co-generating plants, because of their limited radioactive inventory. Large scale nuclear desalination plants need a heat source of the order of a few hundreds of MW(th), which is close to the size range of a nuclear power plant. The siting of such plants requires a far greater degree of depth and effort. References [52–66] provide relevant information on siting nuclear power plants.

12.2. NUCLEAR DESALINATION PLANT SITE CHARACTERISTICS AND REQUIREMENTS

12.2.1. Site location and infrastructure

The distance between load centres and possible sites is one of the important factors to be considered in the siting survey. For desalination plants, whether nuclear or not, this distance is generally more meaningful than for power plants since the water transmission cost is higher than the electricity transmission cost. Furthermore, the topographical conditions, in particular elevation rises and falls, have a strong impact on the water transmission cost.

Since water transmission and distribution are more costly than those of electricity, the topographical data, both at the possible nuclear desalination plant sites and at the consumption centres, should be evaluated for the economic purposes. Mountainous or hilly areas between the plant and the consumer centre introduce a significant cost penalty.

At a nuclear desalination plant, the nuclear power portion of the plant has a very strong influence on the site location. The nuclear plant requires adequate and reliable startup power. An adequate supply of water for cooling purposes must be available. Both cooling water quality and temperature are relevant factors in this regard. Adequate communication links should be available at the site, and transportation routes are necessary for conveying the large, heavy equipment of the nuclear desalination plant to the site.

The extent of work necessary for site preparation and, later on, for construction is a relevant factor in a site survey. Some of these aspects can be evaluated through analysis of topographic maps, whereas other aspects such as soil characteristics require some data collection. Most of these aspects and factors are similar for nuclear and fossil fired plants.

12.2.2. Effects of the site on the plant

The effects of the site on the plant include all environmental phenomena and human induced events that may affect the performance, safety and reliability of the plant. Oceanographic and topographical conditions such as seawater quality, and external events such as earthquakes, flooding, extreme meteorological events, air crashes and explosions, need to be considered.

As a result of studying these characteristics, a site may be eliminated because of a significant probability of occurrence of extreme events against which it is not practical to protect the plant. Design bases are determined (design input data and parameters) for other extreme events against which it is practical to protect the plant. These define, in engineering terms, the effects against which measures must be taken when designing the plant.

All site specific conditions which must be considered for nuclear power plants must also be applied to nuclear desalination plants [53–62], such as:

- Geological characteristics,
- Seismology,
- Volcanism,
- Flooding,
- Oceanographic and topographical conditions.

Nuclear seawater desalination plants use sea water as feed for both the desalination plant as well as the cooling water for the nuclear plant, usually through a common intake. Seawater quality and its oceanographic data have an influence on the desalination plant cost and performance. Important quality parameters of sea water include physical, chemical, biological, toxicological and radiological characteristics. Other important data include daily, seasonal and annual oceanographic characteristics.

12.2.3. Impact of the plant on the site

The factors related to the potential impact of the plant on the site are important for the determination of the consequences of potential accidents and normal releases. The main impact is the effect on the population in the site area or region. As in the previous section, the relevant features addressed in the nuclear power plant siting also apply to all nuclear desalination plants. These features include:

Population distribution

The main objective of studying the population distribution is to ensure the feasibility of an effective emergency plan. Many factors play a role in this assessment, in addition to the plant and site characteristics. Especially relevant are the overall population density and its distribution within the region, the general level of current and foreseen socioeconomical development, and the transportation and communication systems, which become most important in an emergency.

Radioactive release

The radioactivity released from the nuclear plant in anticipated operational occurrences and accident conditions should be carefully evaluated (relevant guidelines exist for single-purpose nuclear power plants). The possibility of radioactivity ingress into feedwater for the desalination plant should be included. Therefore, dispersion of radioactivity in the sea water, especially the sea currents in the area, should be carefully evaluated.

Regarding the direct impact on the population in the area, the radiation doses may be calculated and their acceptability assessed using the same methodology as practised in nuclear power plant siting. The studies during the site survey stage are directed towards avoiding locations where the dispersion conditions are unfavourable. During the site evaluation phase, the site dispersion characteristics under various meteorological and wind conditions should be precisely studied. This information will be used in the preliminary safety report to assess the impact of radioactive releases and to provide necessary information for preparing the emergency plan.

Environmental considerations

A nuclear desalination plant can impact the aquatic environment mainly by subjecting the aquatic organisms to possible temperature increases and salinity changes in the vicinity of the cooling water and brine discharges. Aquatic organisms in water bodies on or near the site may also be affected by dredging operations and clearing of vegetation.

Some of these potential environmental and health impacts are common to both nuclear and fossil fired plants, e.g. those resulting from the discharge of brine, waste heat (usually cooling water) and chemicals. Other impacts are specific to specific fuels and technologies, e.g. those from the airborne pollutants from fossil fuelled desalination plants and from radioactive wastes and effluents of nuclear desalination plants.

Both nuclear and non-nuclear desalination plants discharge heated brine, which is several degrees centigrade warmer than the ambient seawater temperature. The brine may also contain chemicals which originate from intake water pretreatment, cleaning wastes, plant drains and sanitary wastes. The chemical contents of these discharges will vary from plant to plant but will not substantially differ between nuclear and non-nuclear desalination. The discharge of highly saline brine itself can have an adverse environmental impact on aquatic life unless properly accounted for in the design of the discharge system. Regular discharge of dense brine and warm cooling water could help to safely disperse the brine and reduce its environmental impact.

All environmental impacts and health risks should be properly evaluated together with the other requirements and objectives of water and electricity production. This environmental impact analysis may require that appropriate models and data be developed specifically for the proposed site and type of plant expected to be constructed and operated.

12.2.4. Impact of extreme external events

The extreme external events that are relevant to nuclear desalination plant design are the natural and the human induced extreme external events that could damage the plant if it is not properly protected. Natural extreme events are disastrous natural phenomena, such as tornadoes, earthquakes, surges, floods, etc. Human induced extreme events are disastrous events produced by human activities, such as air crashes, chemical explosions, drifting explosive clouds, etc. A nuclear desalination plant has to be protected against any disastrous event of sufficient probability of occurrence [53–59].

12.2.5. Socioeconomical and cultural aspects

The construction and operation of a nuclear desalination plant involves several non-safety-related factors that influence local population. In areas of high unemployment, a plant may generate a significant number of jobs during the construction phase. On the other hand, the workforce associated with the plant may also place demands on local infrastructure resources (housing, schools, transportation, medical services, recreation, etc.). Construction of a nuclear desalination plant may also require provision of infrastructures for an international community involved in plant construction. It is desirable that possible adverse social impacts of the plant be minimized and social benefits enhanced.

The construction and operation of a nuclear desalination plant expand local habitability on the one hand, but may also generate traffic related noise and visual effects which may disturb some local residents, on the other hand. It may also disturb or limit the access to important archaeological remains, if present, and may modify the landscape in a way unappealing to the local communities. With some effort, acceptable solutions may be found in all these cases.

An important impact on the terrestrial environment occurs during the clearing of terrain for the construction of plant facilities. Other construction and operational activities may generate noise, dust and emissions of biocides. The existing and planned land use in the site area such as agriculture, recreational facilities or tourism should also be taken into account.

12.3. SITE SURVEY STAGE

The objective of a site survey is the identification of one or more preferred candidate sites within a region with a high probability of being suitable for construction of a nuclear desalination plant. The region should be large enough to provide a sufficient number of attractive options for candidate site selection. All site characteristics that could affect site suitability should be considered in the site survey. These have been identified and briefly discussed in Section 12.2.

A site survey programme is usually developed at the beginning of the survey. The programme should include:

- Identification, description and/or specification of the tasks to be performed during the site survey;
- Sequence diagrams showing the relationship between the various tasks and site characteristics to be considered at each phase;
- Criteria adopted for the regional analysis, screening of potential sites and comparison of candidate sites (the criteria should be listed for each site characteristic);
- Outline of the procedures for applying these criterias and a list of sources of information needed for their application;
- Comprehensive schedule.

On the basis of the site survey results, the preferred candidate sites can be identified and ranked. All the data and information collected or developed should be documented in the final report because they represent the starting point for the following stage of site evaluation.

12.3.1. Procedure and methodology

The site survey for a nuclear desalination plant may reasonably follow the procedures for nuclear power plants, which are divided into the following phases:

Phase 1: Regional analysis and identification of potential sites;
Phase 2: Screening of potential sites and selection of candidate sites;
Phase 3: Comparison of candidate sites and identification of preferred candidate sites.

Figure 12.1 illustrates the procedure that leads to identification of candidate sites.

In each of these phases, those relevant site characteristics are considered that either may lead to the rejection of unacceptable areas or sites, or lead to the identification of more suitable ones.

The main safety requirements that should be satisfied during a site survey are that all safety characteristics be considered at least once, and that the suitability of the site with respect to each safety related factor be confirmed.

Two approaches may be followed in performing a site survey: a ‘parallel approach’ or a ‘series approach’. In the parallel approach, all the necessary information is collected for all areas and sites. In the series approach, all the necessary information is collected only for areas and sites not rejected previously. In general, the parallel approach is favoured in site surveys because it is not necessary to await the result of the rejection process before proceeding with the collection of additional information, as described in the following paragraphs.

Phase I — Regional analysis and selection of potential sites

In the regional analysis, available information on certain site characteristics is used to reject major areas of the region from further consideration. The region of interest is usually very large, and a detailed survey of every part cannot be performed, nor is it necessary. The site characteristics selected for the regional analysis are preferably ones for which information is readily available and simple rejection criteria may be adopted (such as cooling water availability, water and electric load and transmission considerations, access, population density, surface faulting, topography, volcanism, oceanography, flooding and seismicity). Much of the

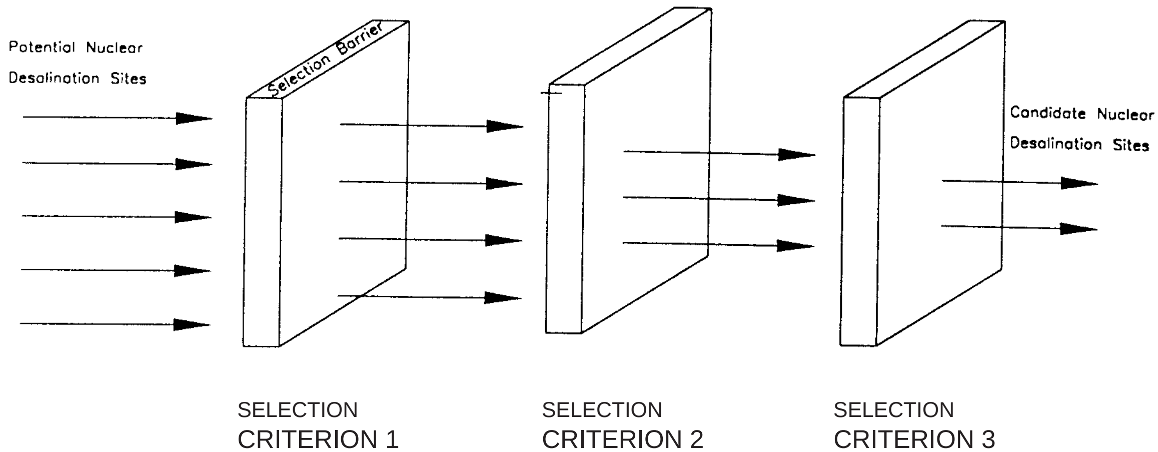

FIG. 12.1. Schematic of procedure that leads to candidate sites.

information needed for the characteristics selected for the regional analysis are already available or easily obtained from maps, census data, existing geological and seismic data or cursory surveys of the region.

The main result of the regional analysis is the identification of the areas that have no disqualifying features. Within these areas, sites of a few square kilometres are identified as ‘potential sites’. These potential sites are somewhat larger than required for a nuclear desalination plant site so that during a later stage of the siting process the exact plant location can easily be accommodated therein. The identification of these potential sites may be accomplished by the application of good technical judgement. The overall objective is to obtain a set of potential sites that include a complete representation of the different areas of the region so that the selection process may proceed in a comprehensive manner. A considerable number of potential sites will usually result from the process, although smaller or greater numbers are also possible.

Phase 2 — Screening of potential sites and selection of candidate sites

In this phase, the potential sites are screened by using site characteristics not considered in the regional analysis, as well as more refined criteria than those used for the previous phase. It will not be economically or technically feasible (nor is it necessary) to make an in-depth study of all site characteristics of all potential sites. Some potential sites may be quickly rejected on the basis of site characteristics for which sufficient negative information can be readily determined. It should be understood that at this phase one deals with sites, while in the preceding phase broad areas were dealt with. Therefore, certain characteristics such as foundation conditions or cooling-water structures can be used to exclude a site at this stage.

Further screening of potential sites may be accomplished by using simplified techniques of suitability scaling and comparison methodologies. This screening phase should result in a more manageable number of ‘candidate sites’.

Phase 3 — Comparison of candidate sites

The comparison of candidate sites is performed on the basis of more detailed information and a limited amount of fieldwork. The greater level of detail can be accommodated because of the fewer number of sites in this phase. All characteristics of candidate sites that were taken into account in the previous phases should be confirmed. Detailed information on the characteristics of the candidate sites should be gathered and evaluated by using sophisticated scaling and comparison techniques.

Since this is the last phase of the site survey, a check should be made to ensure that no relevant safety related site characteristics have been overlooked. The analysis should be well documented since it will be required for the subsequent stage of site evaluation.

At the conclusion of this phase, the remaining candidate sites are ranked according to preference and a complete report on the entire site survey is prepared. The final site selection invariably involves judgements based on safety, economics, environmental impact and other considerations.

12.3.2. Organization and management

The site survey should be performed with co-operation of water and electricity utilities. To achieve this task in the most efficient manner, the responsibility of each partner should be fixed, and the lead organization should be identified.

The site survey work may be carried out by the local and/or foreign staff based on the experience of the staff in the country. However, in all cases, the local staff performs a substantial portion of work because usually they are more knowledgeable about local conditions and can process some information that is available only in the local language.

The site survey must be performed and organized in such a way that all the relevant information is collected and properly analysed to determine, in particular, its quality and completeness. Data should be compiled in a format that allows their retrieval, comparison and use to the fullest possible extent. The organization of the data analysis must allow for the prompt identification of information gaps and for the assessment of the need and methods for filling in such gaps.

A review of the site survey results by the regulatory body is normally required. Regulatory body staff members should closely follow the development of the site survey work. Another important responsibility of the regulatory staff is the development or selection of a set of standards (nuclear and drinking water) for siting. It is difficult to develop a site survey if these standards have not been established. This may represent a difficult task for the regulatory body of countries embarking on a first nuclear project. The adoption of the codes of practice and guides from the IAEA's NUSS programme may help to resolve this difficulty.

12.3.3. Selection of preferred candidate sites

On the basis of the ranking of the candidate sites, the most preferred site could be selected (at least tentatively) at this stage. This procedure would require a relatively high degree of confidence that the subsequent site evaluation studies will not result in the rejection of the chosen site, nor in a change in the order of preference. Should there be any reasonable doubt, the definitive site selection should be kept open at this stage, and the subsequent site evaluation studies should be expanded to include more than one (possibly two or three) sites. In such cases, the effort involved in evaluating a second or third site may turn out to be useful in a long term nuclear desalination programme.

12.4. SITE EVALUATION STAGE

The objective of the site evaluation is different from the objective of a site survey because now the site is identified and the studies and investigations are deeper and more extensive. All the characteristics of the site are assessed during the site evaluation with the intent to confirm the final site selection.

The evaluation of the site from the desalination point of view consists primarily of quantifying the effects of seawater temperature and quality.

Evaluation of the safety related site characteristics is especially important. This part of the evaluation fundamentally consists of:

(1) Proving that the site presents no characteristics that would constitute an impediment to a safe design;
(2) Evaluating the design basis for plant protection features against extreme external events as well as against expected events that the plant should withstand while continuing in operation;
(3) Assessing the site characteristics related to the potential impact of the plant on the environment during normal operation and accident conditions. The radioactivity levels in the discharges from the nuclear plants should also be evaluated if the discharge is to be used as feed for the desalination plant.

12.4.1. Procedure and methodology

The site evaluation methodology consists of systematically collecting or developing all the relevant information on each particular site characteristic. It is first necessary to study each aspect in general for the whole region, then once more in detail for the site vicinity and the site itself.

Procedures for site evaluation

The following steps are recommended in performing a site evaluation:

(1) The regulatory authority establishes or selects the standards according to which the site will be evaluated and reviewed.
(2) The organization responsible for the site evaluation defines the approach for performing the work. Depending on the approach adopted, the site evaluation group is organized, and consultants or a specialized company are selected if required.
(3) The site evaluation group (or specialized company) collects all relevant information; performs a critical analysis; prepares a programme of investigations; develops the design basis for the critical events and models for

dispersion in air and water; performs all special studies and investigations; and obtains all the results and data needed for evaluating the site.

(4) All results are reviewed by the responsible organization (utility) and included in a site report to be presented to the regulatory authority.

(5) The regulatory authority reviews the site report and may issue a formal or an informal site approval. Before approving the site, the regulatory authority might require additional studies or information.

To help assure a complete and thorough evaluation, a quality assurance programme should be established for site evaluation.

Selection of standards for siting

The applicable standards have to be available before site evaluation can start. The utility needs to know which siting standards will be applied by the country's regulatory authority, because the design basis depends on these standards. Different national and international standards concerning siting may apply, depending on the country.

Among the international standards for nuclear power plants, a complete set has been developed by the IAEA. It is composed of one code of practice on siting (50-C-S) [52] and a series of siting safety guides [53–66].

All Safety Codes and Guides of the IAEA are prepared for possible application in any country and thus represent the most convenient set to be adopted by a regulatory body in a country that has not yet developed its own standards.

There are no set standards available specifically for seawater desalination plants. As the desalination plants will be located at nuclear power stations, the standards for protecting against events such as earthquake, flood, volcanoes, tides and currents would also encompass the desalination plants. The standards for thermal discharges from the desalination plant will be also similar to those for the power station. However, the brine and chemicals discharges of nuclear desalination plants need be carefully controlled to protect the marine environment. The radioactivity content of the desalination plant feed is important because the standards for radioactivity content in the product water are much more stringent.

Approaches of the responsible organization (utility) for site evaluation

The lead organization in the site survey stage should continue to take the leading responsibility in the site evaluation stage.

The possible site evaluation approaches are:

(1) Performing the work directly, with some assistance, if needed, from specialized consultants who have experience in site evaluation;

(2) Performing part of the work directly (with the assistance of consultants) and part of the work with one or more specialized companies;
(3) Assigning all the work to a specialized company, retaining only a supervisory role.

The feasibility of the first option, i.e. the site evaluation performed directly by the utility, depends mainly on the availability of qualified expert staff. This approach is rarely adopted for a first nuclear power project, but it might be adopted for the second or third plant in the country if the utility has used the earlier opportunities for training its staff.

There may be temptation to save cost during the site evaluation stage. The site evaluation may be costly; but this cost is small by comparison to the impact of site characteristics on the cost of the plant. This evaluation must be carefully done and sufficient budget must be allowed.

When the evaluation of the site is performed partly by the utility and partly with specialized companies, the utility usually carries out those parts of the work that do not require very sophisticated methods. Among the parts of the work that are frequently assigned to specialized companies are those related to seismology and tectonics, and dispersion in groundwater. It is essential that the specialized company has proven experience in siting nuclear power plants. This experience is particularly needed to address the characteristics that are very important for the safety of the site. For example, if the country lies in a highly seismic zone, the company should have experience in siting nuclear power plants in highly seismic areas. If the specialized company is foreign, it should have experience in working abroad, and preferably in the client's country.

The third approach, assigning all site evaluation work to a specialized company, is frequently adopted for the first nuclear plant. It does not necessarily mean that a foreign specialist company does all the site evaluation work. It should be established in the contract that a substantial amount of work is to be performed by local subcontractors. In most nuclear desalination projects, the site evaluation for the desalination plant could be subcontracted locally. With this approach, particular attention has to be paid to selecting the specialized company. It should have extensive experience in:

- siting of nuclear power plants (previous site evaluations of one or two projects would not be sufficient);
- regions with critical characteristics similar to the site to be evaluated;
- working with subcontractors.

It is convenient to contract to a foreign company only those activities requiring specialized skills otherwise unavailable within the country. Local subcontractors may perform all other activities, particularly the collection of information and the supply of services.

It is also essential that an effective QA programme be organized for the site evaluation process, starting from the collection of information and including all activities to be performed. A QA manual should be prepared and strictly implemented under surveillance of the electrical utility.

12.4.2. Organization, staffing and schedule

Independently of the approach adopted, the expertise required to carry out the site evaluation will be in general similar to that required for the site survey stage. The knowledge and experience of the experts who have to carry out site evaluation will have to be extensive, because their work will include developing sophisticated physical models to evaluate design bases and dispersions, among other aspects. Moreover, a significant amount of fieldwork has to be performed on the site such as drilling, seismic prospecting, meteorology measurements and collection of soil samples for analysis. For many of the measurement programmes a full year's data are necessary.

12.5. SITE REVIEW AND APPROVAL BY THE REGULATORY BODY

The main nuclear safety related results to be obtained from the site evaluation studies are as follows:

- Investigations demonstrate that there is no risk from events against which the plant cannot be protected.
- No surface faulting affects the site.
- No important cavities exist underneath the site.
- No liquefaction risks exist.
- An emergency plan is feasible at the site.
- Determination that the plant can be protected against extreme events such as:
  - design basis ground motion,
  - design basis flood,
  - design basis extreme meteorological phenomena,
  - design basis human induced events.
- Modes for dispersion in air and water for normal and potential accidental radioactive release.
- Determination of the population distribution around the site, including the identification of the location of population groups difficult to evacuate.
- Development of the basis for the emergency plan.

However, these are only partial results of the study. A complete understanding of the site characteristics must be achieved to ensure that there are no extreme events for which protective design features cannot be implemented and that reasonable information for other extreme events can be developed and prepared for the plant designer. In addition, all those aspects and characteristics of the site (safety related or not) that may affect the design, construction and ultimate operation of the nuclear desalination plant will have to be investigated, and presented in the site evaluation report.

The site evaluation report generally comprises one section of the PSAR.

The site report produced by the organization responsible for siting is usually submitted to the regulatory authority for review. The regulatory authority may issue a formal or an informal site approval.

It should, however, be pointed out that the task of the regulatory body for the first nuclear plant of a country could be very difficult unless, at a very early stage, appropriate measures are taken. It must be understood that the regulatory staff must be capable of critically reviewing work that might have been performed by reputable international experts with many years of experience in the field of siting.

To be able to perform this review, the regulatory staff should participate in training courses on siting some years before the utility starts to perform the site evaluation work. In addition, one or two leaders of the regulatory siting group should be attached to another country's regulatory body where possible to acquire direct experience in the siting work.

Under these conditions, the only remaining possibility is that the regulatory body employs consultants to assist in performing the review work. However, even if consultants carry out the review of the site reports, the decision to accept the selected site will always ultimately remain the responsibility of the regulatory body. It is therefore essential that the responsible regulatory staff clearly understand the various implications and technical aspects underlying site selection decision making.

Chapter 13

FEASIBILITY OF THE FIRST NUCLEAR DESALINATION PROJECT

13.1. INTRODUCTION

The main objective of a feasibility study is to prove that the nuclear desalination project is feasible within the technical, economic and institutional environment of the country. It is assumed that the country has experience with the acquisition and operation of desalination plants, but only limited experience with nuclear technology. This chapter focuses primarily on the feasibility study for a nuclear plant, which is the more complex issue. A secondary focus is on the feasibility study for coupling the desalination plant to the nuclear plant.

Once the planning studies referred to in Chapter 10 have established the demand for desalted water and nuclear energy as a viable alternative to other energy sources, the next step consists of an in-depth feasibility study of the first nuclear desalination project. A well performed nuclear planning study will make a considerable contribution to a feasibility study. The planning study can provide useful input data and information in several important economic and technical areas. This includes maximum unit sizes that can be accommodated by the electric grid system, long range development programme, timing for the addition of new electricity and water production capacity, possible site locations, and the economic ground rules that will be used in the feasibility study.

The feasibility study is primarily intended to provide the relevant authorities with all necessary detailed information needed to decide on the implementation of the project. It will also be important for the project financial negotiations, as it is usually requested by all financing institutions.

13.2. SCOPE AND RESPONSIBILITY FOR THE FEASIBILITY STUDY

The basic scope of a feasibility study will include the following:

- Evaluate in detail the integration of the nuclear plant into the electric power system, if applicable, and integration of the desalination plant into the water supply scheme;

- Determine the capacity and main features of the nuclear and desalination plants;
- Determine the preferred site and identify any specific problems associated with the selected site (might be a separate study or part of the feasibility study);
- Determine which reactor type(s) should be the basis for bids;
- Determine which type of desalination technology and coupling scheme with the nuclear reactor should be the basis for bids;
- Carry out detailed cost and economic evaluations and compare with alternative options;
- Determine the organizational and human resources requirements to implement the project and to operate the plant;
- Determine the overall project schedule;
- Determine the financial viability of the project and the possible sources for financing;
- Determine the contractual approach to be adopted for the acquisition of the plant;
- Analyse the international market for nuclear reactors, fuel cycle, desalination equipment and essential materials and services;
- Define the country's infrastructure requirements and survey the national participation possibilities;
- Define the nuclear safety criteria to be applied.

The feasibility study should provide detailed analyses and information on all these aspects, with specific recommendations to enable the authorities to make appropriate decisions for project implementation. Typically, a feasibility study would include various contents as listed in Table 13.I.

The selection of personnel to carry out the feasibility studies is very important. It is essential that the best available resources and experienced people be made available for performing the studies. The local staff should be carefully selected at the highest possible technical level within the various organizations participating in the study. Those personnel that were involved in previous power and water planning studies would logically expand their work into the feasibility study and form a team with other professionals, preferably with experience from other projects. The feasibility study usually requires two to three years, not including site survey and qualification. The latter would be an on-going activity during the feasibility study and could be completed later.

While the local authorities should normally be responsible for performing the feasibility study, parts or all of it can be delegated to experienced foreign consultants. The main reason for this delegation is that the feasibility study will be important to the negotiations for project financing, and it is assumed to carry more weight if performed by reputable, experienced foreign consultants. It is essential to carefully define the scope of the study and the terms of reference before the study is started. Assistance from the IAEA could be requested for guidance and help in such feasibility studies.

13.3. MARKET ANALYSIS OF POTABLE WATER AND ELECTRICITY

After the planning study, in which the long term potable water requirement has been reasonably assessed, a market analysis of potable water is carried out. The objective of the market analysis is to provide necessary important information to determine the required desalination capacity, type of technology, plant capacity and operating characteristics including reliability, operating concerns and cost. This information is also used to identify suitable equipment and vendors for potential bids. This will depend on the commercially available equipment, proven experience and system reliability criteria.

Expansion of the potable water requirement to suit the available unit size may be considered if the overall cost–benefit analysis is attractive. Status of water management system and water demand forecast should be analysed and integrated in the expansion planning. This may necessitate modification of the potable water supply infrastructure.

The electric system market analysis should be performed following fundamentally the same methodology as outlined in Ref. [59]. The feasibility study is expected to provide a critical review of the planned long term electric system expansion.

The electricity market analysis should be focused on the period when the nuclear desalination plant would be integrated into the system, within the framework of the long term analysis.

Aspects of the electric system which require special consideration are:

- Cold and spinning reserves available in the system,
- Power transmission capacity of the grid during critical conditions,
- Power control and load dispatching system,
- Voltage and frequency fluctuation control equipment,
- Probabilities of supply interruptions and grid disturbances.

The main technical characteristics of the nuclear power plants, related to their integration into the electric system, are:

- Startup capability,
- Load change and load following capability,
- Effects of power cycling on components and fuel elements,
- Ability to withstand externally induced disturbances.

13.4. DETERMINATION OF PLANT CAPACITY AND SITE

A feasibility study on the long term implementation of a nuclear desalination programme requires adequate attention to be given to selection of the optimum plant capacity and site. The information developed during the market studies for water and electricity will form the basis for this selection. The required nuclear plant capacity should be assessed keeping in view the existing power demand by the nearby industry and the available transmission network. It also depends on the commercial availability of nuclear power units, their operational characteristics, grid characteristics and system reliability criteria. The capacity of the desalination plant should be based on the present and projected water requirement of the industries as well as the population around.

Both the effect of introducing the nuclear power plant on the interconnected grid, and the effect of the grid on the technical and economic characteristics of the nuclear power plant should be evaluated. Achievement of the economic benefits from introducing nuclear power plants with larger capacity involves technical difficulties and costs, which should be included in the overall cost/benefit evaluation. There is a definite limit to the maximum power plant capacity an electric system can accommodate.

The determination of the desalination plant capacity should consider possible future expansion against projected demand increase. Flexibility of expanding the desalination plant capacity is interrelated to the selected desalination process.

Selection of the site should be carried out in concert with selection of the plant capacity. A survey of candidate sites should be carried out with the following information developed for each candidate:

- Location, geology, hydrology and meteorology,
- Population distribution within 50 km from projected plant site,
- Proximity to national electric transmission/distribution networks and potable water supplier,
- Accessibility of site,
- Availability and cost of construction materials,
- Availability of skilled labour,
- Legal/administrative/land rights.

13.5. IDENTIFICATION OF SUPPLY OPTIONS

It is assumed that the first nuclear project will be implemented mainly through import from an experienced foreign supplier or suppliers. This will be supplemented by national participation, which would vary from case to case, depending mainly on the available infrastructure within the country (see Chapter 9).

One of the main objectives of the supply option evaluation is to identify the commercially available reactor and desalination plant types and capacities. The reactors should be suitable for desalination and should offer distinct economic and technical features for the case under consideration. It is not necessarily the purpose of the supply option evaluation to select a particular type of reactor system. Rather, it will support selection of the reference concepts for detailed economic and technical analysis and comparison with each other and with alternative projects. The evaluation will also facilitate the decisions to be taken after the project is committed and will help define the approach to be followed during plant acquisition (see Chapter 14).

A general survey of the various types of reactor system has been presented in Chapter 3. It is recommended that reactor types proven at the time of decision be considered for the first nuclear desalination plant in a country. Obviously, they must also be commercially available for export. Each reactor type and available design presents a number of distinctive features, with advantages and disadvantages for the specific case under study. These features should be evaluated and used to form the basis upon which the final project decisions are made during the subsequent stage.

However, it should be noted that the designs of modern commercial nuclear power plants, which have been developed and standardized for the conditions in industrialized countries, might not be applicable without modifications in local systems.

The choice of reactor type for the nuclear desalination plant should be seen as a possible long term commitment to that type for a series of additional units to be built within the scope of the nuclear desalination programme. Similarly, this choice includes commitment to the type of fuel cycle and associated supply requirements.

Among other factors that should be taken into account in the choice of reactor type and desalination plant are the possibilities for local participation in the project, financing prospects, and transfer of technology. A long term perspective should be taken in considering these. If the project is regarded as the first of a series of essentially the same type of nuclear desalination plants, the prospects of increasing local participation with each successive project seem to be better than for a series including different types of reactor. Technology transfer can also be established on a systematic basis.

The analysis of the nuclear power reactor and desalination plant supply market also includes the evaluation of the potential supplier countries as well as the supplier industry. The international trade in nuclear equipment and materials is conducted under the control and supervision of the governments involved and is under strong political influence. Depending on the political and commercial relations between the importing country and the potential exporters, the effective availability of suppliers might be limited to a few (or even one) potential supplier. This would imply also a possible limitation on the choice of the available reactor types.

Regarding the evaluation of the potential supplier(s), the following factors are especially relevant:

- Commercial interest,
- Reliability,
- Experience,
- Technical capability and resources,
- Financial resources.

The evaluation is elaborate and requires objective value judgements based on thorough analysis of relevant aspects, such as:

- Supplier’s willingness to provide technical and economic information as well as the quality, detail and depth of such information;
- Expression of intent to bid in a formal enquiry and willingness to present a preliminary non-binding bid, if requested to do so;
- Experience of former or current clients with the supplier;
- Adherence to agreements and contractual commitments in the past, especially regarding unilateral actions;
- Current issues that might affect the future reliability of the supplier;
- Supplier’s experience in producing and providing the offered goods or services,
- Supplier’s export experience, in general, and to the interested country, in particular;
- Restrictions regarding the use of technology;
- Willingness to transfer technology;
- Supplier’s qualified personnel resources;
- Supplier’s technical, industrial and financial resources as well as his organization and efficiency;
- Operating experience of plants, systems and equipment previously provided by the supplier.

To perform an evaluation, the potential buyer may establish direct contact with the potential suppliers; he may request information and then analyse and confirm it to his satisfaction. During the feasibility study, the buyer should obtain a clear understanding of his prospects regarding project acquisition, potential suppliers and any relevant constraints.

A nuclear desalination project is a major undertaking involving a large financial commitment. It also involves sophisticated equipment, which may incorporate new technology. Hence, importing a nuclear desalination plant involves commercial and technical risks greater than in other large industrial projects. These risks range from the economic burden of capital and operating costs exceeding expectations to the risk of not having the plant available when the energy/water is needed. In addition, there is the nuclear safety risk. Protection against such risks is generally obtained through the procurement of proven equipment from experienced manufacturers. Also, the supplier who intends to protect his standing in the export market will share some of the risks involved in the project and hence will, in principle, not offer his product unless he is satisfied with his own level of risk.

The nuclear plants that are available for export at present can be considered as reasonable commercial risks from the point of view of ‘provenness’. It should be emphasized, however, that the buyer's design review must be careful, detailed and well informed, in particular in order to ascertain where new and unproved systems, components or design features are involved, and if they are acceptable.

The supply of a nuclear reactor for desalination and the supply of its fuel must be considered simultaneously. In fact, the fuel supply possibly requires an even more careful consideration than the supply of the reactor itself because fuel must be provided during the whole lifetime of the plant. Procurement of fuel must be planned as part of the national long term policy on the nuclear fuel cycle.

Assuming that a country starting its nuclear programme will limit its selection to proven and commercially available reactor types, it has the basic choice between adopting a natural uranium or an enriched uranium fuel cycle. In certain cases, the decision may be based on a purely economic comparison of the two systems. It also can be influenced by special financing arrangements or conditions favouring fuel supplies, fuel cycle services, or availability of indigenous uranium resources. Whatever fuel cycle (natural or enriched) is chosen, assurance of supply should be considered for each essential stage of the cycle. Natural uranium can be acquired on the world market from several suppliers using long term contracts and the spot market (Chapter 3).

For most countries, enrichment of uranium will remain an imported service for many years. Long term contracts with suppliers seem to offer, at present, an adequate assurance of supply. There are more sources of supply for fuel element fabrication than for reactors. First fuel charges and options for a few years’ refuelling are usually included in the plant bids. The assurance of external supply of nuclear fuel, together with fuel cycle materials and services over a long term basis, is closely related to the non-proliferation assurances and the development of domestic capability. A network of international treaties, agreements, instruments and practices provides the framework for the supply of nuclear materials, equipment and technology, and for non-proliferation.

Assurances regarding spent fuel management and disposal of radioactive waste are also to be considered by the buyer. The options for handling of spent fuel include the following:

- Extended spent fuel storage at the reactor site or in suitable sites away from the reactor, with no reprocessing of the spent fuel;

- Establishment of a national fuel cycle centre for fuel fabrication, reprocessing and recycling of separated plutonium and uranium;
- Use of outside reprocessing services with possible arrangements for storing separated plutonium and subsequently using it in recycled fuel;
- Return the spent fuel to the supplier's country.

For the initial stages of a nuclear programme, the first option of extended spent fuel storage and the third option of using outside reprocessing services are, at present, the most practical approaches. Management and disposal of radioactive wastes are always national responsibilities. There are several available methods, and provisions should be made for locating a suitable depository.

13.6. TECHNICAL ASPECTS OF SUPPLY OPTIONS

The analysis of the technical aspects of various supply options will be part of the feasibility study. The degree of detail will vary from case to case, but as a minimum it must be carried out in such depth as to provide a realistic basis for detailed cost and economic evaluations. It should also provide the basis for preparing bid specifications in the next phase of the project, by identifying important site dependent design features and criteria. The main requirements are:

- Preparation of overall plant descriptions, design and performance data;
- Preparation of general plant layouts for the specific site.

Within the scope of this work, full consideration should be given to the project management approach and to the potential influence of local participation. Further, all factors related to detailed site investigations need to be established.

The technical descriptions of proven, commercially available nuclear desalination plants are normally provided by suppliers on request in adequate detail and depth for the purpose of a feasibility study. These descriptions usually correspond to a typical plant, which could be the basis of an offer. They would be subject to adjustments and modifications according to the buyer's specific site and other requirements.

Within the scope of the feasibility study, it is sufficient to study the available technical descriptions complemented by the analysis of the characteristics and performance of similar plants. Emphasis should be placed on identifying problem areas and any design differences between operating plants and the current technical descriptions, especially any new, unproven features.

Special attention should be dedicated to the study of those features, systems, components and equipment that might be supplied by the national industry, in order to complete a survey of the potential national participation in the plant construction.

The analysis of the reference plant operational characteristics/constraints such as startup, load following capability, refuelling schedule, fuel burnup, core stretch-out, efficiency and planned maintenance requirements will provide information for the study of the plant integration into the electric and water supply systems. The analysis will also enable estimates of load factors for the economic evaluation.

13.7. INSTITUTIONAL ASPECTS

The introduction of nuclear power for electricity generation and seawater desalination needs new infrastructure requirements and involves national commitments on a long term basis. These include ongoing political and institutional policy commitments over a long period of time and availability of substantial human and financial resources. Hence, the institutional aspects of a large scale energy and water production programme must be clearly understood and addressed, and clear policy commitments must be established for maintaining programme continuity. The formulation and execution of a nuclear desalination programme require an organizational structure whose main task is to define the programme’s policy, scope, size, schedule, budget and human resources requirements. This organization could be formed by the various authorities concerned with nuclear power development, water production, storage, transport and distribution, and energy resources and development.

The safety and regulation of nuclear power plants, with emphasis on their use as energy sources for seawater desalination, is also an institutional issue. It requires the establishment of a comprehensive infrastructure capable of ensuring that all applicable international codes, conventions and requirements have been adhered to. Experience shows that public and political acceptance of nuclear energy strongly depends on the perception of risks incurred and of the benefits obtained from using this energy source. Opponents tend to exaggerate risks and ignore benefits, and this view is often transmitted to the public at large by the media. The concept of public participation from an early stage of the nuclear desalination programme needs to be recognized, and public acceptance committees should be created to undertake careful planning for public acceptance in co-operation with mass media.

13.8. INFRASTRUCTURE REQUIREMENTS AND DEVELOPMENT

The infrastructure requirements for participation in nuclear power programmes have been discussed in Chapter 8. Development of the necessary infrastructure for a nuclear desalination programme requires formulation of necessary legal regulatory and organizational framework.

Relevant national legal requirements must be addressed. Issues will include:

- Nuclear law (including nuclear safety, radiation protection),
- Third party liability,
- Ownership.

Relevant national regulatory requirements must be addressed. Reference may also be made to regulations in the buyer's country and/or to international conventions. Regulatory issues will include:

- Nuclear safety requirements,
- Radioactive waste management,
- Water quality standards.

A capable and competent organization is needed to administer and implement the nuclear desalination project. The feasibility study should include a review of the existing organizational structure for electricity and water supply in the country. This organizational structure will vary from country to country, and the government's involvement may range from some control of private utilities to the establishment of national authorities within the Ministries of Water, Energy and/or Electricity. These utilities or authorities might be in charge of the project, but this responsibility could also be assigned to a National Atomic Energy Commission or to an entity especially created for this purpose.

On the basis of the current structure of whatever entities are in charge of the project, the feasibility study must analyse and recommend organizational arrangements for project implementation and for plant operation and maintenance. The study should recommend whether a single entity should be in charge, or the method of splitting responsibilities among two or more entities.

Detailed organizational charts for the project should be prepared. These diagrams should show the organizations for project management and all other activities during plant acquisition, construction and operation. Plans for staff recruitment and training should be included.

The preferred organizational structures and number of personnel involved will depend upon many factors characteristic of the particular country, utility and the project. The staffing requirements should be established for each activity and function/task with definitions of the numbers of involved personnel, their disciplines and professional qualifications.

13.9. NATIONAL PARTICIPATION

In the feasibility study, a survey should be undertaken of the local industrial manufacturing, engineering and construction capabilities to assess their possible contribution to project implementation. This survey will provide input data and information for evaluating the contracting approach that should be adopted. The potential for national participation might prove to be better than expected even for countries with relatively modest industrial infrastructures, or it may constitute a major constraint to the feasibility of the project.

Experience shows that the question of national participation is often evaluated in a superficial way. If it is left to the acquisition stage and is evaluated by the suppliers, the results will often lead to a very low rate of national participation, in spite of any ‘goodwill’ or ‘best effort’ statements or contractual clauses for adequate national participation.

On the basis of the technical aspects of the project, the evaluation of national infrastructure should include a systematic survey of the major national engineering, construction and manufacturing firms with emphasis on:

- Technical capability,
- Experience,
- Reliability,
- Quality,
- Costs,
- Delivery schedules.

The survey must be detailed, analysing the industry for the potential supply of each item (similar items might be grouped together), classified according to the following categories and in order of priority:

(1) Goods and services that must be supplied locally because importing them would not be feasible;
(2) Goods and services that could be produced by a national industry with little or no additional efforts;
(3) Goods and services of special interest for national supply, due to considerations such as long term assurance of supply or important spin-off benefits to national industrial development.

The feasibility study should contain the outline of a human resources development programme using guidance given in Ref. [35].

The feasibility study should also contain a strategy outline and recommendations regarding the implementation of the national participation goals. These recommendations should refer to the contractual approach to be adopted and to the development of a consistent set of governmental actions and incentives promoting national participation and transfer of technology.

13.10. PROJECT SCHEDULE AND IMPLEMENTATION

One of the most important aspects of the project is its schedule, which should be analysed in detail. Options are to define the shortest possible schedule, the reasonably expected schedule and the worst case schedule. The shortest possible schedule defines the ideal minimum time required for project completion and indicates possible shortcuts that could be taken to accelerate project implementation, if conditions should permit it. The reasonably expected schedule is the one that should be used for project planning. It depends on local conditions and the approach to project implementation. The worst case schedule provides part of the basis for estimating project contingencies.

By the time the feasibility study is finished and a corresponding report prepared, the siting study should have reached the stage where the site is selected and sufficiently qualified so that its final approval becomes probable. The feasibility report can then be presented to the relevant authorities for evaluation and for deciding whether to proceed with the project.

In principle, the feasibility study report should contain all detailed information needed for this decision. In practice, however, the evaluation of the feasibility report usually produces requests for additional information or studies. This process of evaluation, additional studies and decision making should normally take a few months and certainly not longer than a year. The more people and organizations are involved in the evaluation process and the less they were involved in the feasibility study itself, the longer it will take to reach a decision. If the evaluation process is excessively protracted, the feasibility study could become obsolete and consequently would have to be revised and updated.

Once the decision to implement the project is adopted, the acquisition phase will start (see Chapter 14). The most important decisions regarding the project are taken at this stage, and both financing arrangements and international agreements require time and effort. The regulatory procedures including site review and approval and plant construction authorization can proceed in parallel with plant acquisition, but may constitute the critical path in the overall project schedule.

The feasibility study should define the project schedule for the specific conditions of the country, taking into account all relevant factors and aspects.

13.11. COMPARATIVE ECONOMIC EVALUATION

The feasibility study should include a complete economic evaluation of the project with the intention of determining the plant costs and of determining whether the nuclear electricity and water production are economically competitive with alternative options.

Cost estimates should be in as much detail and as precise as possible. They should be determined on the basis of the various reference plant designs that could be candidates for the selected site. Economic information should be obtained from all available sources, mainly suppliers of plants, component and equipment manufacturers and construction and engineering firms, both foreign and domestic. There is also published information available on nuclear and desalination economics, but this is difficult to apply directly to the feasibility study of a specific project, because most of this information might be outdated, too general or relevant only to a different specific project.

The methodology to be used in the feasibility study to demonstrate the economic competitiveness of the nuclear desalination project with alternative options is described in Chapter 8. The input data for the project and for its alternative options are especially important and would require a higher degree of accuracy than that needed for planning purposes.

The comparative analysis is performed within a specific set of economic ground rules, assumptions and cost estimates. The assessment of the project should include a sensitivity analysis assigning reasonable ranges of variations to the most relevant parameters and data. More detailed information on this subject is contained in Ref. [68].

13.12. FINANCIAL ASSESSMENT

The feasibility study must include a financial analysis of the investment requirements and a survey of potential sources of project financing (see also Ref. [69]). This is an essential element upon which the viability of the project ultimately depends.

The feasibility study should explore the possible ways and means for securing the project financing through national and foreign financing sources, including commercial financial institutions, and development or aid institutions. Separate financing of the nuclear plant and the desalination plant will often apply, e.g. when the equipment is procured from several countries and/or concessionary financing of the desalination plant can be obtained. A detailed financial analysis of the project will be required and should include:

- Estimates of the financial requirements of the project and comparison with alternatives,
- Review of the experience of the owner's organization in project financing,
- Financial viability analysis of the project.

The evaluation study should take into account the two main products, electricity and water. Therefore, the cost allocation strategy between these two products is an important part of the financial assessment.

The financial requirements of the project include the estimated total investment cost of the project, including the owner’s cost, initial fuel loading and an allowance for working capital during the initial years of operation. Financial requirements should be broken down into foreign and local currency requirements, and the prospects for both domestic and foreign financing possibilities should be reviewed. Local sources should be used to finance as much of the local cost as possible. The importance and difficulties of local financing should not be underestimated.

Since all costs are directly affected by the length of the construction period and by escalation, the financing plan should be worked out to include expected cost escalation and interest during the construction period. Additionally, a supplementary financial plan should be developed in which the impact of a delay in the project implementation is specified. Financial requirements should also include a contingency reserve that allows for possible errors in cost estimates, changes in technical and safety requirements, and construction delays. Similarly, the cost of additional investments such as water pipelines, transmission lines, grid reinforcement, and other infrastructure related and supplementary costs should be taken into account.

A demonstration of the financial soundness of the project should be made through various financial tests. The most significant indicators are:

- the debt/equity ratio,
- the payback period,
- the cost/benefit ratio,
- the number of times the debt service is covered by internal cash generation,
- the number of times the interest is covered by net income,
- the internal rate of return of the project,
- the internal rate of return of other infrastructure projects,
- the impact of tariffs.

A thorough sensitivity analysis should examine potential financial bottlenecks and risks related to the project implementation. In particular, the impact of escalation, investment and operating costs, various financing modes of the project, tariff policy of the utility, etc. should be investigated, and the criteria for judging the project's financial viability should be specified, with comparisons to alternative options.

13.13. OVERALL COST/BENEFIT ASSESSMENT

Implementation of a long term nuclear desalination programme contributes to several spin-off benefits for the country that should be part of a cost/benefit analysis. The most important are sustained industrial growth, and development of skilled human and manufacturing capabilities. In addition, increasing the share of nuclear energy in the country's energy applications benefits the environment in the long term because of the reduction of fossil fuel combustion. These benefits and others should be quantified and compared with the costs of a nuclear desalination programme as well as with other alternatives.

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Chapter 14

NUCLEAR DESALINATION PLANT ACQUISITION

14.1. INTRODUCTION

After completion and evaluation of the planning and feasibility studies including the establishment of the needs and merits of a nuclear desalination programme, the decision to implement the first nuclear desalination project would be made. The first phase of the project is plant acquisition, which includes the steps establishing the organization, preparing specifications for bidding and eventually leading to finalization contracts with vendors for supply of nuclear reactors and desalination plants. The second phase is the construction and commissioning of the plants (Chapter 15).

Most projects would proceed on the basis of competitive bidding. However, some countries may be limited in choice to only one or a few nuclear suppliers for policy or political reasons. Others may select a supplier or a certain reactor and/or desalination plant type at the feasibility study stage.

The purpose of competitive bidding is to enable the buyer to take advantage of the competition between suppliers. If this can be achieved without going through all the time and money consuming steps of a formal international bidding procedure, direct negotiation would be in order.

An international bidding procedure is no guarantee that the buyer will receive the optimal offer. The preparation of a serious offer involves considerable effort and expense for the supplier, which he might decide not to expend if, in his judgement, his chances are remote or if he feels unable or uncomfortable to meet the requirements included in the specifications. However, without bidding, the buyer cannot make any real comparison between what is offered by the available suppliers, and he would lose possible benefits from competition.

The selection of suppliers would in practice constitute the start of the acquisition procedure. The establishment of a project organization and staffing and the completion of data and information requirements would still be needed. The other tasks would be included into the direct contract negotiations.

14.2. OVERALL SCHEDULE

The overall schedule for the plant acquisition would be about four to five years, assuming no major delays in decision making. Table 14.I shows the major tasks included in the plant acquisition phase. In a direct negotiation approach, the list of tasks in Table 14.I would still be valid, but with a substantially reduced scope.

Practically all major technical, economic, financial, policy and political decisions regarding the project are made during the acquisition phase. It is desirable that the execution of each task be accomplished in the shortest possible time to enable the subsequent stage of project implementation to start in time to meet the schedule for plant operation. Priority, however, should always be given to the quality of the performance of each task. Even small mistakes or minor omissions committed at this stage can become very expensive later on.

14.3. ROLE OF THE LOCAL ORGANIZATION

The organizational and human resources requirements for nuclear projects and related activities were discussed in Chapter 9. For plant acquisition, specific organization and staffing skills are needed to carry out the acquisition tasks. This may be accomplished by re-orienting the project group set up for the feasibility study, with the addition of selected staff in defined areas of experience. Alternatively, a new group can be set up specifically for plant acquisition. In either case, the extent of outside experience needed to cover the areas that cannot be met by locally recruited staff should be specified. An extensive amount of work will be needed for the preparation of acquisition reports and documents.

The establishment of the local organization composed of highly qualified engineers and experienced professionals is therefore an immediate and important task to be undertaken. For the initial tasks, the size of this local organization is usually not very large, probably of the order of 10 to 20 professionals under the direction and co-ordination of a project manager. The team will have to be expanded to about 30–40 professionals during contract negotiations. It is emphasized that it is not the number of people that is important, but rather their quality and experience.

If local talent is not sufficient, it would be necessary to employ a competent foreign consulting engineering firm to assist the buyer with the plant acquisition. However, the role of a consultant is mainly advisory. A consultant without a strong counterpart of qualified local staff will probably not be able to produce effective results and thus can be wasteful and costly. The buyer can never delegate his prime responsibilities to a consultant, and should he be unable to put together a basic organization with qualified staff for the acquisition, he may not be ready to acquire a nuclear desalination plant at all.

Careful consideration should be given to the selection of the consultant and to the terms of the agreement for his services. The recommended procedure for making this selection in a timely and effective manner is to request bids from a limited,

TABLE 14.I. MAJOR TASKS INVOLVED IN PLANT ACQUISITION

Tasks	Duration	Remarks
1. Establishment of the organization and staffing	Up to several months	Depends on what has been achieved in the feasibility and siting studies, and on what approach (owner's staff or consultants) is adopted for the preparation of specifications.
2. Completion of data and information requirements		The lack of essential data and information or the need for selecting and contracting consultants could mean substantial delays at this stage.
3. Definition of contractual approach	Up to several months	Consideration should be given to the impact of the contractual approach on the subsequent overall project schedule.
4. Preparation of specifications and invitation of bids	About six months for a turnkey	A year or more is required for a split package or multiple package. Requires a decision that would probably involve national authorities.
5. Preparation of bids	Up to a year	A few months more might be needed: if the buyer requests extensive national participation; if the specifications are very demanding and strict; or if they require substantial modification of available commercial designs.
6. Evaluation of bids and selection of supplier(s)	6–12 months	Probably will involve national authorities, which might need several months to reach a decision.
7. Arrangements for financing	(parallel)	May be delegated to supplier as part of bid package.
8. Negotiation and finalization of contracts	Additional six months to a year	This may overlap somewhat with the bid evaluation. After this formal act and depending on the contract terms, ratifications, international as well as local financing agreements and arrangements, and possibly downpayments will be needed to establish the contract(s) as effectively valid. These requirements might need several additional months to be completed.
Overall schedule	4–5 years	For steps 1–8.

preselected list of well known firms. The preselection of the firms should be based on the following considerations:

- Experience in nuclear and/or desalination projects and in the types of reactor and desalination systems considered for the project;
- Experience in other projects in the country and familiarity with the prevailing conditions of the country and the site;
- Experience in the scope of work in all areas and stages of project implementation;
- Reputation, and impartiality towards prospective suppliers;
- Advantages and disadvantages of having a consultant from a nuclear supplier country or from another country;
- Ability to provide adequate numbers of qualified staff with experience in nuclear and/or desalination projects to ensure continuity and efficiency in carrying out the work.

Taking into account the large financial and other commitments involved in the acquisition of a nuclear desalination project, the selection of the consultant should not necessarily be based on the least cost offer. The cost of the consultant firm is a factor to be considered in evaluating the various consultant firms' bids, but should not be the primary consideration. Quality, reputation and guarantees of obtaining the best possible advice and support should constitute the main decision factors.

It is obvious that there would be an advantage in retaining the same consultant for every phase of project implementation, but it is also necessary to ensure that the best possible advice is obtained at each stage.

14.4. DATA AND INFORMATION REQUIREMENTS

Data and information regarding the site and the national and local (site related) infrastructures are especially relevant to the preparation of bid specifications (Section 14.6) and must be available in sufficient detail and depth to enable the bidders to prepare their offers. Information on the local infrastructure will be needed for project planning purposes and will affect project cost and schedule. Especially relevant are:

- Availability of construction materials,
- The local labour market,
- Construction industry and equipment in the area,
- Local construction and labour rules, regulations, customs,
- Housing,

- Hospital and first aid facilities,
- Recreational facilities,
- Schools,
- Security,
- Access,
- Telecommunication,
- Electricity supply,
- Water supply,
- Docking and transport facilities,
- Cranes and other lifting facilities.

Nuclear desalination plants will usually have to be sited at some distance from industrial and population centres for regulatory and public acceptance reasons, although not too far, in order to limit water transport costs. The site may have weak infrastructures. The information and data on what services are effectively available should be complemented by information regarding plans, schedules and costs to remedy deficiencies or, otherwise, provide the necessary facilities or services that are unavailable. This might lead to an early initiation of site development work, even before plant acquisition is completed.

14.5. DEFINITION OF CONTRACTUAL APPROACHES

One of the key decisions that the owner must make before the preparation of the specifications and bid documents is the choice of the contractual approach for plant acquisition. This decision also involves considerations of how the project management and, in particular, the construction management are to be organized and how the responsibilities for the project work and for the final quality and reliability of the plant are to be shared.

Because of the importance of this decision and its consequences for project implementation, it should receive the greatest attention and should be based on careful analysis and evaluation of all relevant factors, taking into account the prevailing conditions and available resources in the country.

Nuclear desalination plant acquisition means the acquisition of two technologies. At one extreme, a single contractor may be given complete responsibility to design, build and commission the complete plant, including both a nuclear reactor and a desalination plant, handing it over to the owner for operation. At the other extreme, the owner may buy only the basic hardware of the nuclear system from a reactor supplier, designing the rest of the plant and buying all the other equipment himself from other suppliers. Basically, there are several main types of contract approach that have been applied for nuclear plants to date, namely:

Turnkey — A single contractor or a consortium of contractors takes the overall responsibility for the whole work. A possible variation is an approach with the plant being leased, rather than sold, to the water/power supplier.

Split package — The overall responsibility is divided between a relatively small number of contractors, each in charge of a large section of the work. The involvement of an architect–engineering (A–E) firm is needed.

Multiple package — The owner, by himself or with the help of his A–E, assumes the overall responsibility for engineering and project management of the plant, issuing a large number of contracts to various contractors for carrying out parts of the work.

Independent projects — The buyer places a contract with an independent third party for supply of water and/or power. The independent third party constructs and operates the plant. Variants include 'build-own-operate' (BOO) and 'build-own-transfer' (BOT). The independent third party takes responsibility for financing, construction and operation.

The main factors to be considered in the evaluation and selection of the type of contractual approach may include the following:

- Local capabilities and conditions, including existing management, engineering and construction capabilities, industrial infrastructure, national planning and implementation policy of the first project and subsequent projects in the long term programme;
- Experience in project management of similar projects, particularly of fossil fuelled power and desalination plants;
- Potential contractors and their capability, reliability and experience with different contractual approaches;
- Economic and competitiveness considerations;
- Foreign financing possibilities.

14.5.1. Turnkey contracts

In a turnkey contract, the complete plant, ready for commercial operation, is procured from one main contractor. The turnkey order demands that the main contractor take comprehensive responsibility for completing all parts and phases of the project to the satisfaction of the client, including design, engineering, construction, erection, supply and installation, testing and commissioning of the plant. The main contractor will also be in charge of the overall project management.

The main contractor might be a single company or a group of contractors operating as a consortium with usually one member acting as the sponsor or prime contractor. In the latter case, it is extremely important that the consortium be the only party directly responsible to the owner. This must be clearly defined and specified in the contract.

In a turnkey approach, the main contractor is fully responsible to the owner for:

- Plant generating capacity and efficiency,
- Plant quality and functionality,
- Plant completion date,
- Plant investment costs, excluding items within the owner's scope of supply.

The main contractor must guarantee both his own delivery and services, and the deliveries and services of all his subcontractors. Additional requirements could include the preferential use of local material, equipment and labour.

A turnkey order for a nuclear desalination plant will be placed only after all technical and commercial conditions for determining the scope of supply and performance are agreed upon with the main contractor. All provisions, from the site development to test operation and plant acceptance, can be contained in a single, complete contract document. The essential advantage of this system lies in the homogeneity of responsibility because a single, main contractor is responsible to the buyer for all risks. In particular, the turnkey approach has the following advantages:

- Better possibilities for a high degree of integration, and homogeneity in the scope of supply;
- Guarantees affecting the entire plant, e.g. net power output, water production, efficiencies, delivery times, material and workmanship; guarantees for all systems and components;
- Reduced risk of overall schedule delays;
- Simple and quick handling of the licensing procedures because licensing matters that affect the whole plant can be better co-ordinated and solved;
- Better utilization of standard techniques for the whole plant;
- Greater flexibility in making up for delays through rearrangement of construction procedures or commissioning work;
- Easier interface management.

Turnkey contracting also presents disadvantages:

- Limited possibilities for competitive bidding for major systems;
- Less direct control by the buyer, because the turnkey contractor will have overall responsibility for the project management. The buyer's direct control over the project will be limited to whatever contractual arrangements are agreed.

- Most likely a higher bid price for the whole plant because, under a turnkey contract, the vendor accepts a considerable economic risk for delays and failures;
- Possible reduced international competition, because all suppliers might not be willing to accept turnkey contracts;
- More limited transfer of technology (unless specifically provided for in the contract), because the owner's involvement in the design and construction of the project is limited;
- Larger risk of delays and overall project failure if the vendor is not experienced or reliable;
- Less potential for national participation.

In summary, the turnkey approach may be preferred when there is little or no project management and/or heavy construction experience in the country and when a large amount of training over a long time period would be required to attain the necessary skills.

14.5.2. Split package

In a non-turnkey contractual approach, the buyer places a number of separate contracts for various portions of the plant design and construction. The buyer assumes the responsibility for overall project management, either directly by himself or through an architect–engineer (A–E). The buyer also takes responsibility for making all key project decisions. Non-turnkey contracts may be divided into two main types, namely the split package approach and the multiple package approach.

In the split package approach, the responsibility for design and construction of the plant is divided among a relatively small number of contractors, who manage, engineer, construct and/or manufacture large functionally complete portions of the work, e.g. entire systems, buildings, etc. Each portion is called a package.

If time permits, a sequential bidding procedure can be utilized for a split package approach. In this case, bids would first be invited and assessed for the nuclear steam supply system (NSSS). The bid specification for the conventional island or turbine–steam system and, very likely later, for the desalination plant can then be issued with much better defined interfaces.

14.5.3. Multiple package

In a multiple package approach, the buyer (either within his own organization or through his A–E) assumes the direct responsibility for the design and construction management of the project with support from a large number of contracts. This approach has been adopted as a normal contracting method in many countries.

Bids are invited for the NSSS (including initial fuel loading), turbine generator and desalination equipment packages; the suppliers are selected; and contracts are placed. The buyer (or his A–E) then designs the balance of plant around this equipment. The buyer will produce a very large part of the safety report; supervise construction or even erect the plant with an in-house construction staff. This approach clearly offers the maximum opportunity for the buyer to design and construct the plant that suits him best. It also offers the best possibility for a low cost plant, provided the buyer is well qualified and experienced. On the other hand, it gives the buyer (or his A–E) the maximum amount of work and responsibility for the proper technical design, the cost, the schedule and the plant performance.

14.5.4. Independent projects (BOT and BOO)

In a BOT approach, a number of foreign investors form a consortium. The consortium establishes a joint venture company (JVC) with a local utility, and this JVC sells the electricity and/or water to the utility. These foreign investors procure most of the funds for the project, which are used to:

- build a plant with foreign engineering expertise;
- operate the plant through foreign investors/operators for a certain period until all costs, debt service and equity are recovered by means of an electricity and water tariff;
- transfer the ownership of the plant to the country in which it is built.

The JVC acts as the owner and operator of the plant. The supplier is expected to take an equity position in this joint venture, most likely together with the State owned or private utility responsible for the generation of electricity and/or potable water. The joint venture has to enter into a power/water sales agreement with the local utilities. After a defined period, during which the return on investor equity will be effected and the project loans repaid, the ownership of the plant will be transferred to the local utility.

When a nuclear plant is implemented under a BOT approach in developing countries, the following advantages may be generally expected:

- attraction of foreign capital in the form of non-government debt for power plants,
- reduction of the risks related to construction and operation under the consortium’s expertise and experience.
- provision of practical opportunities for training and technology transfer during the course of construction and operation.

However, it should be noted that there are some arguments against the BOT approach. Most notable is the potential reduction in national participation and delay in technology transfer. A variant of the BOT is the BOO approach. The BOO does not involve transferring the plant to the utility. A BOO plant can, in principle, continue in private hands throughout the useful life of the project or to some earlier date agreed upon by the host government and the private owner.

Any BOT or BOO arrangement for a nuclear desalination plant must address special concerns applicable to a nuclear power plant, including:

- Third party liability,
- Decommissioning,
- Physical protection,
- Safeguards,
- Safety,
- Environment protection.

Up to now, however, there is no nuclear project in the world adopting the BOT or BOO approach, because of the difficulty in defining the responsibility between owner and host country for the third party liability.

14.5.5. Use of architect–engineers

Utilities with no previous nuclear experience should only use a non-turnkey contracting approach (except BOO or BOT) with the help of a competent A–E. In such a case, key factors for project success will be selection of a qualified A–E as well as the proper division of activities and responsibilities between the parties involved.

The division of activities and responsibilities between the owner and the A–E depends to a great extent on the availability of qualified personnel among the owner's staff. The A–E customarily takes lead responsibility for:

- Overall project management,
- Procurement,
- Project engineering,
- Erection and equipment installation,
- Commissioning,
- Quality control,
- Schedule and cost control.

The selection of an A–E for a nuclear desalination project should be based on his competence in both nuclear power and desalination fields and on the key personnel that he could make available for the project.

14.6. BID INVITATION SPECIFICATIONS

14.6.1. Purpose, scope and procedures

The preparation of formal bid specifications is required for any type of competitive (or even non-competitive) bidding. The content will depend on the contractual approach and on the scope of supply requested by the buyer.

Bid specifications are intended to provide essential project and technical information to the prospective suppliers who are invited to present their bids. This information should be as complete and precise as possible, so that the suppliers obtain a clear understanding of what the buyer wishes to purchase, what are his requirements and what are the conditions and circumstances under which the suppliers' tasks are expected to be performed. Furthermore, the bid specifications are intended to instruct

TABLE 14.II. MAJOR TASKS INVOLVED IN PLANT ACQUISITION

A. Information provided by the owner	B. Information requested from the bidder
1. Invitation letter	1. General
2. Administrative instructions	1.1. Technical description
3. General information	1.2. Safety analysis report of bidder's standard design
3.1. Project description	1.3. Scope of supply (foreign and local)
3.2. Site information and data	1.4. Commercial conditions
3.3. Electric system	1.5. Quality assurance programme
3.4. National infrastructure	1.6. Deviations and exceptions
4. Technical requirements and criteria	1.7. Relevant experience
4.1. Design	2. Summary of selected information
4.2. Construction	2.1.1. Technical description
4.3. Operation	2.1.1. Design
4.4. Safety and licensing	2.1.2. Construction
4.5. Quality assurance	2.1.3. Operation
4.6. Training	2.1.4. Safety
4.7. Schedule	2.1.5. Quality assurance
4.8. Documentation	2.2. Commercial conditions
4.9. Codes and standards	2.2.1. Prices and currency
5. Scope of supply of owner and bidder	2.2.2. Escalation formula, indices
6. Technology transfer	2.2.3. Payment schedule
7. Terms and conditions (draft contract)	2.2.4. Financing
	3. Guarantees and warranties

the bidders on the manner of presenting their information in order to facilitate the buyer's bid evaluation. Finally, the bid specifications are intended to serve as the basis for the contract documents to be developed together with the successful bidder.

Table 14.II contains a summary of contents, which might serve as a guide for the type of information to be included in the bid specifications for a nuclear desalination plant or constituent package (NSSS, turbine generator, etc.).

Sample bid specifications may be available upon request from utilities that have prepared them in the past and could be consulted as useful reference material. However, bid specifications always refer to specific situations and therefore cannot be adopted without extensive modification.

The preparation of bid specifications for a nuclear desalination plant is a highly specialized task requiring experienced staff. Part of the essential experience will already have been developed during the planning and feasibility studies. Any experience acquired during the bidding and acquisition of fossil fired desalination plants will be very useful. If the owner is an electric utility, it should have experienced staff in the acquisition, construction and operation of conventional plants. There should also be qualified professionals available within the country who are experienced in the acquisition of large industrial plants, and others who have received specialized training and education in subjects relevant to nuclear technology.

It is recommended that the buyer organize a team from his available staff, augmented by others recruited for the specific purpose of preparing the bid specifications. Depending on the contractual approach, about 15 to 25 qualified professionals would be needed. It is generally advisable to have also the assistance of a well qualified consultant to supply any missing experience and knowledge to the owner's team.

The preparation of the bid specifications constitutes the first stage of the plant acquisition process. Since the bid specifications are both a technical and a contractual document, they must be clear, precise, unambiguous, consistent and comprehensive. It is advisable to have the specifications reviewed by people experienced in preparing and handling contracts, even if they have no nuclear experience. Nuclear engineers might have a profound technical and scientific knowledge in their speciality, but are not necessarily knowledgeable and experienced in the preparation of bid specifications and contracts.

The buyer may further assist the bidders in the preparation of their bids, by giving them access to the site and to any additional studies and surveys that have been performed with regard to the nuclear desalination project. Direct contact of the bidders with local industries and relevant organizations should be promoted.

Further detailed information on the subject of bid specifications is contained in Ref. [70].

14.6.2. Terms and conditions (draft contract)

The buyer should always include in the bid specifications a draft contract with the terms and conditions he wishes to agree upon with the successful bidder. The draft contract should be clear and precise and should contain reasonable terms and conditions designed to protect the owner, but also equitable and acceptable to the bidders. The bidders must provide comments and justifications regarding their deviations from and exceptions to the buyer's terms and conditions. The draft contract, together with the comments of the successful bidder, will form the basis for the contract negotiations.

The draft contract should address the administrative, organizational, commercial, legal and technical matters that are of overall importance to the project and need to be settled in the final contract document. It should define the responsibilities of the supplier regarding his supplies and services to be provided from abroad as well as through local sources. The supplies and services comprise studies and technical documents, design, manufacture, inspection of manufacture, tests, transport, insurance and storage, erection and testing of material and equipment, pre-operational testing, commissioning, demonstration run, compliance with the guarantees and warranties, and assistance and services during operation and maintenance.

Typically, the draft contract includes the following items:

- Basis for the contract,
- Scope of supply and services,
- General agreements,
- Risks, liabilities and title,
- Insurance requirements,
- Licensability and licensing conditions,
- Inspection and control,
- Schedule,
- Technical guarantees and warranties,
- Acceptance and final takeover,
- Price, price revisions, terms of payment,
- Changes and modifications,
- Force majeure,
- Contract modifications or cancellation,
- Applicable language, laws and arbitration,
- Government agreement, letter of support.

The draft contract should, in particular, address the various aspects of risk of loss, damage, liabilities and transfer of title. In a turnkey project, the supplier should carry the risk of any loss or damage until the date of acceptance, except the nuclear risk, which is always borne by the owner. In the event of injury suffered by persons, or loss or damage sustained by or occasioned to third parties, their properties or possessions, the liabilities of the supplier and the owner should be determined by the law of the country where the injury, loss or damage occurred. The transfer of title and property in all or any materials, goods, equipment or systems intended for inclusion in the nuclear desalination plant should pass to the owner upon the same being delivered to or received at the site or on takeover of the plant.

Guarantees and warranties should cover design, material, workmanship, delivery and performance, following the usual practice.

All general matters, such as prices, price revisions, terms of payment, force majeure, cancellation of the contract, applicable law and arbitration courts, can be dealt with in a conventional way as for other contracts. It is emphasized that the draft contract must be prepared with extreme care by specialists in this field, including good industrial lawyers with international experience. It is further advisable to provide a set of definitions that are used consistently throughout all documents.

14.7. BID PREPARATION

Once the bid invitation has been issued, the suppliers will start preparing their bids. This task will require six to eight months for a turnkey project and somewhat less (four to five months) for each of the principal packages in non-turnkey approaches. If harmonized or sequential bidding procedures are adopted for non-turnkey projects, the bid preparation phase will overlap with bid evaluation and will last considerably longer. The cost of preparing a bid for a nuclear desalination plant may be of the order of several hundred thousand to some million dollars.

Although the bid preparation by the potential suppliers will be the main activity during this phase, there will also some tasks for the buyer, consisting of:

- Proceeding with additional studies that might be required for site evaluation,
- Maintaining contact with the bidders and providing them with additional or clarifying information as required,
- Preparing for the bid evaluation.

It is intended that the bid specifications should be complete, clear and unambiguous, but it must be recognized that the bidders will undoubtedly find mistakes and omissions, which will require clarification by the buyer. The bidders will also find at least some of the buyer's requirements unacceptable or too difficult and expensive to comply with and will approach him with requests for modifications.

As it is desirable that the bids should correspond as far as possible to the bid specifications, the buyer might want to reconsider his requirements and modify the specifications accordingly.

This will generate a constant correspondence and flow of information, which should be channelled by the buyer to all holders of the bid specifications, simultaneously. Every communication of the buyer that clarifies, modifies or adds to the bid specifications must be in writing. It must be incorporated into the specifications and communicated to all bidders.

The buyer should use the bid preparation period to prepare for the evaluation of the bids. The bids will have a limited validity, and the evaluation should proceed as smoothly and rapidly as possible. Preparatory actions that will facilitate the performance of the bid evaluation include:

- Organization of the evaluation team,
- Assignment of responsibilities,
- Development of evaluation methodology,
- Analysis by the evaluation team of the available technical information on the bidders' products,
- Pre-evaluation of the bidders,
- Cost estimates of items within the owner's scope of supply.

14.8. BID EVALUATION

The evaluation of the bids received from suppliers in response to the bid invitation is a major task leading to the selection of the supplier(s) and the final decision to construct the nuclear desalination plant. The buyer has a direct responsibility to perform the bid evaluation within his organization and with his own staff. As expertise is needed in many different fields and disciplines, assistance from an experienced and impartial consultant might be required for specific tasks, especially for a first project.

The period required for bid evaluation is usually six months to a year. At least about 40 experienced professionals will be needed, most of them engineers in various disciplines, but also lawyers and economists. A core of top level management staff will have the task of directing and co-ordinating the evaluation effort.

Regarding the evaluation approach in a competitive bidding, the two stage approach is in generally recommended: a preliminary and a detailed evaluation phase. The preliminary evaluation, which can be performed in a month or two, has the objective of selecting the preferred bids (possibly two or three) that will then be evaluated in detail during the second phase. As a minimum, the preliminary evaluation must eliminate all the bids that do not technically fit the buyer’s main bid specifications. This approach helps to reduce the workload while maintaining the important competition during the detailed evaluation period.

The bid evaluation can be subdivided according to the following different aspects which apply to both nuclear and desalination plants:

- Technical,
- Safety,
- Economic,
- Financial,
- Contractual conditions,
- Organizational and management,
- National participation and technology transfer.

Some of these aspects will be linked; e.g. the safety evaluation could be part of the technical evaluation, and the economic evaluation will include the financial factors:

The first task of the bid evaluation is to establish the evaluation factors to be considered. The establishment of their relative importance or weight is often difficult and in some cases might be beyond the scope of responsibility or capability of the owner's evaluation group. Some aspects, especially those affecting national policy and financial matters, would probably involve high governmental levels. An overview of selected aspects of bid evaluation is provided below. Two IAEA Guidebooks [68, 71] can be referred to for further details.

Technical bid evaluation

The main objective of the technical bid evaluation is to determine the technical acceptability of the bid. The technical bid evaluation is essential and independent of the acquisition approach adopted since the success or failure of the project ultimately depends on the overall technical performance of the plant. In general, the scope of the technical bid evaluation includes:

- Checking the bid for completeness of the information requested,
- Checking the scope, interfaces and limits of supply and services,
- The evaluation of the technical features of the equipment and structures as well as the adequacy of the services,
- The preparation of questionnaires, evaluation reports (including the identification of problem areas) and of suitable technical documents.

The bid evaluation also includes the assurance of adequate provisions for safety and reliability. The nuclear desalination plant must be licensable in the country with known risks of extra costs for additional licensing requirements and should further give assurance of adequate operability, maintainability, water quality, environmental impacts and design life.

Economic evaluation

The main objective of the economic evaluation is to establish the cost of the plant and to rank the bids in accordance with an economic figure of merit. Economic evaluation factors used in practice include the following:

- Total investment required,
- Unit electricity and water production cost,
- Present worth of lifetime expenditures,
- Expenditures to be paid before start of operation,
- Expenditures in foreign currency,
- Internal rate of return,
- Cost/benefit ratio and
- Payback period for the investments.

It will depend on the particular situation whether one of these factors or some combination is regarded as decisive for the economic order of merit. Frequently, the construction of a nuclear plant is among the largest single projects of the country. Hence, the economic and financial analysis of the bids should also take into account the national point of view.

Contractual conditions

The evaluation of the contractual conditions fundamentally consists of identifying any exceptions or deviations contained in the bids with respect to the owner's bid specifications and to evaluating their effect and importance.

Most of the differences between the conditions specified by the buyer versus those offered by the bidders can be resolved during contract negotiations by compromise and agreement. However, some differences might be of such fundamental nature that they could eliminate the prospective supplier from the bidding procedure, unless he is willing to modify his position. It is desirable to identify such fundamental exceptions or deviations at an early stage of the bid evaluation procedure. Negotiations should be started as soon as possible to resolve the differences because, if the positions of the buyer and bidder are not reconcilable and mutual agreement does not appear likely, further evaluation of the particular supplier's bid would be useless.

Organizational aspects

The evaluation of organizational aspects could be considered separately or included in the scope of the technical evaluation. Its main purpose is to establish a measure of confidence based on technical judgement as to whether the project can be implemented within the schedule and cost commitments of the bid. Project management is possibly the most relevant aspect to be analysed in detail, together with the proposed organizational structure for handling subcontracting and interfacing.

National participation and technology transfer

Detail and depth of the evaluation of national participation and technology transfer depends strongly on the national policy in this matter. This aspect could become one of the decisive evaluation factors in case of ambitious national participation goals with a serious commitment to implement them. In this case, the evaluation must include detailed quantitative and qualitative assessments of the commitments contained in the bid rather than accepting ‘goodwill’ clauses or expressions of ‘best effort’ from the bidder.

Overall bid evaluation

The overall bid evaluation is normally performed by several specialist teams working in parallel on the different aspects and directed and co-ordinated by a manager. The evaluation (project) manager reports directly to the decision maker level of his organization. Setting up an ad hoc bid evaluation committee to assist and advise both the decision makers and the manager is advisable, in view of the magnitude of the project as well as the interdisciplinary character of the work.

The evaluation of the policy and political aspects of the bids can probably not be performed by the bid evaluation team. However, the team does have the task of providing the national decision makers with all relevant information on the issues involved, pointing out advantages, disadvantages and potential problem areas, such as international commitments and agreements, export licensing, and assurance of supply.

After selecting the supplier(s), it is customary for the buyer to issue a letter of intent, which communicates to the suppliers the buyer's intention to proceed with the contractual arrangements. This letter of intent should contain a brief summary of the principal aspects of the supply to be contracted and should refer to the documents that are to be used as a basis of the contract. The letter of intent might also contain a limited authorization for work to be performed by the supplier, such as ordering materials and equipment with long delivery times. This authorization in effect already constitutes a limited contract and as such commits both the buyer and supplier. Its issue will depend on the buyer's confidence in reaching a satisfactory conclusion of the contract within a reasonable period and on his urgency in starting (and finishing) the project.

Because of the extent of the technical information, it is in most cases not possible to finalize the technical contract specifications before placing a letter of intent. This can be acceptable if the basis for completing the technical specifications is clear and agreements have been reached during the technical contract negotiations on those parts that need completion. However, it is essential to make a record of the agreements reached during such technical contract negotiations, as they would eventually form the basis for completing the technical specifications. The technical contract specifications must be agreed upon before the contract is signed.

14.9. CONTRACT NEGOTIATIONS

All the tasks performed during the acquisition phase culminate in the finalization of the contracts. The primary task during contract negotiations is to set out the contractual terms and conditions in a clear and precise manner and to define the supplier’s responsibilities regarding the scope of supply, services, warranties, guarantees, code compliance, standards and regulations adopted for the plant.

For a large project like a nuclear desalination project, there will always be several contracts. Even under a turnkey approach with one main contract for the supply of the plant, there will be additional contracts for the desalination plant, owner's scope of supply, fuel and fuel cycle services and for financing. For a split package approach, a contract will be needed for each package, and for a multiple package approach there might be as many as a hundred contracts involved. Each contract needs careful preparation because, together, these documents will precisely define the activities to be performed, the goods and services to be supplied, and the terms and conditions under which the project will be done.

Contracting can be divided into the following stages:

(1) Contract negotiation: all major terms and conditions are clearly stated and agreed upon;
(2) Contract finalization: the final contract documents are prepared on the basis of the previous agreements;
(3) Contract signing by duly authorized representatives of the parties;
(4) Contract validation, whereby specific conditions of compliance must be met before the contract is effectively valid.

A few practical measures can be taken to avoid potential problem areas in contracting. Minutes should be recorded at all meetings. A language problem may be involved if the languages of the supplier and buyer country differ. There must be one accepted official language, usually the language of the buyer, for all written documents and communications.

During contract negotiations, the bid specifications and the bid have to be combined into one single contract, which should be clear, precise, complete, fair, equitable and to the ultimate benefit of both parties.

The most important contractual negotiations should be carried out during the bid evaluation phase, because improvements to bids and mutual agreements are much easier to obtain before the buyer has definitely selected his suppliers. The selection of suppliers is fundamentally equivalent to accepting the suppliers' bids, including any amendments and modifications that have been agreed upon as of that date. Afterwards, it would not be reasonable to expect the suppliers to substantially alter their bids, nor would it be reasonable for the buyer to request major additional improvements unless he is ready to pay for them.

Contract finalization usually requires about six months for a turnkey contract or three to four months for an individual package under a non-turnkey contract. Absolute priority should be given to achieving a good contract. Nothing relevant should be left open, and the temptation to leave details 'to be mutually agreed upon later' should be thoroughly resisted. This would only create the potential for trouble spots.

The signing of the contract represents the commitment of the parties, but there are usually some conditions included in the contract itself that have to be complied with before the contract effectively becomes valid. Such conditions might be:

- Financing agreements,
- Downpayments,
- Governmental ratification or approval,
- Bilateral or international agreements,
- Safeguards agreement,
- Export license,
- Regulatory and licensing requirements.

Compliance with such conditions, if required, might need several months or longer. In an extreme case they might delay the project indefinitely and, if no mutually satisfactory solutions can be found, this would ultimately lead to cancellation of the contract.

14.10. FINANCING ARRANGEMENTS

A nuclear desalination project is only viable if financing is assured. This might constitute a major constraint to countries poor in capital and financial resources or where many different investment requirements compete for the available resources. Because of the relatively large investment requirements of a nuclear desalination plant, its financing should be viewed within the framework of the country's overall electricity and water supply, and even within the country's overall economy if it represents a sizeable addition.

If the buyer has difficulty in obtaining suitable financing on his own, he may request financed offers in the bid specifications. The reactor, power plant or desalination plant vendors might offer some partial financing to directly finance their supplies. The vendors might have access to their national export financing institutes, whose objective is to facilitate exports, and consequently may offer preferential terms. There is a common interest between the vendor and his national financing institute to promote the sale.

The financing arrangements have to be negotiated directly between the buyer and the financing institute. The vendor will usually provide assistance. This could be of fundamental importance for obtaining loans on the best possible terms. Financial institutes are usually reluctant to commit themselves before a supply contract is finalized between the buyer and the vendor. However, if the acceptability of the bids is subject to being accompanied by a financing offer, the financial institute(s) might issue a conditional letter(s) of intent.

Preliminary discussions can and should be held with the financing institutes during and even before the bidding process, but the final financing contract negotiations are only started after the supplier is selected and at least a letter of intent for the supply is issued. Financing institutes may even insist that the supply contract be signed before the start of financing contract negotiations. The buyer, on the other hand, would normally be reluctant to commit himself to a supplier before having a clear understanding of at least the principal terms and conditions of the financing contract. This conflicting situation is usually resolved by making the letter of intent and the contract for supply conditional to the finalization of financial arrangements satisfactory to the buyer. In some cases, the vendor can issue a 'guarantee bond' assuring the buyer that he will fulfil his financial commitments by raising loans for the buyer at foreseen interest rates.

Financial institutes have standard contracts, but special contracts containing special terms and conditions are usually drawn up for the large amounts involved in a nuclear desalination plant and if preferential loans are involved. Some of the terms and conditions might not be acceptable to the buyer and consequently have to be negotiated. The buyer's lawyers and economists as well as those of the buyer's government would be likely to perform the contract negotiations. Technical knowledge regarding the nuclear desalination project is practically not required in these negotiations.

Financing arrangements culminating in the signing of the financing contracts might require several months and sometimes even a year or more. If the supply contract is conditional to completion of the financing arrangements, there is an evident urgency involved, because the supply contract does not become effectively valid and major project work cannot start until financing arrangements have been completed.

Financing requirements, constraints and sources are discussed in more detail in Ref. [69].

14.11. INTERNATIONAL AGREEMENTS AND COMMITMENTS

The acquisition of a nuclear desalination plant requires proper understanding between the buyer and the supplier regarding the supply of nuclear fuel elements as well as other related equipment needed for smooth, trouble free operation of the facility. Such an understanding needs to be legalized and a firm commitment must be obtained from the supplier. A failure to obtain an assured fuel supply would not only mean being left with an unproductive investment but would also negatively affect the power and water supply.

The international concerns regarding assurance that nuclear energy is used exclusively for peaceful purposes are related to the nuclear reactor and its fuel. To this end, the use of the energy produced, i.e. desalination of sea water, is in itself irrelevant. For this reason, a country will obtain nuclear technology, nuclear reactors, nuclear fuels, materials and equipment from a foreign supplier only if it can provide adequate evidence of their exclusive use for peaceful applications. Such evidence must attain the full satisfaction of the potential supplier and the international community. Hence, a suitable commitment from the buyers is warranted.

Chapter 15

OVERVIEW OF DESIGN, CONSTRUCTION AND OPERATION

15.1. INTRODUCTION

In this chapter, a brief overview of design, construction and operation aspects of a nuclear desalination plant is presented. The main objective is to provide general guidance for achieving a successful project through adequate implementation of all project activities including design, construction and operation.

The role of the plant utility in ensuring successful transition from project inception to desalted water production is a vital one. The utility must assume overall responsibility for the project and the full responsibility for management, operation and maintenance, even for the first nuclear desalination plant. It must aim to develop its own capabilities to fulfil these responsibilities successfully. It may seek advice and assistance of foreign services whenever required.

The role of national participation in the design, construction and erection, operation and maintenance of a nuclear desalination plant is also very important. It helps reduce the foreign exchange content of the overall cost, provides encouragement and employment to the local population and can help improve the industrial capability.

The extent of national participation should be worked out so as not to compromise the quality and safety aspects of the plant nor to jeopardize the project schedule. The limitations of the national participation must be considered carefully. It is important to recognize that a realistic approach to national participation is an important element of success [35, 37].

The owner/utility must take into account the water needs to determine the size of the nuclear desalination plant and the construction schedule. The owner should work out the details of the implementation policy and project execution methodology including bidding and financial aspects. The owner is also responsible for getting the plant licensed and for establishing programmes for quality assurance, quality control and radioactive waste management and disposal. He may also be directly involved in certain other activities such as grid expansion (if required), water intake and discharge.

The owner/utility may delegate the responsibility for overall direction and co-ordination of different project implementation activities to a main contractor under the turnkey approach or to an experienced A–E under a non-turnkey approach. The owner/utility does, however, retain the direct responsibility for control and supervision of the project under any type of contractual approach. To fulfil this responsibility, he should have his own project management organization, headed by an experienced project manager. He may seek the assistance of experienced consultants in this regard, as well.

15.2. PROJECT MANAGEMENT

Project management includes managing the general engineering work, co-ordinating and expediting the various engineering disciplines, recruiting and managing personnel, procurement and accounting. It also covers the management controls and information the total project requires for meeting the target cost and schedule.

Project management activities start with the decision to go ahead with a nuclear desalination project and end with handing over the operating plant to another body which will be responsible for its operation and maintenance [36]. Clearly defined schedule and budget targets from the early planning stage right through to the functioning product are required. The careful choice of the right lead project management personnel, proper planning, establishment of a correct project organization and its support are important steps towards successful project implementation.

The project manager should be a model representative of good management practices because he is ultimately responsible for the cost, schedule and technical performance throughout the project. The project manager should use his control and communication functions to assist in early diagnosis of any problems which then must be brought to the attention of the owner’s general management. He supports the overall technical quality by providing, either directly or with the help of others, an independent check on many of the important project decisions and project data.

Some of the project management activities can be shared between suppliers and owner. The scope and responsibilities of each party should be clarified in the contract. In a turnkey contract all the activity items fall under the responsibility of the supplier.

15.2.1. Project management in the planning phase

The planning phase is intimately connected with, and will benefit from, accompanying activities such as personnel development and the establishment of the legal framework for the regulatory and licensing infrastructure. Although the main responsibility in energy planning may be in the hands of the government, the future operating organization, e.g. the utility, should preferably have a small group participating in these early activities. Further project management tasks commence with the feasibility and siting studies, the evaluation of the type and size of the proposed nuclear desalination plant and the plant safety requirements.

The major project management activities during the planning phase are:

- Pre-project activities,
- Bid invitation,
- Bid specification and bid evaluation, and
- Negotiation and closing of the contract.

15.2.2. Project management in the execution phase

From the standpoint of resources, time span and complexity, the execution of a nuclear power desalination project is a major undertaking, which is beyond comprehension, direction and control by a single person. The necessary team effort and highly professional approach to engineering and manufacturing require specialized direction in many different disciplines. Project management under delegation from top management is needed to co-ordinate and control such a large and diverse operation.

The schedules for construction and commissioning could be, in addition to the preceding design and engineering period of about three to five years, about two to three years for a desalination facility, three to four years for a small, dedicated reactor and five to seven years for a medium or large co-generation plant. These schedules are approximate goals, which could be achieved if delays due to technical or institutional problems (which occur in practically every major project) are kept short or can be compensated for by rescheduling of tasks.

Concerning the construction schedule, it may be practical to start nuclear plant construction first and desalination plant construction later, in order to have them ready for operation at the same time. This would levelize the cash flow requirements, and the owner may also benefit from improvements of desalting technology in the meantime. However, if it is necessary to secure sufficient water supply to the construction site, it may be practical to install at least part of the desalination plant first.

Local participation in the execution of a nuclear desalination plant would mean utilization of material and human resources within the country. This has both technical and financial implications. Independent development of local resources may require extensive effort and involve high cost. Thus, the extent of national participation may vary from country to country, depending largely on the availability of the resources needed. Countries having lesser manufacturing capabilities and infrastructure may prefer the turnkey approach, whereas countries with substantial infrastructure may prefer the split package or multi-package approach involving a higher degree of national participation. In any case, there is an obligation to have a certain minimum of local participation, as there are some essential activities for which full responsibility must be borne by national organizations and which should be primarily executed by local human resources. Also, the owner, regulatory bodies and other relevant organizations have vital responsibilities in the project and must, to the extent feasible, play an active role.

15.2.3. Structure of project management

Project management in the widest sense is the function of defining, steering, controlling and correcting a project or major parts of it. Steering a technically, organizationally and financially complex project usually implies a complex management structure but with simplified and streamlined co-ordination. Project management therefore constitutes a management arrangement and involves a system of special management techniques.

The project manager is, above all, responsible for the satisfactory completion of a high quality product. He uses the contract, the specifications, the budget and the schedule as control instruments and employs numerous administrative and technical procedures as well as his personal contacts, knowledge and authority. Figure 15.1 shows an example of an organizational structure that might be used for a nuclear power plant project, and Fig. 15.2 illustrates the main contractor project management concept.

15.2.4. Project execution

This phase involves performing the major engineering activities of the plant and ordering, producing and installing large amounts of materials and equipment. Therefore, this phase involves mobilizing the most important human resources and incurring the largest part of the overall cost. Thus, the highest degree of co-ordination is necessary. It is in this phase that project management has to show its strength and use all its tools. The stage begins with the signed contract and ends with turning over the completed and tested plant to the operating organization.

This activity comprises:

- Definition of the project,
- Division of responsibilities of participants,
- Tools and methods for project execution,
- Site management, and
- Project execution.

15.2.5. Project control

Project control is one of project management's key tasks. The most important elements in project control are schedule control, cost control and QC/QA. While planning and organizing have an initial peak and executive activities vary considerably over the duration period of a project, control measures must always be present and applied to both near and long term tasks. Control therefore affects all partners and all phases of a project; however, it naturally peaks during project execution.

The highest level of management activities consists of:

- Schedule and resources control,
- Cost control,
- QA and QC.

Other management activities include:

- Interface and integration control,
- Review and approval of design and engineering,
- Inspection and test control,
- Measuring progress, and
- Design change control.

15.3. QUALITY ASSURANCE AND QUALITY CONTROL

Quality assurance provides adequate confidence through planned and systematic actions that an item or facility will perform satisfactorily in service. Quality control refers to QA actions, which provide a means to control and measure the characteristics of an item, process or facility in accordance with the established requirements. The requirement for high quality is one of the main features distinguishing a nuclear from a conventional project. Safety and reliability can only be ensured by proper implementation of the QA and QC performance and procedures.

QA and QC start with establishing the quality requirements for any safety related engineering, material selection or manufacturing activity and end with the safe and redundant filing of records that confirm that the product complies with the quality requirements. QA and QC work must be initiated in the precontract phase as part of bid specification and continues into the design and procurement of equipment and materials. It is especially vital during construction and commissioning of the project.

QA and QC during the engineering and construction management phases of a nuclear desalination plant must be carefully carried out in an appropriate manner. QA

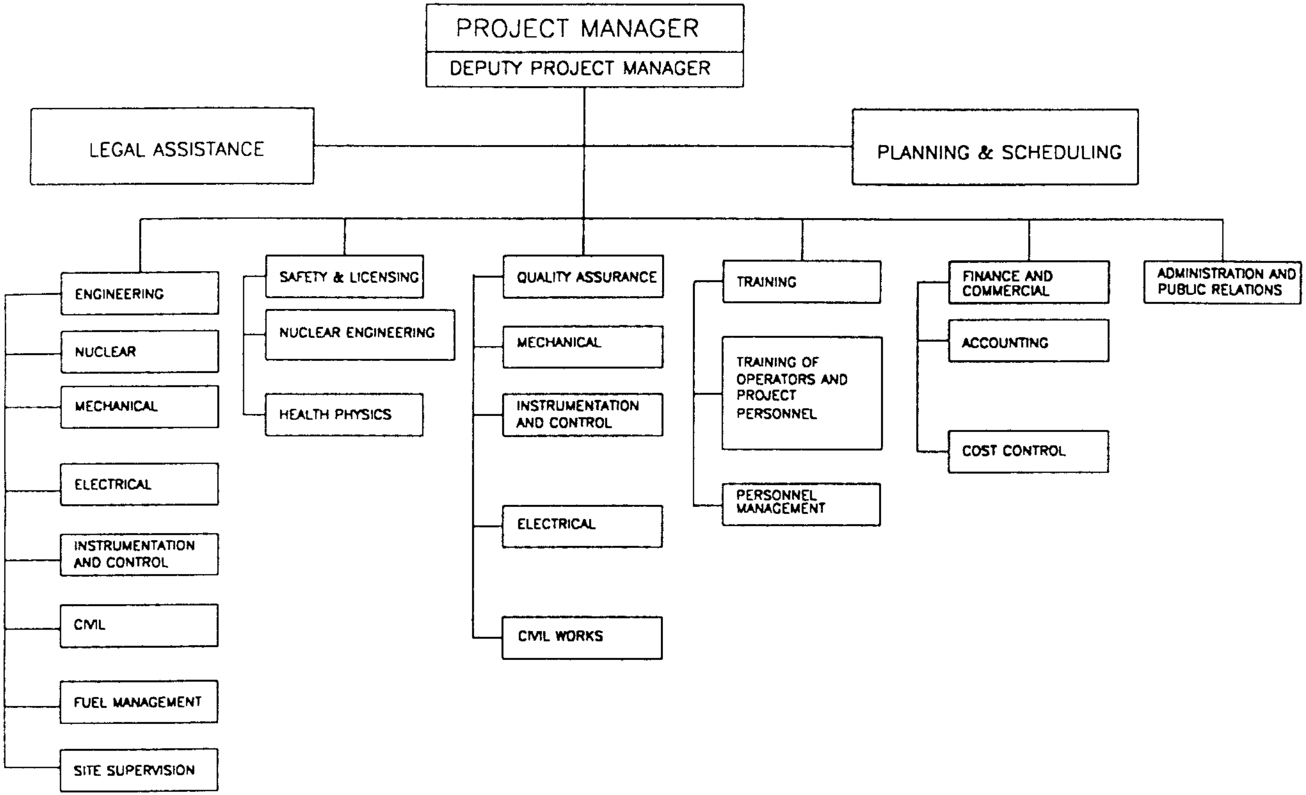

FIG. 15.1. Example of an organizational structure for a nuclear power plant project.

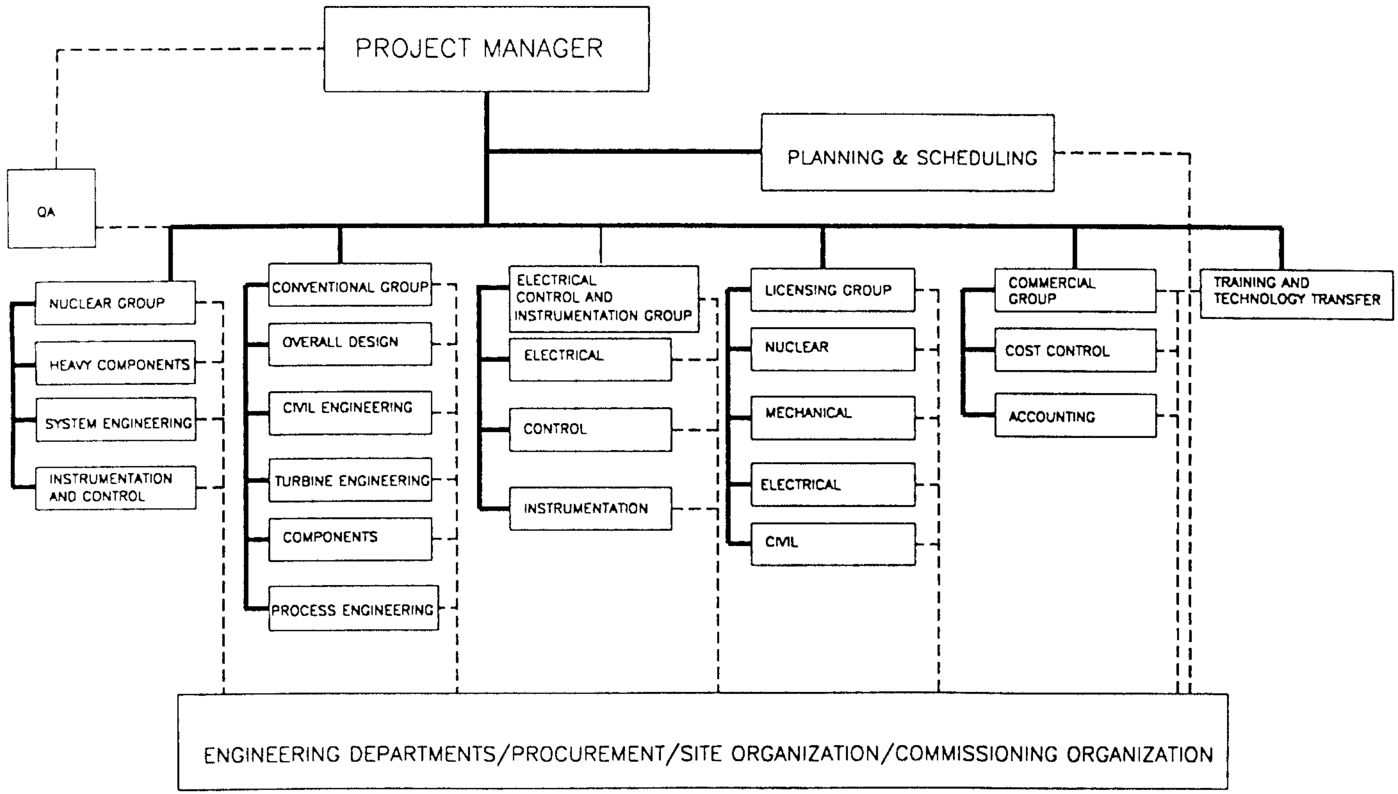

FIG. 15.2. Concept for main contractor project management.

applied to performance tests of instruments, control and automation systems must be ensured and verified. QA and QC work also includes non-destructive testing and evaluation, survey inspection and inspection of correct use of materials. It continues during the entire operating life of the plant. The regulatory body is also involved in a supervisory capacity by performing inspections and audits to see that the project's QA and QC provisions are effectively implemented.

The owner is responsible for implementing the overall QA programme for the plant. He should fulfil this responsibility either directly or through contractual arrangements that extend the constituent activities of the QA programme to a qualified third party. The owner may still require a QA group for co-ordination and supervision because the owner is responsible for overall QA programme management and co-ordination.

The owner is obviously concerned with the efficient and reliable operation of the plant but must assign the highest priority to safe operation. Thus, the owner's QA programme must be applied to all activities that may affect nuclear safety, extending from the design stage through the manufacturing, construction, commissioning and operation stages. The QA programme should prevent safety system malfunctions by promoting a sound conservative design, construction, and selection of materials. The QA programme should also promote professional safety consciousness in all operation activities. This includes application of QC to the product water from the desalination plant to assure compliance with potable water standards.

15.4. DESIGN AND ENGINEERING

The design and engineering services include conceptual and preliminary design including review, preparation of licensing documentation, detailed designs, equipment specifications, construction, fabrication, erection, installation and commissioning support and as-built documentation.

During the acquisition phase of the project, preliminary design outlines should be developed. It is relatively simple for a turnkey approach, but more complex for split package or multiple package approaches. Preliminary design is basically the owner's responsibility, but may be delegated to experienced A–E firms.

Conceptual, preliminary and detailed design are the tasks of the turnkey contractor or of suppliers and A–Es (in case of a non-turnkey project). The owner is responsible for design review, surveillance and control in order to verify that the supply is within the established scope and contractual terms and conditions. The owner must also verify that the design is in strict conformity with the criteria, rules, standards and regulations applicable for licensing compliance.

Design and engineering should take into account the requirements imposed by the plant operating characteristics, particularly during startup and shutdown. It should also consider the need for electricity grid and water supply connections, provisions for standby power and water and for future expansion. Design considerations for the seawater intake and outfall system should also be taken into account so as to serve the requirements of both the desalination plant and the nuclear reactor in a satisfactory manner.

A number of leading consultants and suppliers are available to carry out design and engineering services for a nuclear desalination plant. Several codes and standards such as US standards, Japanese standards and European standards (including German, British, French and Italian standards) are available for carrying out the mechanical design and structural analysis of nuclear and desalination vessels. Such codes and standards also regulate the electrical and safety equipment designs.

In most countries, areas for national participation in design and engineering can be found in the civil and steel construction sectors. Other areas could be in the power supply and electrical system interconnection, cooling water systems, demineralized water plant, heating ventilation and air conditioning systems, conventional systems and facilities in general.

15.5. CIVIL WORKS

Civil works represent one of the major activities in constructing a nuclear desalination plant. The execution of the civil works is complicated by the fact that the construction schedule requires overlapping of several individual activities involving civil works including site preparation, installation, erection and commissioning. Also, application of QA and QC to civil works is vital for their successful completion.

It is important to have significant national participation in this activity because it requires thorough knowledge of national building codes, characteristics of indigenously supplied building material and characteristics of local geology, hydrology, seismology, soil conditions, flood patterns, etc.

Site preparation and the provision of the necessary site facilities and infrastructure precedes the construction of plant buildings and structures [13].

Site preparation is usually within the owner’s scope of supply, even in the case of a turnkey approach. It is in the owner’s interest to complete the site preparation and provide the site infrastructure in the shortest possible time to avoid delays in the following construction activities. The owner may start this work even before the contract is finalized. Site preparations do not demand special nuclear or desalination expertise, except for information on the site infrastructure requirements. Among the construction materials, concrete, structural and standard steel might need some special attention. The rest should not be difficult to supply from national sources close to the site.

Erection of plant buildings and structures will be a new experience for a country building its first nuclear desalination plant, so certain preparatory actions should be taken in order to avoid problems which might cause delays and/or higher costs. Potential problem areas are as follows:

- Availability of construction materials in sufficient quantity and quality,
- Availability of major construction equipment of adequate capacity,
- Qualifications of construction companies regarding size, capability and reliability to undertake the job,
- Qualification of the supervisory staff of construction companies,
- Availability of qualified human resources in technical trades such as pipe fitters, welders, electricians, etc.

Compared to a conventional fossil fuelled desalination plant, the civil engineering and construction of a nuclear desalination plant require more technical knowledge, effort and care. Considerable amount of quality civil work is required for the nuclear system, desalination plant, coupling system including steam piping, seawater intake/outfall system, etc. Civil structures for the nuclear as well as the desalination plant should take into account seismic design considerations, mechanical vibration isolation, wind loading, durability and repair of concrete structures. The civil contractors will have to install their own technical and administrative site management to meet specifications and schedules and take corrective actions when needed.

Only experienced civil contractors are suited to carry out these civil works to the required standards and schedules. The quality control of the civil works has to be performed by a group independent of the contractor.

15.6. MANUFACTURING OF NUCLEAR REACTOR EQUIPMENT AND COMPONENTS

The equipment and components used in the construction of the nuclear reactor cover a wide range of complexity and required quality. Some of them are conventional while others are specific to the nuclear system. The main equipment are reactor vessel, steam generator, pumps, valves, turbine generator, instrumentation and electronic equipment and electrical equipment. The materials include conventional and specialized steels, high nickel alloys and zirconium alloys. Several industries play key roles in producing nuclear reactor components and materials. Manufacturing is the most significant area for providing opportunities for national participation, provided certain qualifications and requirements are met.

A substantial portion of the nuclear reactor components is manufactured to meet stringent specifications, which were developed through many years of experience in the nuclear industry. American standards are well known. European standards, such as German standards, British standards, French standards, Italian standards as well as Japanese standards and standards within the country, are also widely used. Any manufacturer entering the nuclear equipment and component manufacturing must follow these or equivalent standards.

The reactor vessel of a nuclear power plant is the most massive and critical piece of any equipment. The steam generators are nuclear class components and are also manufactured to the highest standards of quality. There are a number of heat exchanger manufacturers that are able to manufacture the steam generators to the required specifications and standards. A number of pumps and valves are used in the plant belonging to nuclear or to non-nuclear class. If a pump and valve manufacturing facility exists in the country, it can be upgraded to meet the necessary standards and quality assurance requirements. Industrial infrastructure existing in the country can also take the advantage of nuclear grade manufacturing for expanding the range and upgrading the quality of electrical, instrumentation and electronic equipment manufactured locally.

15.7. MANUFACTURING OF DESALINATION UNIT EQUIPMENT AND COMPONENTS

The type of required equipment and components varies depending on the desalination process. A thermal desalination plant requires evaporators, heat exchangers, a chemical pretreatment system, an evacuation system, pumps and valves, piping and supports, chemical storage tanks, instruments and process control. This equipment either is, or is similar to, conventional process equipment. In RO plants, the main equipment are clarifier, sand filter, cartridge filter, dosing systems, high pressure pumps with energy recovery units and membrane modules. Modules of different makes are available and may be selected by the users on the basis of their requirements. The equipment and components are manufactured as per applicable codes and standards established in the USA, Europe, Japan and other countries equivalently.

The material of construction of the different pieces of equipment of desalination plants should be carefully selected on the basis of their technoeconomic evaluation for ensuring 25 to 30 years plant life. The commonly used materials are Cu–Ni, aluminium brass, titanium alloys, stainless steel, Monel etc.

A number of companies supply desalination plants based on distillation and/or membrane processes. However, significant opportunities do exist for local participation in the manufacture of conventional items, such as shells, heat exchangers, piping and fittings. The manufacturing of RO membranes, high pressure pumps and other special equipment made of high alloys requires substantial know-how and experience.

15.8. INSTALLATION OF EQUIPMENT, COMPONENTS AND SYSTEMS

The magnitude of the effort involved in the installation of equipment, components and systems is similar to that of civil works. The construction of a nuclear reactor may take five to seven years, whereas that of the desalination plant requires only about two to three years for completion. Since the two systems can be closely interfaced, both functionally and physically, the successful installation work mainly depends on the efficient construction management and proper co-ordination. Installation of plant equipment, components and systems also partially overlaps the erection of plant buildings and structures.

The installation schedule should allow sufficient time for the electrical works, instruments and automation and other ancillary components for nuclear reactor as well as desalination plant. It should include installation of the system for transporting water from the desalination plant, which may involve installing an extended pipeline. In addition, QA and QC activities play a strong role in installation and interface with the mechanical, electrical and instrumentation installation work.

National participation is highly desirable during installation. It helps to build a trained workforce to undertake the subsequent responsibilities of operation and maintenance of the nuclear reactor and desalination plant. It affords an excellent opportunity to work with the high quality standards, which are characteristic of nuclear desalination plant installation. The workforce must learn to carry these standards over to the plant operation and maintenance activities, as there can be no compromise in matters of quality for ensuring safe and reliable operation. A thorough knowledge of the level, potential and constraints of the national human resources market is a prerequisite for participation in the installation activities.

15.9. COMMISSIONING

Commissioning of a nuclear desalination plant covers a period starting after the installation work of the nuclear desalination systems and ending with the initiation of plant commercial operation. It involves all activities required to test the operational capacity and to determine the safety, efficiency and reliability of individual systems and components as well as of the overall plant. A successful commissioning plan should encompass the following points:

- Before the start of construction, general provisions should be made regarding the distribution and assignment of responsibilities and setting up the organizational framework to carry out the commissioning task.

- Detailed preparations for commissioning consisting of written procedures and instructions, their review and approval and training of staff are carried out during the installation of equipment, components and systems.
- Cold functional tests are carried out for the nuclear reactor, coupling interface and the desalination plant, respectively, before commissioning. The important functional tests for desalination plant include air tests for leaks, hydrostatic tests, tests of safety valves in steam lines and rupture disks in evaporators, steam turbine tests and tests for electric motors.
- After the plant has been installed and all inspections and functional tests have been completed, an acceptance test sequence is conducted to demonstrate that the plant is capable of achieving the design electrical output and producing the required quality of water. The sequence is carried out in four parts: trial operation, initial operation, reliability test and performance test.

Commissioning must be carried out by well qualified staff. In addition, staff of the equipment and component manufacturers are involved as well as the plant operation and maintenance personnel for whom active participation in this activity is considered an essential part of their training. It is essential that all commissioning activities be documented and evaluated.

After completion of the acceptance test sequence, the plant is handed over to the operation and maintenance personnel.

15.10. OPERATION AND MAINTENANCE

The owner must take full responsibility for the operation and maintenance of a nuclear desalination plant. He is responsible for the management of both nuclear reactor and desalination plant. He cannot share this responsibility with anyone else, though he can and normally does obtain some assistance from the plant designer and constructor, especially in the early stages of plant operation. Also, he will most likely rely, in part, on contractors and subcontractors as well as manufacturers of equipment and components for plant maintenance purposes, in particular during major overhauls and revisions as well as for repair and modifications.

During the project feasibility study phase, only general outlines of plant operations and maintenance activities have to be prepared. Specific detailed preparations for operation and maintenance start with the bid specifications, where input is required from experienced plant operating staff. During bid evaluation and contract negotiation, the involvement of experienced operation staff is very important. This is the stage where all major characteristics and technical aspects of the plant will be defined, including its operability and maintainability features. These features are best assessed at this stage. Otherwise, including them later during design and construction of the plant will increase the risk of additions or modifications, which are always expensive to the owner and usually difficult for the supplier.

Safe and reliable operation of a nuclear desalination plant will be enhanced by having a well designed and constructed plant, and by having a well trained, competent and dedicated operations and maintenance staff. Both conditions have to be fulfilled. Assurance regarding the quality of plant design and construction starts with the preparation of bid specifications and proceeds throughout the evaluation of bids, selection of the supplier(s) and all stages of project implementation, plant erection, equipment and component manufacturing, installation, testing and final plant commissioning.

Desalination plant operation includes the operation of seawater intake system, pre-treatment system, desalination equipment, associated equipment, product water treatment plant and other auxiliaries. A fully equipped chemical control laboratory is also needed for analysis purposes. Maintenance services required for the plant can be classified as (a) routine scheduled maintenance, (b) preventive maintenance based upon experience, and (c) breakdown maintenance. Because of the extent of these activities, plant operation and maintenance may require working in round-the-clock shifts.

To ensure the availability of a well trained, competent and dedicated operations and maintenance staff, timely recruitment and careful selection of personnel is the first condition to be fulfilled. This must be followed by intensive training of these personnel and supervisors. Furthermore, comprehensive operations and maintenance procedures and documents are needed, mostly in the local language, covering all aspects from startup to shutdown.

The owner's project management staff have the lead role in directing and co-ordinating all these tasks during project implementation, until plant operation is started. From this stage on, the plant superintendent and his staff assume full responsibility for operation and maintenance. This transition should occur smoothly and is best achieved by early involvement of the plant superintendent and his top level staff in the project and by effective co-operation between project management and the operations and maintenance organization.

For a country introducing its first nuclear desalination plant, a generous approach towards the number of people to be trained and the length and depth of their training is recommended. The training and retraining of operation and maintenance personnel is a constant activity during the lifetime of a nuclear desalination plant. The owner should make provisions for performing this activity both to fulfil the needs of the first plant and those of the follow-up units of a nuclear desalination programme. The first nuclear desalination plant in a country constitutes possibly its most valuable training ground. Operation and maintenance staff of the desalination plant should have the capability to analyse plant performance and suggest design improvements in order to enhance the process availability.

ABBREVIATIONS

A–E	Architect–engineer
AGR	Advanced gas cooled reactor
ANSI	American National Standards Institute
ASME	American Society of Mechanical Engineers
ASTM	American Society of Testing and Materials
BOO	Build–own–operate
BOT	Build–operate–transfer
Bq/L	Becquerel/litre
BWR	Boiling water reactor
ED	Electrodialysis
EDR	Electrodialysis reversal
FBR	Fast breeder reactor
FSAR	Final safety analysis report
GCR	Gas cooled reactor
GOR	Gain output ratio
HDPE	High density polyethlene
HEU	High enriched uranium
HLW	High level waste
HTGR	High temperature gas cooled reactor
HT-MED	High temperature multieffect distillation
HTTF	Horizontal tube thin film
HWP	Heavy water plant
ILW	Intermediate level waste
JVC	Joint venture company
LEU	Low enriched uranium
LLW	Low level waste
LMFBR	Liquid metal fast breeder reactor
LTE	Low temperature vacuum evaporation
LT-MED	Low temperature multieffect distillation
MD	Membrane distillation
MED	Multieffect distillation
MELT	Multieffect low temperature
MGD	Million gallons per day
MOX	Mixed oxide
MSF	Multistage flash
MVC	Mechanical vapour compression
NDP	Nuclear desalination plant
NHR	Nuclear heating reactor
NPP	Nuclear power plant

NPT	Treaty on the Non-Proliferation of Nuclear Weapons
NU	Natural uranium
NTU	Nephelometric units
O&M	Operation and maintenance
PP	Polypropylene
ppm	Parts per million
PSAR	Preliminary safety analysis report
PVC	Polyvinyl chloride
PWR	Pressurized water reactor
PHWR	Pressurized heavy water reactor
QA	Quality assurance
QC	Quality control
R&D	Research and development
RO	Reverse osmosis
SMART	System integrated modular advanced reactor
SMRs	Small and medium reactor systems
SS	Stainless steel
TCU	Total colour units
TDS	Total dissolved solids
TVC	Thermal vapour compression
USPHS	United States Public Health Service
VC	Vapour compression
VTE	Vertical tube evaporator

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