Nuclear Desalination of Sea Water
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NUCLEAR DESALINATION
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NUCLEAR DESALINATION OF SEA WATER

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ON BEHALF OF THE
GOVERNMENT OF THE REPUBLIC OF KOREA
IN CO-OPERATION WITH THE
GLOBAL TECHNOLOGY DEVELOPMENT CENTER
AND THE
INTERNATIONAL DESALINATION ASSOCIATION
AND HELD IN
TAEJON, 26–30 MAY 1997

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FOREWORD

The water resources in many parts of the world are not sufficient to meet the needs of the population. In many cases, natural fresh water resources are being threatened by pollution and increasing salinity, therefore the demand for clean potable water is growing, particularly in areas of high population growth.

The solution to such pressing water problems may be desalination of sea water, which is one of the most promising alternatives for supplying potable water. The world’s collective desalination capacity has also increased over past decades, a trend that is expected to continue into the next century. Nuclear power plants could play an important role in solving these problems as more countries become interested in using nuclear energy to desalt sea water.

Since 1989, renewed interest in nuclear desalination has been expressed by some Member States. Therefore, the IAEA has undertaken studies to assess the technical and economic potential of using nuclear power plants for sea water desalination, with the relevant expertise and support provided by a growing number of IAEA Member States and international organizations.

In addition to these studies, several national and bilateral projects on nuclear desalination are being carried out or are in the planning stage. These programmes and activities can be considered as a basis for international co-operation and support, and also of benefit to other interested countries.

In recognition of the growing global interest in nuclear desalination, the IAEA organized a Symposium on Desalination of Seawater with Nuclear Energy in Taejon, Republic of Korea, from 26 to 30 May 1997. The Symposium was hosted by the Korea Atomic Energy Research Institute on behalf of the Government of the Republic of Korea, and held in co-operation with the Global Technology Development Center and the International Desalination Association. It provided a forum for the review of the latest technological experience, design and development of nuclear desalination systems, and their future prospects.

About 250 participants from 24 Member States and seven international organizations took part in the Symposium. A wide variety of topics related to nuclear desalination were reviewed and discussed. These covered the activities of some organizations and institutes, the experience gained in existing nuclear desalination plants and their facilities, national and bilateral programmes, including research, design and development, forecasts for the future and the challenges that lie ahead.

It is hoped that the Proceedings will be of value to technical, financial and regulatory decision makers associated with nuclear desalination.

The IAEA wishes to thank the authors and participants for their contributions, the discussion leaders who acted as Chairpersons of the various technical sessions and panels, and the Government of the Republic of Korea for the substantial support provided. These contributed greatly to the smooth running and success of the Symposium.
EDITORIAL NOTE

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Chang Hyo KIM
President,
Korean Nuclear Society,
Seoul, Republic of Korea
OPENING STATEMENTS

Seung Yun Kim
President,
Korea Atomic Energy Research Institute,
Taejon, Republic of Korea

I would like to extend my warmest welcome to all participants, not only those from home but also those from abroad, to the IAEA Symposium on Desalination of Seawater with Nuclear Energy.

I am particularly pleased to note that a new era in the peaceful uses of nuclear energy is being opened at this Symposium, with representatives of more than 20 countries worldwide. In the hope that industrial application of nuclear energy for sea water desalination is at hand, some 50 papers and R&D results will be presented, covering every facet of nuclear desalination.

As you well know, as a result of the active promotion of the peaceful uses of nuclear energy, with the IAEA playing a major role, nuclear energy has contributed to the public welfare in various areas such as medicine, agriculture and industry, in addition to power generation.

In the Republic of Korea, nuclear energy supplies about 40% of the electricity demands. In the medical field, new radioisotopes for the diagnosis and treatment of diseases, including cancer, are being developed. Peaceful applications of nuclear energy are becoming common in everyday life. Their benefits in the future can significantly alter the direction of all our lives.

Many countries have shown great interest in active R&D on the use of nuclear generated heat for sea water desalination. It is significant that the main focus has shifted from the generation of power and the application of radioisotopes to areas such as the overcoming of limited supplies of fossil fuels and the securing of stable and good quality water resources worldwide.

I am confident that this Symposium will provide an important opportunity for further promotion of the desalination of sea water using nuclear energy.

Over the past years, the Republic of Korea has shown great interest in this field. It has introduced a plan for the development of small and medium sized reactors for sea water desalination with extensive support from the government as well as active participation by academic and industrial organizations.

With the development of 300 MW(th) reactors by the 21st century, nuclear desalination projects should be implemented through co-operation with organizations in the Republic of Korea, as well as many international organizations and countries throughout the world.
Through an active exchange of information and technical co-operation, we can further develop our resources and ideas in these areas.

As a result of the efforts made to localize nuclear power related technologies at the Korea Atomic Energy Research Institute, we have become self-reliant in the design of power reactor systems and nuclear fuels. Having achieved these technologies, the institute has now reached a turning point. Focus should be given to new and innovative areas such as the development of advanced reactors and sea water desalination reactors, while placing emphasis on the promotion of these technologies. Taking these points into consideration, I am sure that the nuclear desalination project will become one of our strategic nuclear research programmes, so mapping out our future direction.

Therefore, the opening of this Symposium is a significant milestone for the people of the Republic of Korea, and for all the participants here, in that it provides a forum for future actions concerning improved nuclear desalination technologies. It is my desire that the active discussions held during this Symposium will be of great benefit to all the participants, and a meaningful occasion for the nuclear community as well as for the future of the human race.
OPENING STATEMENT

Hans Blix
Director General,
International Atomic Energy Agency,
Vienna

1. INTRODUCTION

It is a great pleasure for me to welcome you to this IAEA Symposium on Desalination of Seawater with Nuclear Energy.

I should like, at the outset, to express appreciation to two international organizations that have helped significantly to bring about this Symposium: the International Desalination Association and the Global Technology Development Center. I should also like to thank the Government of the Republic of Korea and the Korea Atomic Energy Research Institute warmly for their substantial support.

Let me also state my personal conviction that nuclear energy will come to be increasingly used in the future to desalinate water for drinking.

Water is essential to life and to civilization. Four great civilizations in the history of the human species arose along rivers: the Nile in Egypt, the Tigris and the Euphrates in Mesopotamia, the Indus in India and the Yellow River in China. Fresh water is a precondition for human life and industrial development. However, economic development and population growth is today jeopardizing the adequacy of potable water resources in many regions of the world. Increased pollution and salinity of the natural fresh water resources are worsening the situation.

How can we tackle this grave and growing problem? Slowing the growth of the world’s population is one necessity. Let me give you some staggering figures to illustrate where our successful species has been moving, with dizzying speed. It has been calculated that at the time of Christ the population of the earth was about $350 \times 10^6$; in 1900 it was $1.5 \times 10^9$; in 1990 it was about $5 \times 10^9$; and in the year 2000 it is expected to be about $6 \times 10^9$. Thus, in the last 10 years of this century the world’s population will increase by almost as much as it did in the first 1900 years from the birth of Christ. Such proliferation is not sustainable, and needs to be drastically slowed. Although recent trends give some ground for optimism, the process will take time. Meanwhile, we must seek to make better use of existing resources and to expand resources, notably fresh water, food and energy. With regard to all three, nuclear techniques, although not liked by all, can be of great help.

Desalination is one of the most promising options for supplying potable water. The cumulative worldwide desalination capacity has increased steadily in the past decades, and this trend is expected to continue into the next century. According to the World Meteorological Organization, water consumption increased sixfold between
1900 and 1995, twice the rate of population growth. To meet this increasing demand for fresh water, the installation of sea water desalination facilities has increased dramatically since the early 1960s. The cumulative capacity, installed and contracted, had reached more than $20 \times 10^6$ m$^3$/d by 1995.

The relevant reasons that have led in past decades to the deployment of nuclear power for electricity generation included economic competitiveness, diversification of the energy supply, promotion of technological development and protection of the environment. Some of these reasons could also favour the choice of nuclear energy for sea water desalination.

Within the IAEA, the feasibility of using nuclear energy for sea water desalination was surveyed as early as in the 1960s and 1970s. However, interest was then focused on electricity generation and district heating. In 1989, renewed interest in nuclear desalination was expressed by several Member States in an IAEA General Conference Resolution (GC(XXXIII)/RES/515). As a result, the Agency resumed its study in 1989, and the technical and economic potential of nuclear reactors for sea water desalination have been assessed in the light of the experience gained in recent years.

Use of nuclear generated heat for distillation processes is similar to that of nuclear heat for district heating and industrial processes. 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 worldwide for over 20 years, without any serious problems arising. Nuclear co-generation plants have been built and operated in Bulgaria, Canada, Germany, Hungary, India, Japan, Kazakhstan, the Russian Federation, Slovakia, Switzerland and the United States of America. Almost 500 reactor-years of quite satisfactory and encouraging operational experience have been accumulated. The plants have operated safely and reliably. The design precautions to prevent the transfer of radioactivity into the district heating grid network, the industrial products or the desalted water have proved to be effective and reliable. Greater use of nuclear power for district heating in cold climates and for producing industrial heat could help restrain the CO$_2$ emissions that would result from alternative use of fossil fuels for these purposes.

2. EXPERIENCE WITH NUCLEAR DESALINATION

Desalination facilities connected to nuclear power plants in Japan and Kazakhstan have been producing desalted water for many years, so a good deal of experience has been accumulated. Several Member States have begun to show interest in this option, and ongoing or planned national and bilateral projects will contribute
to further experience in nuclear desalination. Such projects would be useful for possible broader commercial deployment, which could contribute towards solving the drinking water supply problems in the next century. These projects include activities in China, India, the Republic of Korea, Morocco and the Russian Federation. Together with studies and R&D work in some other interested Member States, these projects contribute to a demonstration programme that could form the basis for international co-operation and support. It will be important to utilize the experience gained from these programmes, and to avoid duplicating activities.

In the course of the studies that have been undertaken to date it has been found that sea water desalination using nuclear energy could be a realistic option for many Member States. Thus, the expanding demand for sea water desalination installations presents a potential market for the introduction and commercial deployment of nuclear desalination. This constitutes the challenging background of our Symposium.

3. CURRENT STATUS AND POTENTIAL USE OF NUCLEAR POWER

So far, nuclear energy has been exploited chiefly for electricity generation. Desalination of water is only one of several other uses that could be made of this source of energy. Let me share some thoughts with you on this subject.

To be attractive as a source of energy, nuclear must be economically competitive with other options and acceptable to the public.

It is clear that nuclear power is now a mature technology — a generally viable option for electricity generation. Since developing countries are often capital starved and nuclear power calls for high up front investments, and since many of these countries also cannot provide the necessary industrial or technical infrastructure, nuclear power is concentrated in industrialized countries, which account for more than 90% of the total operating nuclear capacity.

Currently, nuclear power economics are favourable when compared with alternative sources in a number of locations, but not everywhere. The achievement of high availability and load factors is important, and large efforts, especially in the sphere of management and safety, are dedicated to this end. Many operators have achieved consistently high availability, others have improved the availability spectacularly in relatively short periods of time. The worldwide average availability of nuclear power plants shows a steadily improving trend.

In the Republic of Korea, the average availability factor in 1996 exceeded 87%, with nuclear electricity generating costs being cheaper than the other sources of generation used in the country’s electricity system. I note also that in the Republic of Korea the application of nuclear energy for sea water desalination is being investigated, and that the domestic design of an advanced reactor is planned to be completed by the end of the century.
Indeed, one cannot avoid being impressed by the rapid deployment of nuclear power in China, Japan and the Republic of Korea, especially when it is compared with the stagnation that we witness in western industrialized states. What makes the difference? Part of the reason for the difference no doubt lies in the fact that there is a rapidly growing demand for electricity in the economically fast developing East Asian countries, while western industrialized countries, for various reasons, have experienced a stagnating demand. Also, the relatively easy availability of inexpensive natural gas has made nuclear generated electricity less competitive than that produced in combined cycle gas plants in many western industrialized states. This certainly raises a challenge for the nuclear industry to improve the economy of nuclear power.

There is little doubt that, especially for Japan and the Republic of Korea, both of which have huge energy dependent industries and poor domestic energy resources, nuclear power offers an important measure of self-reliance. Nuclear fuel can be stocked for long periods of operation, thus operators can immunize themselves against the delivery interruptions that have sometimes afflicted fossil fuels.

If cost and energy independence are factors that can be relatively easily examined, it is more difficult to assess the factor of public acceptance in different countries. What one can clearly see in many western industrialized countries is that the opposition is sufficiently strong for governments to be, perhaps not convinced, but influenced by it. Whatever the weight of a similar opinion in East Asia, the imperatives of providing vast new reliable energy sources for people and industry have led the Governments of China, Japan and the Republic of Korea to continue pursuing their ambitious nuclear power programmes. It may well be that their successful examples will, one day, trigger a nuclear revival in the West.

Some of the factors that influence the public’s attitude to nuclear energy are not easily defined and assessed. Despite all the research done and the knowledge gained on radiation, it is clearly a phenomenon with which the public has not yet come to terms. Perhaps we have to await another generation that has learned more about it at school?

The linkage, in the minds of some, between nuclear power and nuclear weapons is another possibly relevant factor. Yet, in Japan, where the linkage should be strongest, it has not stood in the way of highly successful, large nuclear power development. Whatever the relevance of this factor, it should be diminishing in importance as global nuclear disarmament and regional nuclear weapon free zones reduce the relevance of nuclear weapons. The belligerent atom is put back in the bottle. The peaceful atom dominates the scene.

In my view, the environmental consequences of different energy sources will come to play, and in fact already do play, an increasing role in the public’s acceptance of any source, and I am profoundly convinced that this factor will speak firmly for future expanded use of nuclear power in those countries that have sufficient technological capacity.
The intensifying discussion on the risk of global warming strongly suggests that the present global level of use of coal, oil and gas is not sustainable. Two large international conferences will face the issue this year: a special session of the General Assembly of the United Nations on Sustainable Development to be held at the end of June in New York, and the Third Session of the Parties to the Convention on Climate Change, which will meet in Kyoto towards the end of this year.

There will certainly be no grand plan, no grand consensus, not even a joint blueprint on global energy policies. Governments, just as people, do not easily agree in this field and often have widely differing interests to protect. However, on one starting point there is growing consensus, namely, that globally we must restrain the emissions of CO\textsubscript{2} linked to the burning of all fossil fuels. Furthermore, there is no viable technical method in sight that could segregate and neutralize these emissions. They must be restricted, by more efficient burning and by less burning.

Opponents of nuclear power try to tell us that solar and wind power and biomass could give us effective alternatives to both fossil fuels and nuclear power. While these sources are welcome, have their niches and should be further developed, it is not credible to suggest that they could provide the world with the large amounts of base load power that will be needed for growing populations and industrial and social development. Let me develop this thought. Are ardent advocates of renewable sources suggesting that China, to take an important example, use some 3000–5000 km\textsuperscript{2} to grow the biomass that would be needed to generate 1000 MW rather than build a 1000 MW nuclear plant? Or cover 50–60 km\textsuperscript{2} to install the solar cells or windmills that would be needed? Are these advocates blind to the reality that the alternative to the nuclear power plant is mainly the burning of coal?

In my view, the well meaning but somewhat dreamy advocacy of solar and wind power and biomass combined with a rejection of nuclear power contribute to a continued undesirable expanded use of fossil fuels, an expansion that could be avoided or at least significantly restrained by increased use of nuclear power. Let me illustrate: if today’s some 442 nuclear power plants were closed, and the base load electricity that they now generate without CO\textsubscript{2} emission were generated by coal fired plants, some 2600 million tonnes of CO\textsubscript{2} would be added to the world’s atmosphere, i.e. 9% of all the CO\textsubscript{2} emissions from fossil fuels worldwide.

As the public’s concern about global warming grows, as I think it should do, the urge to find realistic substitutes for some of the fossil fuels used for energy generation will increase. It is my firm conviction that nuclear energy is the strongest candidate. The resource base in uranium and thorium is vast and, if one day breeders were extensively used, could be almost limitless. The safety record of nuclear power is excellent when compared with other energy sources, even if Chernobyl is included. However, the public demands higher safety in nuclear power than in other energy production. This can and must be supplied. The IAEA Convention on Nuclear Safety has entered into force, so we now have basic safety rules that will come to bind all
Member States — and procedures for peer review. A global nuclear safety culture is developing. A similar situation exists regarding the disposal of nuclear wastes from the civilian sector. A new IAEA convention laying down basic rules that bind all the parties in this field — and laying down rules for peer review — is expected to be ready shortly. The problem with nuclear waste disposal is not so much adequate technology, which does exist, as psychology. We must bring home to the public the understanding that there are not only ‘alternative energies’ but also ‘alternative wastes’. High level nuclear waste will be put in its entirety deep into the crust of the earth from where the uranium once came. The alternative waste of fossil fuels is emitted into the world’s atmosphere, producing acid rain, dying lakes and forests and, possibly, global warming and climate change.

Let me conclude by expressing the hope that this Symposium will show that nuclear energy can play a very important role in producing drinking water through desalination.

I wish you a successful Symposium.
It is a great pleasure and privilege for me to be here today on the opening day of the Symposium on Desalination of Seawater with Nuclear Energy, which is being jointly hosted by the IAEA and the Korea Atomic Energy Research Institute (KAERI).

As you know, this year the IAEA celebrates the 40th anniversary of its founding as an institution devoted to promoting the use of nuclear energy for peaceful purposes throughout the world. In the Republic of Korea, it is 30 years since the establishment of the Ministry of Science and Technology, which is in overall charge of the use of nuclear energy.

Thus, I believe that the co-hosting of this symposium by the IAEA and KAERI is very significant in that it symbolizes not only the existence of strong and growing ties between the two organizations but also their joint determination to work closely with each other to promote international co-operation and the exchange of information, for example, through our forum today, the purpose of which is to present initiatives on nuclear desalination that will open a new chapter in the peaceful uses of nuclear energy for the future.

Use of nuclear energy for sea water desalination has recently been in the limelight as a sure solution to the acute problem of potable water shortages in many parts of the world.

Worldwide, the amount of water consumed substantially exceeds the amount of accessible potable water. Desalination of sea water is a must for arid and semi-arid regions, as well as islands and islets, that suffer from a deficit in potable water.

Because there is growing concern about global pollution of the environment from the burning of fossil fuels, the IAEA and several Member States have shown great interest in active R&D on the use of nuclear reactor generated heat for sea water desalination.

I am confident that this Symposium will provide an important opportunity for the exchange of information on this form of desalination of sea water. In addition, knowledge can be shared on current potable water demands worldwide, on the R&D work being carried out on desalination, and on the activities of international organizations in this field.

Since the late 1950s, the nuclear power programme of the Republic of Korea has been recognized as an exemplary success. Currently, nuclear energy supplies about 40% of the country's electricity needs.

One thing is certain: the demand for electricity will continue to grow. This is driven by continuous economic growth and improved standards of living in the
Republic of Korea. It is estimated that the electricity demand will double by the year 2010. This means that the country will need more nuclear power plants to meet these growing needs.

To achieve this, we launched an ambitious project and succeeded in developing the Korean Standard Nuclear Power Plant (KSNPP) with improved safety and efficiency features. On the basis of the experience and technical expertise gained from this programme, we are now following an active R&D path towards developing technologies for next generation reactors.

Small and medium sized reactors, which are suitable for most of the nuclear desalination applications, are also being developed for co-generation and desalination. From this point of view, the impressive accomplishments achieved by the Republic of Korea in developing its nuclear technology make it most fitting that this Symposium is being held in our country.

It is my sincere desire that this Symposium will contribute greatly towards the full industrial application of the nuclear desalination option in the future as well as the expansion of peaceful uses of nuclear energy in the world through the exchange of new ideas and technologies.

I would like to express my sincere gratitude to all the participants, especially the authors of papers, for their support and invaluable contribution.

In addition, I would like to express my deep appreciation to the staff of the IAEA and KAERI, who have made such a special effort to organize this Symposium.

Matching the name ‘Queen of the Seasons’, May is the best time of year in our country, with grass and trees that are bright green. I hope that all our guests from abroad will enjoy the scenic beauty and rich cultural heritage of the Republic of Korea, and will have a memorable and fruitful time during their stay in Taejon.
OVERVIEWS
(Session 1)

Chairpersons

Seung Koo LEE
Republic of Korea

Poong Eil JUHN
IAEA
WATER DEMAND AND SUPPLY

R. HELMER
World Health Organization,
Geneva

Abstract

WATER DEMAND AND SUPPLY.

Major international conferences have dealt with the growing concern over the ever increasing use of limited fresh water resources on the planet, including the United Nations Water Conference held in Mar del Plata (1977), the Dublin Conference (1992) and the UN Conference on Environment and Development held in Rio de Janeiro (1992). In April 1997, the UN Commission on Sustainable Development was presented with a report on a Comprehensive Assessment of the Freshwater Resources of the World, in which all UN agencies concerned with water participated. Matching the ever growing demands with the limited supply of a finite resource has led to tremendous stress on natural fresh water. This starts with low water stress, when about 10% of the available fresh water is being used. Use of more than 40% of the available water indicates serious scarcity, and usually increasing dependence on desalination and overexploitation of aquifers. On the basis of population increase projections for the year 2025, and extrapolating current trends, as much as two-thirds of the world’s population may be living in moderate or high water stress situations. With increasing water stress and scarcity, drastic changes in the way water business is being done will have to be introduced, particularly in low income countries. Agricultural practices, in particular, have to be introduced that reduce losses. Improved strategies have to make use of rigorously enforced demand management, better resource management, waste water reuse to the extent possible, and finally desalination of sea water and brackish groundwaters. Some of the current water intensive patterns of development may even have to be abandoned.

1. INTRODUCTION

The Mar del Plata Action Plan, adopted by the United Nations Water Conference in 1977, already stipulated that “all peoples, whatever their stage of development and their social and economic conditions, have the right to have access to drinking water in quantities and of a quality equal to their basic needs” [1]. Consequently, the water resources management sector is called upon to balance the often pressing demands of competing water users. The needs of municipalities, industry and agriculture have to be reconciled, and a steady flow of supply generated to consumers in urban agglomerations and rural settlements. Similarly, water and sewage utilities have to harmonize drinking water supplies and quality requirements with the orderly evacuation of sewage and trade effluents without jeopardizing the
environment. Also, consumers demand reliable services and low tariffs, and ultimately it is society as a whole that carries the responsibility, most pronounced in developing countries, of managing water supplies in conformity with the notion of water as an economic and social good.

These demands were taken up by the Global Consultation on Safe Water and Sanitation for the 1990s held in New Delhi, India, in 1990, the International Conference on Water and the Environment: Development Issues for the 21st Century held in Dublin, Ireland, and the UN Conference on Environment and Development held in Rio de Janeiro, Brazil, both in 1992. Since then, the Interministerial Conference on Drinking-Water Supply and Environmental Sanitation held in Noordwijk, Netherlands, in 1994, reinforced these concerns. Most recently, the Committee on Natural Resources of the Economic and Social Council "noted with alarm that some 80 countries, comprising 40% of the world's population, are already suffering from serious water shortages and that, in many cases, the scarcity of water resources has become the limiting factor to economic and social development". It further noted that "ever-increasing water pollution has become a major problem throughout the world, including coastal zones". The UN Commission on Sustainable Development, at its second session in 1994, noted that in many countries a rapid deterioration in water quality, serious water shortages and reduced availability of fresh water were severely affecting human health, ecosystems and economic development.

Most recently, in April 1997, the UN Commission on Sustainable Development was presented with a report on a Comprehensive Assessment of the Freshwater Resources of the World, in which all UN agencies concerned with water participated [2]. The key conclusions of this report have been taken into consideration in this paper.

2. GLOBAL WATER AVAILABILITY

Although about 70% of the planet is covered with water, the reality is that 97.5% of all water on earth is salt water, leaving only 2.5% as fresh water. Nearly 70% of this fresh water is frozen in the icecaps of Antarctica and Greenland, and most of the remainder is present as soil moisture, or lies in deep underground aquifers as groundwater not accessible to human use. As a result, less than 1% of the world's fresh water, or about 0.007% of all the water on earth, is readily accessible for direct human use [2]. This is the water found in lakes, rivers, reservoirs and those underground sources that are shallow enough to be tapped at an affordable cost. Only this amount is regularly renewed by rain and snowfall, and is therefore available on a sustainable basis.
It has been estimated that the amount of the fresh water readily accessible for human use is about 9000 km$^3$/a. Another 3500 km$^3$ is captured and stored by dams and reservoirs. Utilizing the remaining water resources for human needs becomes increasingly costly, because of topography, distance and environmental impacts. Currently, about half the 12 500 km$^3$ of water that is readily available is actually being used. Given an expected population increase of about 50% in the next 50 years, coupled with the expected increases in demand as a result of economic growth and life style changes, this does not leave enough for increased consumption. Also, water has to remain in rivers to maintain healthy ecosystems, including fisheries. Recreation, navigation and hydropower generation all require the preservation of an adequate amount of water. When the global water picture is examined at the country level, some countries still enjoy large amounts of water per capita, while others are already facing serious difficulties. Future increases in demand due to population growth and increased economic activities will inevitably impinge further on the limited available water resources.

As a result of the globally uneven availability of fresh water, water scarcity has become a reality in many countries in the arid and semi-arid parts of the world, and variability from season to season makes much of the water supply unavailable when it is most needed. This particularly affects the demands for irrigation water, which account for the bulk of the water consumed globally. On the basis of global runoff, the theoretical average per capita water availability is estimated at 7600 m$^3$ per person per year; this may seem like an adequate amount, but it was estimated at double this amount 30 years ago. In reality, for people in many parts of the world the actual amount available is much less. Water withdrawal at the global level was estimated at 3800 km$^3$ in 1995 which, together with instream requirements, amounts to 54% of the global runoff that is geographically and temporally accessible [2]. Scarcity may result from natural variation in runoff or storage, or the inability to deliver the water to where it is needed, or be due to increasing demands that can simply not be supported in a sustainable manner from existing resources. Not only is demand increasing but pollution is reducing the useability for high quality purposes such as domestic water supplies.

3. SECTORAL WATER DEMANDS

The major forms of water withdrawal and consumption are for agriculture, industry and domestic use, as shown in Table I [2]. Most of the water withdrawn by industries and municipalities is used and then returned to lakes and rivers or other water courses, often degraded in quality. Water withdrawn for irrigation purposes is partly consumed in the process of crop production, and partly required to flush salts
### TABLE I. WATER WITHDRAWAL AND CONSUMPTION BY SECTOR

<table>
<thead>
<tr>
<th>Sector</th>
<th>Water withdrawal (%)</th>
<th>Water consumption (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agriculture</td>
<td>70.1</td>
<td>93.5</td>
</tr>
<tr>
<td>Industry</td>
<td>20.0</td>
<td>3.8</td>
</tr>
<tr>
<td>Municipalities</td>
<td>9.9</td>
<td>2.7</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>100</td>
<td>100</td>
</tr>
</tbody>
</table>

Source: Ref. [2].

out of the soil. However, most irrigation is inefficient, and only about 60% of the withdrawn water returns to river basins and groundwater.

As a result, global withdrawals of water to satisfy demands have grown dramatically in this century. Between 1900 and 1995, water withdrawals increased over sixfold, which is more than double the rate of population growth. This rapid growth in water demand is due to the increasing reliance on irrigation to achieve food security, the growth of industrial uses and the increasing use per capita for domestic purposes.

On a global average, irrigated agriculture takes about 70% of the water withdrawals; this figure rises to 90% in the dry tropics. Agriculture is by far the largest consumptive use of water, representing 87% of the total. Traditionally, most food is grown on rain fed lands, relying on soil moisture supplied by rainfall; however, as the food demand rises, this is increasingly supplemented by irrigation, using water drawn from lakes, rivers and underground aquifers. Irrigated agriculture contributes nearly 40% of the world's food production from just 17% of the cultivated land. Much of the dramatic increase in food production of recent decades, including the Green Revolution, requires high yield plant varieties, combined with fertilizers and pest control, and depends on irrigation to ensure adequate and timely water for high growth. Water withdrawals for irrigation have increased by over 60% since 1960 [2].

Water for thirsty cities was one of the central themes at the June 1996 UN Conference on Human Settlements – HABITAT II. For many cities of the developing world, the top environmental priority is improving access to clean water and sanitation as the single most effective means of alleviating human distress. When services were introduced to cities in Europe in the 19th and 20th centuries, health improved dramatically and life expectancy increased rapidly [3].

Growth of megacities will become the biggest threat to health in the 21st century, with an estimated 61% of the world's population living in urban areas by the year 2025. UN statistics show that between 1950 and 1995 the number of cities in the
industrialized world with a population above 1 million more than doubled, while their number in developing countries increased sixfold, from 34 to 213. Statistics for urban areas show that in 1994 already 83.6% of the urban population in developing countries had access to safe water supplies, whereas sanitation services were provided to only 68.5%, demonstrating how sanitation has lagged behind and how piped water to the house has been a more attractive option than a sewerage line carrying the wastes away. One of the major challenges for the engineer today is the leakage of water supply pipes because of their age. There are striking examples of unaccounted for waters reaching up to 60% of the quantities that are distributed by waterworks [4].

The challenge for the city water utility is to provide the services that people want and are willing to pay for. It is unrealistic to think that developing countries could afford to provide all urban dwellers with in-house piped water supply connections. The policy has usually been to concentrate on house connections for the affluent areas, and standpipes or hand pumps for the peri-urban sector. In contrast, consumers in most industrialized countries pay all the recurrent costs for operation and maintenance, and most of the capital costs. In developing countries, consumers pay far less, only about 35% of the average cost of supplying water [3]. There is ample evidence, however, that most urban people want on-plot water supplies of reasonable reliability, and that they are willing to pay the full cost for these services. Innovative financing or self-help schemes are needed to meet these demands.

A desirable, and with some effort also realistic, goal should be that all urban dwellers have access to at least a certain basic minimum amount of safe household water. Some experts consider 50 L per capita per day as a fair enough long term goal for the people living in peri-urban areas. This should allow for an acceptable quality of life and human dignity. In some parts of the world, already 20 L per capita per day of clean water could mean a substantial improvement, while elsewhere 200 L per capita per day may be deemed sufficient. The UN Conference on Environment and Development held in Rio de Janeiro, June 1992, set as one of the targets, “by the year 2000, to have ensured that all urban residents have access to at least 40 litres per capita per day of safe water...” [5]. This already poses a formidable challenge to the city water utilities in developing countries.

Industrial water use is the one sector where demand has been managed most rationally. Water saving measures have been introduced and the rate of internal recycling shows an upward trend, as given in Table II [6]. Thus, the amount of water required per unit of product has decreased dramatically in recent years.

Water demands are not only for certain volumes of water but also for a specified minimum quality, depending on the type of intended water use. Naturally, drinking water has one of the most stringent requirements, whereas irrigation water only has to meet salinity levels that are dependent on the type of plants grown. Water pollution, however, has made water resources unsuitable for most uses in many parts of the world, affecting rivers, lakes and groundwaters alike. Great efforts have been made in
TABLE II. WATER RECYCLING RATES IN MANUFACTURING INDUSTRIES IN THE UNITED STATES OF AMERICA (NUMBER OF TIMES EACH CUBIC METRE IS USED)

<table>
<thead>
<tr>
<th>Industry</th>
<th>1968</th>
<th>1985</th>
<th>2000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paper and allied products</td>
<td>2.9</td>
<td>6.6</td>
<td>11.8</td>
</tr>
<tr>
<td>Chemicals and allied products</td>
<td>2.1</td>
<td>13.2</td>
<td>28.0</td>
</tr>
<tr>
<td>Petroleum and coal products</td>
<td>5.1</td>
<td>18.3</td>
<td>32.7</td>
</tr>
<tr>
<td>Primary metal industries</td>
<td>1.6</td>
<td>6.0</td>
<td>12.3</td>
</tr>
<tr>
<td>All manufacturing</td>
<td>2.3</td>
<td>8.6</td>
<td>17.1</td>
</tr>
</tbody>
</table>

Source: Ref. [6].

Europe and North America to curb pollution and to restore water quality and aquatic ecosystems. In the developing world, unfortunately, it is estimated that up to 90% of all waste waters are discharged to water courses without receiving any treatment. The consequence is a reduction in availability of the affected fresh water resources, particularly for drinking water supplies.

4. WATER SUPPLIES AND SANITATION

Access to safe drinking water and adequate sanitation is a recognized universal human need. However, in 1994 approximately $1.11 \times 10^9$ people in developing countries lacked access to safe water supplies and $2.87 \times 10^9$ lacked access to adequate sanitation. On a global basis, i.e. including developed countries and countries in economic transition, 20% of the world's population lacked safe water supplies and 50% had no adequate sanitation. Projections for the year 2000 show a reduction in those people without safe water supplies to $0.75 \times 10^9$, but an increase in those deprived of adequate sanitation to $3.31 \times 10^9$ [7]. Thus, the progress achieved during the International Drinking-Water Supply and Sanitation Decade Supply, 1981–1990, will be largely dispelled by the year 2000, as shown in Tables III and IV [7].

Human health is closely linked to a safe and adequate water supply. The World Health Organization (WHO) has calculated that about 5 million people die each year as a result of unsafe water supplies and bad hygienic conditions. Chemical contaminants in drinking water, e.g. pesticides and heavy metals, add to the health burden of water pollution [3]. In support of efforts to provide safe drinking water, WHO has issued Guidelines for Drinking-Water Quality that specify guideline values for health significant water constituents and microbiological agents [8].
TABLE III. WATER SUPPLY COVERAGE PERSPECTIVES IN DEVELOPING COUNTRIES

<table>
<thead>
<tr>
<th>Population (× 10^9)</th>
<th>1990</th>
<th>1994</th>
<th>2000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Population served</td>
<td>2.49</td>
<td>3.27</td>
<td>4.13</td>
</tr>
<tr>
<td>Population unserved</td>
<td>1.58</td>
<td>1.11</td>
<td>0.75</td>
</tr>
<tr>
<td>Total</td>
<td>4.07</td>
<td>4.38</td>
<td>4.88</td>
</tr>
</tbody>
</table>

Source: Ref. [7].

TABLE IV. SANITATION COVERAGE PERSPECTIVES IN DEVELOPING COUNTRIES

<table>
<thead>
<tr>
<th>Population (× 10^9)</th>
<th>1990</th>
<th>1994</th>
<th>2000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Population served</td>
<td>1.47</td>
<td>1.51</td>
<td>1.57</td>
</tr>
<tr>
<td>Population unserved</td>
<td>2.60</td>
<td>2.87</td>
<td>3.31</td>
</tr>
<tr>
<td>Total</td>
<td>4.07</td>
<td>4.38</td>
<td>4.88</td>
</tr>
</tbody>
</table>

Source: Ref. [7].

5. WATER SCARCITY

Matching the ever growing demands with the limited supply of a finite resource has led to tremendous stress on natural fresh waters. In many countries or regions, this has created a shortage of water, relative to demand, and finally reached continuous crisis proportions in semi-arid and arid regions. Water scarcity occurs when the amount of water withdrawn from lakes, rivers or groundwater is so great that the water supplies are no longer adequate to satisfy all human or ecosystem requirements, bringing about increased competition among potential demands. Scarcities are likely to occur sooner in regions where the per capita availability of water is low to start with and where population growth is high. This becomes more serious if the per capita demand is growing because of changes in the consumption patterns.
In preparing the comprehensive assessment report for the UN Commission on Sustainable Development, four different categories of increasing water stress were defined [2]:

1. **Low water stress**: Countries that use less than 10% of their available fresh water generally do not experience major stresses on the available resources.

2. **Moderate water stress**: Use in the range of 10–20% of the available water generally indicates that availability is becoming a limiting factor, and that significant effort and investments are needed to increase the supply and to reduce the demand.

3. **Medium-high water stress**: When water withdrawals are in the range of 20–40% of the available water, management of both the 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 that they have adequate water flows. Developing countries, in particular, will need to make major investments to improve water use efficiency; the portion of Gross National Product allocated to water resources management can become substantial.

4. **High water stress**: Use of more than 40% of the available water indicates serious scarcity, and usually an increasing dependence on desalination as well as use of groundwater at a rate that is faster than it is replenished. This means that there is an urgent need for intensive management of the supply and demand. Current use patterns and withdrawals may not be sustainable, and water scarcity could become the limiting factor to economic growth.

Another key element in water resources management is the coping capability, based on income levels, of countries that face water scarcity and/or water pollution. The ability of countries to cope with water scarcities, including the effects of pollution, depends on a number of factors. Income levels may serve as a rough measure of the ability of different categories of country to deal with water issues. In general, countries with higher per capita incomes are in a better position than low income countries to respond to water scarcity, since the financial resources and the skilled people needed for management and development are more readily available. Because of the low income levels, many developing countries face severe difficulties in creating the necessary institutional mechanisms to install effective national water resources management.

Statistics show that more than half the world’s population falls into the low income category, i.e. with a per capita income of less than US $800 per annum. More than one-third of this population group also falls into the medium–high or high water stress category, i.e. about 950 and 240 million people, respectively. In their situation,
water shortages could become a severe hindrance to socioeconomic development, including irrigation agriculture and industrial production.

At the other end of the spectrum, high income countries (a per capita income of over US $9000) with high water stress are often countries that have fairly large amounts of water, but are approaching stress conditions as a result of continuing overuse and pollution of their water resources, causing problems such as groundwater depletion. Other countries have, however, already used most of their accessible water resources. They have little, if any, scope for increasing the amount of water supplied to demanding users through conventional means without inflicting damage on aquatic ecosystems, or seriously depleting groundwater aquifers. Desalination of sea water would be a valid option in this situation.

6. FUTURE PROSPECTS

There are several key factors that will influence the availability of fresh water for the vital socioeconomic sectors. The increase in the world's population will be the most fundamental factor, since it determines the need for water for a wide array of activities, including food production, industrial development and, above all, drinking water supplies and other domestic uses. Current projections predict an increase from $5.7 \times 10^9$ in 1995 to about $8.3 \times 10^9$ in the year 2025, with most of the increase occurring in the rapidly expanding urban agglomerations in developing countries. Already today, many of these countries experience water shortages, intermittent supply services and considerable stress on their water resources.

Industrial water use is expected to more than double by the year 2025, accompanied by a quadrupling of industrial pollution discharges. Introduction of more water efficient and cleaner production technologies could, however, contain industrial water demands and curb the pollution of water courses. Similarly, modern irrigation techniques could reduce the need for irrigation water without jeopardizing food security. Owing to demographic developments, however, it is unavoidable that all the socioeconomic sectors will make increased demands on the limited water resources. If current demand patterns are extrapolated into the future, it is estimated that two-thirds of the world's population will have to live in moderate or high water stress situations by the year 2025. An enhanced supply of fresh water will not be able to cope with such demands, and modifications in consumption patterns will become unavoidable.

Water resources management will have to be based on more rational policy and strategies, including trade-offs between water quantity and quality when considering demands for different socioeconomic activities. Reuse of water and reclamation of waste water will be important tools for stretching the supply of water, particularly where marginal quality waters are adequate. The supply of high quality water, e.g. for
drinking water or specific industrial manufacturing, could be extended with the desalination of sea water or brackish groundwaters. Beyond these measures to boost supplies, however, only rigorous demand management could avert a looming water crisis.

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STATUS OF SEA WATER DESALINATION TECHNOLOGIES

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Abstract

STATUS OF SEA WATER DESALINATION TECHNOLOGIES.

Sea water desalination is now a technically and economically feasible option to help solve the life threatening problem of fresh water shortages. According to the International Desalination Association 1996 Worldwide Inventory Report, at the end of 1995 a worldwide total of 11 066 desalting units, with a total capacity of 20 300 000 m³/d, had been installed or contracted in 120 countries. The capacity has grown exponentially over the past 10 years. A technical overview is given of various desalination processes currently in use, and their future prospective: multi-stage flash (MSF), multi-effect distillation (MED), vapour compression (VC) and reverse osmosis (RO). For plants rated at more than 4000 m³/d per unit, MSF is still more prevalent than any other process. However, the RO process is increasing its share. The future of desalination technology will depend on reducing the energy costs and further improvements in the technology, the unit size of the membrane and the distillation processes. In many cases, hybrid systems that combine the best features of distillation and RO may be developed and utilized. Hybrid, large scale MED plants may be adopted, and there is likely to be increased use of large scale VC. There will also be significant advances in RO technology.

1. INTRODUCTION

It is now technically and economically feasible to generate large volumes of water of suitable purity through the desalination of sea water.

Although there have been 'growing pains', plants of up to $270 \times 10^6$ gal/d in one location and comprising single trains of over $14 \times 10^6$ gal/d have performed reliably, delivering water of high purity at a cost that is acceptable in the regions where the plants have been built.\(^1\)

Water is no longer the infinitely renewable resource that we once thought it was. In fact, shortages threaten to make water potentially as critical a resource as energy. However, a water crisis, in contrast to an energy crisis, is life threatening.

\(^1\) 1 gal (UK) = $4.546 \times 10^{-3}$ m³.
Unlike oil, fresh water has no viable substitute and its depletion, both in quantity and quality, could have even more profound economic and social effects.

Fresh water, the 'essence of life', can be reliably produced by desalinating sea water. The sea is the ultimate source of water. The challenge is to produce, at an acceptable cost, desalinated water for the continuous health, development and growth of communities. To meet the challenge, large dual purpose power–desalination plants are being built to reduce the production cost of electricity and water. Thermal energy extracted or exhausted from power plants is used effectively in the desalination process. It is estimated that over 25 000 MW of power is combined with desalination plants in the largest use of the co-generation concept. However, not all water demands are coupled to the need for additional electric power. For these situations, the production of fresh water from the sea through use of the reverse osmosis (RO) and vapour compression (VC) technologies is becoming more widespread.

According to the International Desalination Association (IDA) 1996 Worldwide Inventory Report, at the end of 1995 a worldwide total of 11 066 desalting units, with a total capacity of 20 300 000 m³/d (equal to 5.36 × 10⁹ gal/d), had been installed or contracted. Desalination is already used in 120 countries around the world.

The exponential growth of desalination can be illustrated by the fact that 25 years ago (in 1971) the total worldwide capacity was only 1.5 × 10⁶ m³/d (400 × 10⁶ gal/d). In 1976, the total was 1 × 10⁹ gal/d, and over the past 10 years the world's capacity grew from 3 to 5.4 × 10⁹ gal/d.

The Middle East countries, particularly the Gulf Co-operation Council States, are the largest users of desalination technology, with about 50% of the world's capacity installed in the area. The revenue accrued from development of the region's oil and gas resources has been committed to improving regional standards of living. Thus, it has been re-invested in the power and water infrastructure necessary to achieve this goal, establishing the basis for a sustainable industrial and commercial economy.

Saudi Arabia ranks first, with 25.9% of the world's capacity, most of which is made up of sea water multi-stage flash (MSF) desalination units combined with power generation in dual purpose power–desalination plants. The world's largest plant is the Al Jubail Phase II complex, which produces 240 × 10⁶ gal/d of distilled water and 1300 MW of electric power, and has operated successfully since 1982.

Saudi Arabia is followed by the United States of America, which has 15.2% of the world's capacity and over 1900 units consisting of plants using primarily the RO process to treat brackish groundwater or river water.

The United Arab Emirates, with 10.7%, followed by Kuwait, with 7.6%, of the worldwide capacity, are good examples of countries where dual purpose power–desalting is being utilized on a major scale.

In terms of the desalination processes, 48.1% of the total installed or contracted capacity is based on the MSF principle, reflecting a continuing decline from the
proportion reached in 1993 (51.5%). In comparison, the RO process increased its share from 32.7 to 35.9% during the same period.

For plants rated at more than 4000 m³/d (about $1 \times 10^6$ gal/d) per unit, MSF, with 68.4%, is still more prevalent than RO, with 22.4%. Although other water distillation technologies, multi-effect distillation (MED) and VC, are not in great use it is believed that these will play an important role in the future.

It is of interest to note that for plants rated at more than $1 \times 10^6$ gal/d per unit, sea water desalination leads with 77.7% (compared with brackish water, 16.2%) of all the installed or contracted capacity.

2. TECHNICAL COMPARISON OF PROCESSES

A brief description is given of the principal sea water desalination processes, and their advantages and disadvantages.

2.1. Multi-stage flash

MSF desalination currently produces the major portion of fresh water and is used primarily for desalting sea water feed. This process has been in large scale commercial use for over 30 years. The principles involved are simple. The sea water feed is pressurized and heated to the maximum plant temperature. When the heated liquid is discharged into a chamber (effect) maintained slightly below the saturation vapour pressure of the water, a fraction of its water content flashes into steam. The flashed steam is stripped of suspended brine droplets as it passes through a mist eliminator and condenses on the exterior surface of the heat transfer tubing. The condensed liquid drips into trays as hot product water.

The unflashed brine enters a second chamber, where it flashes to steam at a lower temperature, producing a further quantity of product water. Simultaneously, the distillate from the first stage passes to the distillate tray in the second stage, giving up some of its heat and thereby lowering its temperature. The flashing–cooling process is repeated from stage to stage until both the cooled brine and the cooled distillate are finally discharged from the plant as blowdown brine and product water, respectively.

It is common practice to recycle a fraction of the blowdown water, combined with feedwater, through the entire circuit in order to extract an additional fraction of its water content. The recirculating stream, flowing through the interior of the tubes that condense the vapour in each stage, serves to remove the latent heat of condensation. In so doing, the circulating brine is preheated to almost the maximum operating temperature of the process, simultaneously recovering the energy of the condensing vapour. This portion of the MSF plant is called the ‘heat recovery’ section. The preheated brine is
finally brought up to the maximum operating temperature in a brine heater (or prime heater) supplied with steam from an external source.

At the cooling end of the plant, a separate set of tubes is installed in several of the stages in a 'heat rejection' section to remove the waste heat. The coolant there is generally not recycled brine but feedwater (in this example, sea water), of which the greater portion is discharged to waste. A small fraction of this coolant becomes pre-heated makeup water.

In principle, MSF is the simplest of the desalination techniques. Once the inter-stage orifices are adjusted, the plant can operate for long periods without any resetting of flows. One pound of prime steam can produce several pounds of product water. High energy efficiency can be attained by:

1. Incorporating many stages and a large heat transfer surface in the design of a plant;
2. Increasing the maximum brine temperature (but at the risk of increased corrosion and scaling);
3. Using heat exchange tube material of high thermal conductivity or of an enhanced surface contour;
4. Incorporating suitable techniques for the control of scale formation;
5. Using design, operation and maintenance procedures to prevent local accumulation of the non-condensable gases;
6. Solving the problem of a non-equilibrium flash process.

Among the advantages of MSF and other distillation processes is the fact that the composition of the feedwater to the plant has an almost negligible effect on the energy consumption per pound of product water delivered. This contrasts with the performance of other desalination processes in which the energy consumed is a direct function of feed composition. Another advantage is that this process, in common with all the distillation processes, can produce comparatively pure water. Manufacturers typically submit bids containing warranties that the total dissolved solids will be less than 25 mg/L and, in some bids, less than 10 mg/L. All the distillation processes are fully developed and have been in successful commercial operation for a number of years. The pretreatment requirements are not very complex: trash racks, biocide, de-aeration and the injection of acid or a scale control additive. When operated at its design point, the process is stable.

The major advantage of MSF is that large scale units can be achieved. Designs of $20 \times 10^6$ gal/d for the Al Taweelah A Extension in Abu Dhabi show a continuous reduction in both capital and water costs, to approximately $30 \times 10^6$ gal/d.

\[^2\] $1 \text{ lb} = 0.4536 \text{ kg}$.
Optimization of the MSF cross-flow versus the long tube design, once through versus recirculation, the multi-layer flashing stages, narrow topped MSF, the paired stage design and the optimum material selections shows the continuous potential of MSF technology.

The capital costs of MSF plants vary from US $4 to 12·gal⁻¹·d⁻¹ installed capacity.

2.2. Multi-effect distillation

MED is the oldest large scale evaporative process. It has been used for roughly a century for the concentration of chemicals and foodstuffs and for the crystallization of fertilizers and other commercial materials. Its large scale application to desalination, however, has been limited to the past two decades.

The basic principle is straightforward. The feedwater flowing over a heat transfer surface in the first effect is heated by prime steam, resulting in evaporation of a fraction of the water content of the feed. The feed may be inside the heat transfer tubing, while the steam condenses on the outside, or vice versa. In the vertical tube evaporator, the feed descends as a thin film on to the inside of the vertical tubes. The partially concentrated brine is delivered to the second effect, maintained at a slightly lower pressure than the first effect. Likewise, the vapour liberated from the first effect feed is sent to the second effect. There, it condenses on the heat transfer tubes, giving up its latent heat to evaporation, with an additional fraction of water from the brine flowing on to the opposite wall of the tube. The process of evaporation plus condensation is repeated from effect to effect, each at successively lower pressures and temperatures. The combined condensed vapour constitutes the product water. Here, again, one pound of prime steam produces several pounds of product water.

Several design alternatives exist. For example, the feed may flow countercurrently to the vapour, thereby subjecting the most concentrated brine to the maximum evaporative driving force. Conversely, the brine, partially preheated by a fraction of the vapour, may flow concurrently with the steam. The latter pattern has the advantage of minimizing scale formation, since the most concentrated brine is exposed to the lowest temperature. Another design variation uses horizontal rather than vertical heat exchange tubes in a cross-section of a widely used MED plant of the horizontal tube type, in which the prime steam and all the downstream vapours flow inside the horizontal tubes, where they condense and contribute to the product water stream. The brine, meanwhile, is sprayed on to the outside of the tubes, producing vapour. As in the vertical tube plant, the water vapour generated by brine evaporation in each effect of the horizontal tube evaporator (HTE) flows to the next effect, where it supplies heat for additional evaporation at a lower temperature.

In each effect of either a vertical or a horizontal tube plant, a pump typically circulates the feed plus the partially concentrated brine to an upper plenum that
distributes it to the tubes for further evaporation. Circulation of the brine has the additional advantage of ensuring that the heat transfer surface is uniformly wet, thus avoiding the deposition of solids on dry spots.

Each effect serves as a condenser for the vapour from the preceding effect; however, the vapour generated in the last effect is condensed in a final condenser, where the heat is rejected to a stream of cooling water.

As in the MSF process, MED plants can be made more energy efficient by increasing the number of effects and the heat transfer area, or by increasing the maximum operating temperature. On the other hand, when low cost heat is available it is preferable to sacrifice some of the energy efficiency by operating at a lower temperature because of the resultant decrease in the rate of corrosion and scaling. The low corrosion and scaling tendencies of the low temperature multi-effect (LTME) process not only improve reliability and decrease the operating cost but also permit construction of the plant from low cost materials. The heat transfer tubing, which constitutes a major fraction of the cost of the evaporators, is made of an inexpensive aluminium alloy. The plant walls and internals are constructed of low cost carbon steel coated on the interior with an epoxy paint.

One of the commercially available LTME designs reverses the common procedure of passing the brine through the heat exchange tubing. Instead, brine is sprayed on to the outside of the tubing, while the hot vapour flows inside. Thus, in the unlikely event of a leak in the tube wall, the vapour (which is at a higher pressure than the brine) would leak into the brine chamber, thereby avoiding contamination of the product water. A significant improvement in heat transfer is achieved by using double fluted tubes in vertical tube evaporators (VTEs) and oval tubes in HTEs. The MED specific power consumption is below 1.8 kW-h/t of distillate, which is significantly lower than that of MSF, typically 4 kW-h/t.

MED has a long record of successful operation. The energy consumption per pound of distilled product water varies only slightly with the salinity of the feed. A turndown of 40–45% is possible in a MED plant, and can be accomplished rapidly merely by varying the steam supply. Scaling and corrosion problems depend on the maximum temperature, and are relatively minor in plants operating below 176°F (80°C).

The major advantage of the MED process is the ability to produce a significantly higher performance ratio (PR), in excess of 15 lb of product per pound of steam, whereas MSF is practically limited to a PR of 10. The size of the LTME units is growing rapidly: recently, awards were made for units in excess of $4.5 \times 10^6$ gal/d and a design and demonstration module already exists for a $10 \times 10^6$ gal/d unit. MED recently received a great deal of attention as a result of numerous commercial successes of thermal compression MED for medium sized plants in the United Arab Emirates, and large scale MED units in India ($2 \times 17,500$ m$^3$/d) and in Las Palmas, Canary Islands.
The Metropolitan Water District (MWD) of southern California is developing the next generation of large capacity sea water MED technology for future plants in the next century [1].

In co-operation with IDE Technologies Ltd and Parsons (United States of America), the MWD is producing a detailed design of a $5 \times 10^6 \text{ gal/d}$ demonstration plant. This plant will demonstrate the full scale components of a single module for future plants with capacities greater than $30 \times 10^6 \text{ gal/d}$. The following is a simplified description of the MWD–MED process. The design is composed of a vacuum tight concrete tower that consists of 30 VTE effects and a final condenser. Each effect comprises 18 bundles, with about 1600 double fluted aluminium tubes that will operate over brine temperatures ranging from $100^\circ F$ ($38^\circ C$) to $230^\circ F$ ($110^\circ C$). The aluminium alloy double fluted tubes are 2 in. in diameter and 10 ft long.\(^3\) The brine enters the tubes and flows down into a thin film, evaporating as it generates, rapidly moving the water vapour to the centre of the tube. An orifice plate at the bottom of the effect floor controls the flow of brine into the next effect tubes. Each effect is 16 ft high, giving a vertical extent for the process of a little over 500 ft.

The key to cost savings is use of aluminium materials for the high performance heat transfer surfaces, and a concrete pressure shell based on high strength, low porosity concrete. As a result, the construction cost estimate for a $75 \times 10^6 \text{ gal/d}$ plant for the total project is US $184.15 \text{ million}$ at a specific cost of US $2.46 \text{-gal}^{-1} \text{-d}^{-1}$ installed capacity.

The resulting estimate of total water cost is US $2.20/\text{kgal}$ (US $0.58/\text{m}^3$) based on a fuel cost of US $2.25/\text{MBtu}$, a steam cost of US $1.21/1000 \text{ lb}$ (24 psia), an electricity cost of US $0.07/\text{kW-h}$ and amortization for 30 years at 7%.\(^4\)

The principle of MED with two basic configurations of a VTE and an HTE is expected to produce a significant number of new varieties: from an improvement in the heat transfer through the plate and oval configurations, to the use of plastic, mass produced modules with unique utilization of short (0.5 m) aluminium double fluted tubes [2]. All these new ideas will contribute towards the rapid advancement of MED technologies, with the goal of obtaining a high PR and/or lower capital costs. In general, current MED capital costs vary from US $3.50 to 8-\text{-gal}^{-1} \text{-d}^{-1}$.

2.3. Vapour compression

VC is similar to MED. The chief difference is that the vapour produced by evaporation of the brine is not condensed in a separate condenser. Instead, it is returned by a compressor to the steam side of the same evaporator in which it originated, where it

\(^3\) 1 in = $2.54 \times 10^1 \text{ mm}$; 1 ft = $3.048 \times 10^{-1} \text{ m}$.

\(^4\) 1 Btu = $1.055 \times 10^3 \text{ J}$; psia = lbf/in\(^2\) abs = $6.895 \times 10^3 \text{ Pa}$.
condenses on the heat transfer surfaces, giving up its latent heat to evaporate an additional portion of the brine. The energy for evaporation is not derived from a prime steam source, as in the preceding two distillation processes, but from the vapour compressor. The latter, in addition, raises the temperature of the vapour by its compressive action, thereby furnishing the driving force for the transfer of heat from the vapour to the brine.

As in the case of MED plants, the brine is circulated from the bottom sump of the evaporator to the distributor at the top in order to wet the tubes and to achieve the required degree of evaporation. The brine recirculation rate is of an order of magnitude lower than in MSF. The thermal efficiency of the process is improved by transferring the residual heat from the product and the reject brine to the stream of entering feedwater.

Low temperature VC is a simple, reliable and efficient process requiring electric power only, and is inherently the most efficient distillation process. The ‘heat pump’ principle continuously recycles the latent heat exchanged in the evaporation–condensation process within the system.

Using the falling film concept, non-equilibrium flashing is eliminated and a high evaporation heat transfer coefficient is achieved.

With low temperature VC, a high capacity compressor allows operation at low temperature (below 158°F (70°C)), reducing the potential for scaling and corrosion.

Compared with thermal desalination plants, no cooling water is required, resulting in smaller intake and pumping systems and lower energy requirements, and there is no need for a heat rejection section.

Since the temperature of the sea water feed must be raised only by about 102°F (35°C), compared with a minimum of 149°F (65°C) for high temperature distillation, the thermal load on the heat exchange is small and heat is recuperated from the distillate and brine blowdown.

The low temperature of VC permits use of an aluminium alloy for the evaporator–condenser and titanium plates for the feedwater heater. The low temperature and non-flashing process allows use of mild steel with epoxy paint on both sides, and also non-metallic materials for many of the internals.

The development of large scale, high efficiency mechanical VC units presents a good opportunity for single or hybrid purpose desalination processes.

Currently, the largest scale VC unit is 3000 m³/d, or 0.8 x 10⁶ gal/d, in a single unit. It consists of three evaporator–condenser effects coupled to a single high volumetric compressor.

The upgraded design of the mechanical vapour compressors is based on a two rotor concept mounted on a single shaft, one rotor housing the ‘compressor blades’ and the other the ‘induce blades’, allowing a more efficient hydrodynamic configuration. The total efficiency of the high volume compressors is 78%.

The original mechanical VC units were based on a single effect design. Today, a three effect mechanical VC has been built with a unit capacity of 3000 m³/d, or
0.8 × 10⁶ gal/d. This large scale VC guarantees a unit specific electricity consumption of 7.5–8.5 kW·h/m³ of product (excluding the sea water supply). It produces high purity (10–20 ppm) distillate at a high plant availability of 94–96%.

In future, VC units will grow in capacity and the number of effects. A single effect 3 × 10⁶ gal/d (11 000 t/d) VC system with a conventional axial flow compressor and an unconventional radial inflow compressor of novel design has been described by El-Sayed [3].

The design of a VC with four and more effects, and a staging compressor in series or parallel, will allow effective hybridization of power with MED, MSF and RO. This will be particularly important in cases where the power to water ratio has to be minimized in favour of water production.

2.4. Reverse osmosis

Sea water RO is a mature technology. With a carefully designed pretreatment unit, and good plant design and construction, a well maintained RO facility can achieve high reliability. The RO process uses hydraulic pressure as its energy source and operates at an ambient temperature (under 104°F (40°C)), in contrast to distillation, which operates in the range of 125–240°F (51.7–115.6°C). In RO, a fraction of the water content of sea water or brackish water is driven under pressure through a semi-permeable membrane, generally of organic materials. As the name implies, the driving force must exceed the osmotic pressure of the brine, a value which can be found in handbooks. As a rough rule of thumb, the osmotic pressure of the sodium chloride solution (expressed in lb/in²) is 1% of the salt concentration (expressed in ppm or mg/L).

In the distillation processes described earlier, the condensed steam consists of practically pure water contaminated only by drops of saline spray carried over with the steam. In contrast, even perfect RO membranes experience a dynamic balance between the flow of pure water molecules and the diffusion of inorganic ions. This permits a wide range of salt passage, defined as the ratio of salt concentration in the product to salt concentration in the feed. The membrane designer can control salt passage and flux (gal·ft⁻²·d⁻¹ of product water) through the composition of the membrane and the technique of membrane preparation.

Current membrane compositions include cellulose acetate, containing various ratios of triacetate to monoacetate; polyamides, a group of compounds related to nylon; polyimides; polysulphones, used primarily as backing material for the osmotically active films; and asymmetric and thin film composite membranes.

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5 1 in² = 6.452 × 10² mm².
6 1 ft² = 9.290 × 10⁻² m².
To provide more compact installation and to lower the equipment costs, designs have been developed to maximize the membrane surface area in a single pressure vessel. Two designs are currently in use for sea water: spiral wound and hollow fibre.

(1) Spiral wound

Two membrane sheets plus intervening spacers are sealed along three edges. The fourth edge is glued to a slotted or drilled central tube to which a number of such ‘sandwiches’ are attached. Then the entire assembly is rotated to form a cylinder resembling a jelly roll. As the feed flows between the ‘sandwiches’, pressure forces the purified water into their inner channels, where it flows to the central tube and leaves the system as product water. The concentrate emerging from the end of the spiral may be discharged, or may be further concentrated in succeeding spiral units before discharge as reject brine.

(2) Hollow fibre

The membrane material is drawn in the form of hollow fibres of human hair thickness. The ends of the fibres are sealed in resin, and the assembly is placed in a tubular pressure vessel. When pressurized feed enters the tube, water flows through the fibre walls and into the central capillary. Water molecules flow preferentially through the walls, while the greater portion of dissolved materials (organic and inorganic) remains in the concentrate and is discharged to waste.

RO has the advantage of low temperature operation, which minimizes scaling and corrosion. The output of a single module cannot be increased or decreased; however, the modular construction of commercial RO plants permits adjustments in plant capacity simply by increasing or decreasing the number of modules in operation.

Product purity is only fair. A single pass plant can attain about 300–500 mg/L from a sea water source. For greater purity, the product is subjected to a second pass. Certain contaminants are not removed by RO, for example, carbon dioxide or boric oxide, i.e. their concentration in the permeate is identical to that of the feedwater.

Membrane processes experience a sharp increase in energy demand as the feedwater concentration rises. For RO, the pump pressure required by brackish feedwater is 250–400 psig (17.2–27.6 bar); for sea water it is 800–1200 psig (55.2–82.8 bar). In addition, membrane processes are very sensitive to specific contaminants in the feedwater.

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7 psig = pound force per square inch gauge pressure (see footnote 4).
feed, and hence require careful pretreatment. In general, RO requires thorough pre-treatment to avoid deposits that might decrease the product flux or, in extreme cases, could completely destroy the membranes.

The current sea water RO status reflects rapid changes in RO technology and the associated equipment; these improvements have had an impact on the total costs of owning and operating an RO plant. Evaluation of global sea water RO capital and operating costs have been well summarized by Moch and Shields [4].

For low and medium salinity waters, feed at a pressure of 1000 psig (69 bar) is used, while for the high salinity and temperature conditions found in the Red Sea and Arabian Gulf regions RO can utilize feed pressures of up to 1200 psig (83 bar). Depending on the salinity, the conversion ratio can vary from 35% for high salinity to 50% at standard sea water salinity.

Both water production and salt passage increase with temperature. Preheating the feed in hybrid integration with a power plant or a thermal distillation plant may be economically attractive as long as the upper temperature limit of the membrane is not exceeded.

The sea water RO process normally uses only electric energy. The largest power consumer is the high pressure pump. Multi-stage centrifugal pumps (70–85% efficiency) are employed for large single trains that currently reach 2 × 10^6 gal/d. Energy recovery systems based on a reverse running pump, impulse turbines, a hydraulic turbocharger or a work exchanger are now normally employed to recover energy from the high pressure RO reject brine stream. About 25–30% of the total plant energy can be restored. As a result, the total plant energy requirements can vary from 16.0 to 28.0 kW-h/1000 gal or from 4.2 to 7.4 kW-h/m^3 of product. The higher requirements reflect Arabian Gulf waters.

Recent technology advances in pretreatment involve intermittent use of chlorine in the feedwater plus new cleaning chemicals. To a large extent, these advances have solved the problem of biological fouling in open sea water surface intakes.

The capital, energy and membrane replacement costs constitute the major components of the total water costs. Capital amortization constitutes about 35–45% and electric power 30–50% of the total water costs, varying between a low of US $0.75/m^3 to US $1.20/m^3. The actual membrane replacements are normally less than the system guarantees agreed upon by the membrane suppliers. On the basis of actual experience it has been shown that instead of 20% membrane replacement, RO modules have an average plant age in excess of 10 years. The capital costs of the RO plant could vary from US $3.5 to 7-gal_1-d_1, based on larger installed units.

As a result of improvements in membrane technology and packaging, sea water RO plants can offer significantly reduced membrane and operating costs. One other unique potential of RO technology is that it can be effectively utilized in hybrid systems, combining the best features of membrane technology and MSF, MED or VC systems with electric power generation.
3. CONCLUSIONS

With the large capacity and large number of plants committed to desalination, the security and development of many nations depend on current desalination capabilities and advances in desalination technology. The future of desalination technology will depend largely on reducing the energy costs, achieved by optimizing power and water generation. It will also depend on further improvements in the technology, the unit size of the membrane and the distillation processes. Also, in many cases hybrid systems that combine the best features of distillation and RO may be developed and utilized.

It is therefore a major challenge to select the optimum power–desalination technology. It requires understanding of the processes and knowledge of effective integration and hybridization; most important, it is influenced by local conditions and factors.

In the near term it can be projected that desalination technology will adopt hybrid, large scale MED plants, and that there will be increased use of large scale VC. There will also be significant advances in RO technology.

Desalination and power developments have to be in harmony with the environment. In most cases, these projects can be constructed with the proper environmental controls and minimized impacts, not only locally but also regionally and globally.

The desalination and power production requirements will continue to grow in the world, and traditional methods of financing these projects will, of necessity, change as the global economy changes. Privatization will be a significant vehicle in this process.

Finally, it is believed that the power and desalination industry can provide an effective solution to future water problems.

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IAEA ACTIVITIES ON THE NUCLEAR DESALINATION OF SEA WATER

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Abstract

IAEA ACTIVITIES ON THE NUCLEAR DESALINATION OF SEA WATER.

Interest in using nuclear energy to produce potable water, an indispensable resource for human living, has grown worldwide over the past decade. This has been motivated by a wide variety of reasons, inter alia, from the economic competitiveness of nuclear energy to energy supply diversification, from the conservation of limited fossil fuel resources to environmental protection. In response to this trend, since 1989 the IAEA has co-ordinated various feasibility studies on nuclear desalination of sea water with the participation of interested Member States. A number of these states have supported these activities by providing expertise, relevant information and financial resources. An overview is given of what the IAEA has accomplished and how it can play a role in promoting the peaceful use of nuclear energy, thus contributing towards solving the potable water supply problem in the next century. The results of work done within the framework of the IAEA's nuclear desalination programme over the past years have shown that application of nuclear energy to sea water desalination is a realistic option. The challenge ahead is to demonstrate use of a nuclear desalination plant by proceeding with effective development and practical applications.

1. INTRODUCTION

Economic and population growth has jeopardized the availability of potable water in many regions of the world. Increasing pollution and salinity of the natural fresh water resources also compound the problem. The high population growth rate in water short regions is a clear indication of the seriousness of future water supply problems. Desalination offers the best solution for coping with this issue and an increasing number of desalination plants have been installed worldwide, most of which desalt sea water.

Sea water is the largest source of water, and is practically unlimited compared with natural fresh water resources. In many parts of the world, sea water desalination offers one of the most promising alternatives for supplying the required potable water. The worldwide cumulative sea water desalination capacity has increased steadily over the past few decades, and this trend is expected to continue into the next century.
The same reasons for deploying nuclear power for electric energy generation apply to the choice of nuclear power as an energy source for sea water desalination plants. These include economic competitiveness in areas that lack cheap fossil fuel resources, energy supply diversification, conservation of limited fossil fuel resources, promotion of technological development, and environmental protection through avoiding emissions from fossil fuels that cause acid rain and climate change.

The IAEA surveyed the feasibility of using nuclear energy for sea water desalination as early as the 1960s. However, at that time interest in this application was less than that shown in electricity generation, district heating and industrial uses of process heat. The reasons were mainly the uncertainty in nuclear energy costs and the mismatch between the size of the nuclear power plants then available and the desalination plants.

In 1989, the renewed interest in nuclear desalination\(^1\) shown by several Member States led to General Conference Resolution GC(XXXIII)/RES/515 of the IAEA, which requested the Director General to proceed with studies to assess the technical and economic potential of nuclear reactors for sea water desalination in the light of the experience gained in recent years.

State of the art sea water desalination technologies were reviewed, and coupling of nuclear reactors to desalination processes was examined [1]. Site specific economic competitiveness and institutional issues associated with the implementation of nuclear power plants were generally identified as the main hurdles to the potential use of nuclear reactors for desalination.

Sea water desalination has been found to be an established, proven and commercially available technology, with further potential for improvement. Among the existing desalination processes, the following were considered to be the most interesting for large scale water production: reverse osmosis (RO), multi-effect distillation (MED) and multi-stage flash (MSF). Capacity wise, MSF has been the most widely used process, but it is judged to be approaching the limit of its technical potential. Experience with MED has demonstrated relatively good economy; the process also seems to show great potential for providing relatively low cost water. RO was the most promising of the existing processes owing to the advancements made in membrane technology. The investment and operating costs of this process were also estimated to be potentially lower than those of MSF and MED. Therefore, RO was considered to be the most promising process for future generation desalination plants. A hybrid system combining two or more processes also seems to be an attractive option.

\(^1\) ‘Nuclear desalination’ is taken here to mean the production of potable water from sea water in an integrated complex in which both the nuclear reactor and the desalination system are located on a common site, the relevant facilities and services are shared, and the energy used for the desalination process is produced by the nuclear reactor.
Although the experience gained with nuclear desalination was limited at the time, continuing interest was reflected in several studies that were carried out on three main reactor types: water cooled, gas cooled and liquid metal reactors. All were regarded as being technically feasible for coupling with desalination processes.

The economic competitiveness of the selected coupling schemes was also analysed [2]. The relative costs of nuclear and fossil fired plants for providing the energy for desalination depend largely on the unit size required for the intended coupling. When combined with larger units, the overall costs of sea water desalination using nuclear plants were shown to be more economical than those using fossil fired plants.

2. NORTH AFRICAN REGIONAL FEASIBILITY STUDY

In the study on the Potential for Nuclear Desalination as a Source of Low Cost Potable Water in North Africa [3], which was initiated in 1991, emphasis was placed on analysing the electricity and potable water demands, and the available energy and water resources in the participating Member States. The study was performed by the relevant institutions of the five participating countries, with assistance provided by the IAEA. The scope of the study included selection of representative sites, analysis of the site specific economics for various combinations of energy source, and the desalination process appropriate for each site, the financial aspects, local participation, the infrastructure requirements, and the institutional and environmental aspects. The study concluded that small and medium sized reactors (SMRs) are suitable for nuclear desalination applications in most parts of the region, particularly after consideration of the electric grid size and the availability of capital investment. Some of the other findings of the study were:

(1) The North African countries anticipated a population growth to 220 million people by the year 2025. Diminishing resources, increasing salinity and pollution of fresh water, increasing urbanization and industrialization, and the rising living standards will increase the demand for both electricity and water.

(2) The only significant indigenous primary energy sources in the region, oil and natural gas, are expected to be depleted in the next century. By the year 2025, the required installed capacity of electricity would be more than 100 GW(e), which is more than five times the regional installed capacity in 1990.

(3) The bioclimate of all five participating Member States varies from arid to extremely arid. The estimated overall regional water deficit by the year 2025 will be of the order of $40 \times 10^6$ m$^3$/d. Sea water desalination could be of vital interest in closing this gap.
Nuclear power could play an important role in meeting the expanding regional demands for energy, including the electricity and heat requirements of desalination plants.

For each of the five sites, which range in potable water production requirements between 24 000 and 720 000 m³/d, potable water could be produced by nuclear desalination at a cost that is similar to a fossil energy source.

Financing of nuclear power projects in the region may prove to be difficult, because of the financing volume, the potential cost and schedule uncertainties of nuclear power plants, and the general difficulty of some countries to obtain foreign credit.

The RO process coupled contiguously (i.e. on the same site) with the energy source (fossil or nuclear) yielded the lowest water costs. However, neither the possible risks associated with contiguous siting nor any additional expense associated with water transportation from a remote site were reflected in these costs.

Applying the potable water quality standards of the World Health Organization (WHO), the water costs of MED plants were always higher than those of RO plants, and rose significantly if the energy source was a heat only rather than a dual purpose plant.

Hybrid RO/MED plants had water costs that ranged between those of RO and MED plants.

In line with the generic studies described in Ref. [2], the specific water costs (US $/m³ of water produced) increased as the water output requirements decreased. Although no attempt was made to optimize coupling at the lowest water cost for each site, the following results were obtained for specific sites:

(a) The water costs for RO plants coupled continguously to nuclear energy sources ranged between about US $0.7/m³ for the largest plant under the most favourable assumptions (720 000 m³/d) and about US $1/m³ for the smallest plant (24 000 m³/d);

(b) The water costs were about US $0.1–0.2/m³ higher for MED plants coupled to dual purpose energy sources than those for the RO plants, depending on the size of both the plant and the dual purpose energy source;

(c) The nuclear and fossil energy options for providing heat only for the lowest output MED plant (24 000 m³/d) had water costs of about US $2/m³.

3. RECENT ACTIVITIES

Methodologies have been developed that enable site specific technical optimization and economic evaluation [4], as well as allocation of the costs of dual purpose plants and determination of their optimum coupling [5]. A computer program
is now available to interested Member States; it will be demonstrated at this Symposium. A training course on operation of the program has also been held for a group of experts. Application of these methodologies has shown that nuclear desalination of sea water could be technically and economically feasible.

An Advisory Group Meeting (AGM) was held in 1995 to review global experience of coupling nuclear power plants to non-electrical heat application systems such as district heating networks and desalination processes. During this meeting it was reported that about 500 reactor-years of operational experience from nuclear co-generation and heat only reactors are now available. Most of this experience stems from the operation of WWER type reactors in the former Soviet Union and Eastern European countries. It was confirmed that the radioactivity levels in the heat consuming parts of these industrial complexes have always been maintained within regulatory limits. Nuclear energy for sea water desalination plants has been used at locations in Japan and Kazakhstan. While in Japan the desalination plants are mostly for the on-site water supply, the Aktau desalination complex in Kazakhstan supplies water to a nearby populated area.

Taking into consideration the anticipated potential of SMRs for the desalination of sea water using nuclear energy, the status of SMRs being developed, designed or already commercially available has been surveyed, and up to date technical information collected [6].

While most industrialized countries favour large (900–1400 MW(e)) nuclear power stations for domestic application, there is growing interest in small to medium sized reactors in several Member States. A better fit to smaller and weaker grids and a better match of the projected load growth rates are some of the incentives for the development and introduction of SMRs [7]. Most countries suffering from potable water shortages have grids for which SMRs could be the best choice for electricity generation and as an energy source for water desalination.

SMRs are under development for all the principal reactor lines, i.e. water cooled, liquid metal and gas cooled reactors, many of which have been recommended by vendors as possible options for coupling to desalination processes [2]. In principle, each of these reactors could be used as an energy source for desalination. If one limits the time horizon to the next 10 years, then consideration can only be given to those reactors that have been proven or are at an advanced stage of design, and are already licensed or in the licensing process.

It is considered that worldwide there is a large potential for medium capacity (50 000–100 000 m³/d), land based or transportable desalination plants, and that such plants might be coupled to barge mounted (floating) nuclear plants. Therefore, this issue was examined. At a Technical Committee Meeting, some papers were presented by participants from the Russian Federation in which their experience with small desalination plants installed on nuclear powered icebreakers and other surface vessels was described.
A recent review of desalination technology has shown that even though MSF continues to command the largest share, the percentage total capacity has been declining steadily. In comparison, use of RO has increased. MED and vapour compression (VC) distillation also account for a significant fraction. Other sea water desalination processes such as electrodialysis, ion exchange and freezing are not expected to be applied on a large scale in the foreseeable future.

4. OPTIONS IDENTIFICATION PROGRAMME

In view of the increasing level of interest in nuclear desalination, the 1993 session of the General Conference of the IAEA requested the Director General, in Resolution GC(XXXVII)/RES/617, to “consult with interested Member States, the relevant organizations of the United Nations family and other relevant international organizations concerning the implementation of demonstration facilities”. The objective of a demonstration programme is to build confidence, through the design, construction, operation and maintenance of an appropriate facility or facilities, in the fact that nuclear desalination can be technically and economically accomplished, while meeting established safety and reliability criteria.

On the basis of recommendations made at an AGM held in 1994, a new 2 year programme, the Options Identification Programme (OIP), was initiated with the participation of representatives from interested Member States.

The purpose of the OIP, as approved by the General Conference of the IAEA in 1994, was to select from a wide range of possible choices of desalination technologies and reactor types the most practical\(^2\) candidates for demonstration. As this programme was not intended to serve as either a reactor or a desalination process development programme, the demonstration options identified were to be based on reactor and desalination technologies that are already available, without further development at the time of demonstration.

Three options were identified and reported to the 40th Session of the IAEA General Conference in September 1996 as being practical candidates for further

\(^2\) For an option to be ‘practical’, the following conditions should be fulfilled:

1. There is no technical impediment to implementation, and a suitable site exists;
2. It is technically feasible to be implemented on a certain predetermined schedule;
3. The investment cost can be estimated within an acceptable range;
4. The nuclear and desalination technologies used have promising prospects for future commercial application;
5. The design and performance characteristics would be representative of commercial facilities.
consideration as nuclear desalination demonstration projects. The results of this study have been published [8] and the major findings will be presented in another paper at this Symposium [9]. The programme also identified issues related to demonstration and commercial production facilities.

The infrastructure requirements for nuclear desalination plants are recognized as a major issue for Member States with limited nuclear power experience. They are primarily determined by what is required for nuclear facilities. A demonstration project, if implemented in such a Member State, could be a very effective and practical framework for developing its nuclear infrastructure, in particular its nuclear regulatory structure.

In Japan and Kazakhstan, desalination facilities connected to nuclear power plants have been producing desalted water for many years, while a significant number of Member States have expressed an interest in this option. National and bilateral activities, on-going or planned, will add to international experience in nuclear desalination. Such projects should be useful for commercial deployment. These include programmes and activities in China, India, Indonesia, the Republic of Korea, Morocco and the Russian Federation, as well as studies and R&D work in some other interested Member States.

National and bilateral projects can be considered as the basis for international co-operation and support, which is also of benefit to other Member States. It will be important to utilize the experience gained from these programmes, and not to duplicate activities. The projects should be implemented by about the year 2005, thus contributing towards a solution to the potable water supply problem in the next century.

5. FUTURE ACTIVITIES

In the course of the studies performed to date it was found that sea water desalination using nuclear energy is indeed a realistic option for many Member States. Also, the continuing expansion of sea water desalination installations presents a potential market for the introduction and commercial deployment of nuclear desalination.

Upon completion of the Agency's 2 year OIP, sets of practical technical options for demonstrating nuclear desalination were identified. Demonstration programmes have to be directed towards those issues that are relevant to commercial projects. Demonstrations could provide very useful support for promotion and confidence building. Some issues, in particular those technical features that have a major impact on economic competitiveness and on the overall economics of nuclear desalination, need to be demonstrated to confirm assumptions and estimates. Since several countries have on-going nuclear desalination activities, it has been proposed that, within the framework of an IAEA Co-ordinated Research Programme, a programme be
initiated in 1997 to share relevant information, to optimize resources and to integrate related R&D efforts. Participation from interested research institutes in Member States is welcome.

It is also important to continue relevant studies and to assist interested Member States in building up their nuclear infrastructures, e.g. through implementing demonstration programmes. To facilitate the sharing of experience and knowledge as well as effective co-ordination of relevant activities, the IAEA is to establish an International Nuclear Desalination Advisory Group (INDAG) with the participation of those Member States that are operating, developing, designing or planning (or interested in) nuclear desalination plants.

With the co-operation of other international organizations, this Symposium is designed to provide a forum for the review of state of the art technological experience, design and development, and of future prospects for nuclear desalination.

In addition, the Agency's Department of Technical Co-operation is willing to assist, upon request, those Member States concerned with preparatory activities for demonstration projects.

6. CONCLUSIONS

The activities of the IAEA's nuclear desalination of sea water programme have been successfully implemented through international co-operative efforts, with active national participation and related technical and financial support. The results illustrate that application of nuclear energy to sea water desalination is a realistic option. The challenge ahead is to demonstrate use of a nuclear desalination plant by proceeding with effective development and practical applications.

REFERENCES


WATER DESALINATION EXPERIENCE

European Commission activities

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Abstract

WATER DESALINATION EXPERIENCE: EUROPEAN COMMISSION ACTIVITIES.

An overview is given of the experience accumulated on the different desalination plants installed in Europe over the past 30 years. Quantification of the energy consumption, implementation of technology, as well as the lessons learned from several plant performances and costs, are discussed. Various energy sources for desalination are examined. These are largely influenced by regional factors such as whether the projected site is in a remote or densely populated area, and whether an appropriate electric grid is available or not. For communities without electric power and fresh water sources but with salt water resources, a dual purpose plant may be an appropriate solution, as is the case in the Persian–Arabian Gulf. In an area where adequate electric power interconnections are already available, such as the Mediterranean Basin, a single purpose plant may be preferable. In isolated areas with appropriate renewable energy resources (e.g. wind, solar and geothermal) and low energy and water requirements, a combination of renewable energy and desalination may be appropriate. Use of small nuclear reactors for water or electricity production is feasible, but possible economic problems may have to be examined for a specific site. Large reactors will necessarily imply a dual purpose plant, therefore it will have to be connected to electric grids of a suitable size. Without a grid connection, small plants constitute the only option for the reverse osmosis process, while dual purpose plants with electricity as the main product are not feasible.

1. DESALINATION TECHNOLOGIES

The evolution of human communities has always been strongly dependent on a regular supply of energy and fresh water. Although desalination has been around for a long time, it only became significant as an industrial activity at the end of the 1960s. The main driving force for desalination was initially development of the oil industry in the Middle East. Nowadays, desalination plants have been implemented all around the world. In 1991, the installed capacity was 15.6 million m³/d; for the year 2000,
a capacity of 20 million m$^3$/d may be expected if the increase rate of 1991 is assumed to remain constant.

In Europe, Spain has the largest market for desalinated water. Applications on the mainland are at present almost exclusively for industrial purposes, but tourist applications will soon become more relevant. On the Balearic Islands, the main uses are for municipal and touristic needs, and irrigation. In Italy, where the total production is similar, desalinated water is used in comparable proportions for industry and power generation. In Germany, although there is some desalination for municipal uses and power generation, industry is the main consumer. In the United Kingdom, power generation consumes a significant fraction, although the greatest consumer is again industry. The Netherlands uses almost equal amounts for irrigation and industry. In Greece, very little water is desalted; its users are industry and municipalities. Finally, in France desalted water is used exclusively by industry.

The most common processes for water desalination are:

1. **Phase change processes**: multi-stage flash (MSF); multi-effect evaporation (MEE); and vapour compression (VC).
2. **Single phase processes**: reverse osmosis (RO); and electrodialysis (ED).

2. EXPERIENCE

2.1. Energy consumption and water production

To date, all the methods used for desalination of water, in any significant volumes, are energy intensive. The type of energy typically needed may be in the form of steam and/or electricity. Steam is used in the MSF and MEE processes, whereas electricity is used in all the other processes. In all cases, auxiliary energy is needed, usually in the form of electricity, for pumps, dosifiers, vacuum ejectors, etc. The energy consumption of the processes accounts for about 85–90% of the total energy. The currently estimated energy consumption of the different processes for sea water desalination is summarized in Table I [1].

2.2. Implementation of technology worldwide

The desalination technologies employed around the globe vary from country to country [2]. MSF is primarily used in the Gulf countries, accounting for 75% of the global MSF installed capacity. In Europe it is used only in Italy, where 2% of the world’s capacity is installed. RO is more evenly spread throughout the world: 32% has been installed in the United States of America, 21% in Saudi Arabia, 8% in Japan and 8.9% in Europe. The same applies to ED (31% in the USA, 23% in the Middle
TABLE I. ESTIMATED ENERGY CONSUMPTION OF THE DIFFERENT PROCESSES FOR SEA WATER DESALINATION
(The specific energy consumption can be considered to be roughly independent of plant capacity. The share of thermal energy used in the MSF and MEE processes has been recalculated and expressed as an electric energy equivalent to allow for better comparison with other processes) [1]

<table>
<thead>
<tr>
<th>Process</th>
<th>State of maturity</th>
<th>Energy consumption</th>
<th>Electric energy equivalent (kWh/m³)</th>
<th>Scale of application</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSF</td>
<td>Very</td>
<td>Thermal</td>
<td>10–14.5</td>
<td>Small–large</td>
</tr>
<tr>
<td>MEE</td>
<td>Partly</td>
<td>Thermal</td>
<td>6–9</td>
<td>Small–medium</td>
</tr>
<tr>
<td>VC</td>
<td>Partly</td>
<td>Mechanical</td>
<td>7–15</td>
<td>Small</td>
</tr>
<tr>
<td>RO</td>
<td>Yes</td>
<td>Mechanical</td>
<td>4–8</td>
<td>Small–large</td>
</tr>
<tr>
<td>ED</td>
<td>Yes</td>
<td>Electric</td>
<td>5–8</td>
<td>Small–large</td>
</tr>
</tbody>
</table>

East and 15% in Europe) and to VC (20% in the USA, 13% in the Middle East and 22% in Europe). In fact, these figures show that the relative weight of membrane technologies and VC is much higher in developed countries than in the Middle East. However, in Japan almost all the desalination is done using membrane technologies. MEE is represented in the former USSR with 39% of the global capacity (corresponding to only an insignificant fraction of the world’s desalination capacity), with 10% in the Caribbean Islands, 7.2% in the USA and 12.7% in Europe.

Manufacturers of different technologies are also unevenly spread around the world. In terms of capacity, manufacturers from Japan and the Republic of Korea produce 45% of the MSF plants, while 43% are from Europe and 8% from the USA. In the case of RO plants, 23% are produced in the USA, 18.3% in Japan and 12.3% in Europe. Nevertheless, membrane manufacturing only takes place in Japan and in the USA. The situation is quite unique for ED plants, 88% of which are fabricated by a single company in the USA.

The distribution of different technologies may to some extent result from development of the various processes. MSF has been developed for and adapted to large scale production. The technology is quite mature and only few further improvements can be expected. However, the increase in size has led to intensive studies on intelligent control systems that will certainly reduce the operation and maintenance costs and enhance performance. Sharp temperature control, for instance, can reduce scaling and fouling of the heat exchanging surfaces. These improvements will also be used to the advantage of smaller plants.
Concerning MEE, the 1994 International Desalination Association inventory mentions that "this technology is hardly applied anymore"; however, at present a significant effort is being made to get it back on to the desalination market, for several reasons. The enthalpy of the process is more favourable than that of MSF, hence the system is intrinsically more efficient. Use of low temperature steam (70°C) makes it possible to use the heat available from other processes as an energy source, and hence to further reduce energy costs. Co-generation of water and energy using MEE appears to be an efficient global solution. It is a stable process and does not suffer from the instability problems of MSF.

Both MSF and MEE plants benefit from cost reductions from the scale effect, as a certain increase in capacity can be achieved by increasing the size of each component. Furthermore, large scale plants benefit from lower heat losses.

VC plants are compact and small compared with other plants. However, they have not been used for large scale implementation owing to the difficulty in developing adequate compressors. In the small-medium size range, they are quite expensive compared with RO and have higher energy requirements. The performance of VC plants would benefit significantly from advances in heat exchanging surface materials.

Although RO plants seemed to be taking over the desalination market between 1987 and 1989, peaking in 1989 with more than 70% of the capacity installed that year, they have lost much ground to MSF on the world market. The main reasons for this are technical. RO is, by definition, a modular technology. As the plant size increases, the complexity of the system makes it expensive and unreliable. The operational maintenance of RO systems is expensive for two reasons: (1) the costs of the pretreatment of the raw water, mainly chemicals and filters; and (2) the high costs of the membranes, which have to be replaced periodically, depending on the raw water quality.

All the above mentioned methods of water desalination can be applied to either brackish water or sea water and, with the exception of RO and ED, their energy requirements are almost independent of water salinity.

2.3. Operational experience

It has already been pointed out that utilization of desalination technologies in Europe is not particularly significant in terms of production capacity. However, desalination has reached a remarkable degree of usage in certain areas such as Sicily and Sardinia, Malta, the Balearic Islands and, particularly, the Canary Islands, for which the production capacity is roughly 255 000 m³/d, corresponding to 1.3% of the world's capacity. All the commercial processes available on the market have been used over the past 30 years. Accordingly, expertise in operation and maintenance has increased progressively. The most relevant items from this experience are summarized in the following subsections.
2.3.1. Feedwater intake

This particular issue has been shown to be an absolutely critical feature in the design of plants because of its effect on operation and maintenance. There is a great difference between surface sea water intakes and other intakes carried out via shore or beach wells. Generally, preference is given, whenever possible, to properly dug, cemented beach wells. The intake must always be capable of providing enough feedwater flow. Besides, the raw water quality should be as high as possible in terms of suspended solids, bacterial contents, etc.

However, the water quality acceptable for distillation processes is not adequate for membrane processes such as RO. The high bacterial contents in sea water produce biological pollution of the membranes. Thus, feedwater must undergo intensive and costly pretreatment, and membranes have to be cleaned quite frequently.

In contrast, when intake is through a coastal well, the quality of water obtained is much better. It contains less suspended matter and has lower microbial contents.

2.3.2. Pretreatment

The need for adequate pretreatment is very much related to the water intake, as already mentioned. The better the raw water, the easier and cheaper the pretreatment.

2.3.3. Material selection

Another lesson learned during the years of plant operation concerns the use of appropriate materials, particularly metal alloys. Desalination plants constitute an ideal environment for corrosion: saline water at moderate or high temperatures; extreme pH values; dissolved oxygen, sometimes with bacterial activity; and many metallic ions. All these features compel designers and operators to use every available means for reducing and, if possible, avoiding corrosion.

Therefore, besides techniques such as pH control and removal of dissolved oxygen, it is advisable to use appropriate materials; plastic materials are used whenever possible. However, in other cases use of metal alloys is required: copper-nickel, brass, stainless steels (minimum AISI 316L, rather than 904L), steels with a higher molybdenum content, cladding of different alloys, rubber linings and coatings. Standard practice is to use different materials, depending on the area where the plant is to be located.

2.3.4. Energy issues

Desalination technologies have been improved continuously with regard to energy efficiency, i.e. by reducing the specific energy consumption. An obvious
example is RO, which used to require around 10 kW·h/m³ of product water at the end of the 1970s, while nowadays the consumption is around 5 kW·h/m³. For VC, the energy consumption was reduced from around 22 kW·h/m³ in the 1970s to 8–9 kW·h/m³ today.

These improvements result mainly from better heat transfer and better performance of the pumps and vapour compressors. Most refer to improved hydraulics or auxiliary equipment, and not to the desalination process itself, i.e. evaporation or mass transfer through the membranes.

Another issue that influences the water costs is the energy price. Since water supply is a basic requirement, when the water production costs are too high, subsidies (direct or indirect, via a discount in fuel or electricity tariffs) might be necessary.

2.3.5. Institutional affairs

Over the years, the relationship between the various institutions and bodies involved in or somehow connected to water desalination and/or energy supply has passed through various stages. Sometimes, co-operation and understanding have led to satisfactory results, while in other cases the tuning has not been as desirable.

This state of affairs concerns all desalination plants, as strong energy consumers, but mainly dual purpose plants, where the electricity and water are produced in co-generation.

The administrative bodies in charge of water issues, other bodies in charge of energy issues, as well as producers or suppliers, should all work under guidelines agreed to or set down by the administration.

A frequently used argument for the operation of dual purpose plants is the preference given to the production of one service, i.e. either water or electricity. The so-called 'benefit of dual purpose operation' can and should be distributed between both services in a well proportioned way, although preference has mostly been awarded to one without paying attention to the other.

2.3.6. Plant availability and lifetime

The plant availability guaranteed by manufacturers is approximately 95%, which corresponds to less than 20 days of down time per year. Although in some single cases plant availability has achieved values of up to 97%, actual plant availability is lower than the guaranteed value: between 73 and 83% for the five MSF plants in Abu Dhabi over the time period 1990–1993 [3]. It should be noted that successful long term operation of a desalination plant, and therefore also its availability, are highly dependent on its operation and the operations staff. The role of skilled personnel is of great importance.
Regarding the plant lifetime, it should be considered that the different components of the plant have different lifetimes. This explains the large range given for plant lifetimes: from 10 to 35 years for thermal processes and from 8 to 30 years for membrane processes. Membrane guaranteed lifetimes are, on average, of the order of 5 years, but lifetimes of more than 10 years have frequently been recorded.

2.3.7. Costs

The total specific costs of desalination include capital costs, energy costs, consumables (chemicals for pretreatment), membranes in the membrane process, labour and maintenance. They are largely determined by the process and the type of raw water source, but are also dependent on the fresh water quality requirements and the site conditions, e.g. the raw water intake conditions [1]. The production costs of sea water desalination (not including transport, storage and distribution) for 1 m$^3$ of fresh water produced range between 0.6 and 1.9 ECU for MSF, 0.4 and 1.4 ECU for MEE, 0.6 and 2.4 ECU for VC, and 0.5 and 2.0 ECU for RO.\textsuperscript{1} The costs of brackish water desalination are 60–70% lower than those of sea water desalination, ranging between 0.1 and 0.7 ECU for brackish water RO, and 0.2 and 0.6 ECU for ED. The energy costs can be up to 50% of the total costs.

For large distillation plants, MEE could offer a decisive economic advantage over MSF. VC, although more expensive than RO, may be adequate for small plants and in cases where the raw water conditions are not suitable for a membrane process. For large plants, MEE, MSF and sea water RO are comparable in cost, as are ED and brackish water RO.

It is estimated [1] that the total costs are likely to decrease over the next 20 years: of the order of 4–9% for thermal processes and 3–12% for membrane processes. This will primarily result from the lower investment costs of larger plants and the cheaper production costs because of a higher demand. Energy efficiency will improve only slightly and be within the already achievable ranges. There appears to be some chance of achieving larger cost reductions in MEE and RO from on-going exploration of innovations, i.e. novel heat transfer surfaces and innovative raw water pretreatment methods.

3. ENERGY SUPPLY

It is worthwhile to take a brief look at the different energy supplies for desalination, especially from the point of view of cost.

\textsuperscript{1} 1 ECU = US $1.15.
MSF and MEE use low temperature steam: 100–130°C and 70–100°C, respectively. Heat at these temperatures can be supplied as low pressure steam from a back-pressure turbine or as steam extracted from the lower states of a condenser turbine. Use of steam for power production and process heat is called co-generation. Compared with power generation only, co-generation leads to better thermal efficiency, since the waste heat that is normally dissipated to the turbine condenser is partially used for the process. To keep heat losses small, the turbine and the desalination plant are preferably situated on the same site. The efficiency of co-generation desalination plants depends on the type of power plant, the primary energy used (natural gas, oil, coal, renewable and nuclear), the configuration of the combined system and the efficiency of the desalination process. Also, the quality of the potable water produced influences the energy requirement. A measure of efficiency is the gained output ratio (GOR), which expresses the amount of water produced in tonnes per tonne of steam. At present, a typical GOR value is 8, but values of 10 and 12 have already been reached and should become state of the art in the near future.

In the case of VC and RO, coupling of the energy source with the desalination plant is simple, requiring only an electrical connection. Assuming a grid of adequate size, there is no mutual influence between the electricity generating plant and the desalination plant. Consequently, there is no need to locate the two plants on the same site. The desalination plant would normally be built as close as possible to the potable water consumer in order to minimize the water transport costs.

The choice of energy source for desalination is largely influenced by regional factors, e.g. whether the site is in a remote or densely populated area, and whether an appropriate electric grid is available. For communities without a larger electric grid but with salt water resources, dual purpose plants may be an appropriate solution, as, for example, in the Persian–Arabian Gulf. In areas where an adequate electric grid is available, such as the Mediterranean Basin, both concepts are possible: a single purpose plant for RO or VC, or a dual purpose plant for MSF and MEE.

These conclusions apply to fossil or nuclear power plants. In a study performed by the IAEA [4], fossil and nuclear plants of different size were investigated with a view to determining their feasibility and economics. The water costs were found to be in the same range. The scale effect is, however, more pronounced for nuclear plants because of the higher investment costs. This makes nuclear more attractive than fossil in the large unit range (900 MW(e)); the two energy sources have similar costs in the medium range (300–600 MW(e)), while in the 50 MW(e) range fossil plants (diesel) are more advantageous.

In the IAEA study [4], an example of the use of a nuclear plant is given. A 300 MW single purpose electricity generating nuclear power plant, coupled to an RO process and providing all the energy it produces for desalination, would supply all the potable water needs of a population centre with 5 million people (250 L per day and person). A 300 MW dual purpose nuclear plant would provide enough heat to an
MEE process desalination plant to supply 1 million people with potable water, while making 245 MW of electric energy available to the grid.

In isolated areas with appropriate renewable energy resources (e.g. wind, solar and geothermal) and low energy and water requirements, renewable energy could be used for desalination, normally as a single purpose plant. Several pilot plants are in operation with the financial support of the European Commission Non-Nuclear Energy Program.

4. COMPETITIVENESS OF THE EUROPEAN INDUSTRY

In the European Union there are a number of companies capable of designing and/or manufacturing and training operators of large, medium and small sized desalination plants. Only large scale membrane manufacturing companies are lacking in Europe.

The leading membrane manufacturers are undoubtedly companies in the USA such as Dupont, with a 23.5% share of the total market, followed by Hydranautics and Fluid Systems, with 13.9 and 10.6%, respectively, of the total capacity [1].

The plant manufacturers that have built up the biggest share of the total installed capacity since 1964 are the Japanese: four Japanese companies are among the top ten worldwide. The three European companies that are amongst the top ten are in Italy, in the UK and in France. As of 1993, European manufacturers had a market share of approximately 15%.

5. CONCLUSIONS

The desalination technology has been successfully demonstrated in the developed world from a technical, economic and commercial point of view. Technology transfer to developing countries, where the energy and water demands are growing rapidly (an estimated 2–3.3%/a between 1996 and 2015), should not be a problem. Therefore, sustainable regional development, by means of integration into present and new energy and water supply systems with a high overall quality of service to users in the context of more liberalized energy markets and efficient use of synergies, should produce a positive impact.

REFERENCES


NATIONAL PROGRAMMES
AND ACTIVITIES

(Session 2)

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DEVELOPMENT AND ACTIVITIES OF NUCLEAR SEA WATER DESALINATION IN CHINA

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Abstract

DEVELOPMENT AND ACTIVITIES OF NUCLEAR SEA WATER DESALINATION IN CHINA.

In China, 104 cities (with 200 million inhabitants), mostly located in the northern and coastal areas of the country, now face the problem of a serious shortage of fresh water resources. Because the water resources of some cities have been polluted, it has become increasingly more urgent to provide the population with potable water that meets the drinking water standards. Furthermore, a number of coastal islands are also experiencing serious shortages of fresh water. Therefore, sea water desalination has become of great interest to the Chinese Government. The eastern coastal areas are densely inhabited and economically more developed, but their energy resources are very limited. A possible solution may therefore be to develop nuclear desalination with a view to solving the problem of providing potable water to these areas.

1. WATER RESOURCES IN CHINA [1]

China is a country with water shortages. The entire population makes up 22% of the world's total, while the fresh water resources only amount to 5.8%. The per capita fresh water resources account for 27% of the world's average (see Fig. 1).

Moreover, the water resources are not evenly distributed. There are more than 500 cities in China, of which 104 suffer from serious water shortages. Most of these cities are located in the northern and coastal areas of the country, where the economy is relatively developed and the population is about 200 million. Of these cities, 20 are well developed, with a population of 30 million and per capita water resources of only 350 m$^3$/a. Therefore, the available water resources fall far short of the demand for industrial and agricultural purposes, as well as for daily household use. With population increases and economic growth, these water shortages will become ever more severe. It is therefore seen as an urgent socioeconomic task to relieve this situation, and especially to ensure that urban fresh water supplies are available in China's coastal areas. In the foreseeable future, the major solutions to this problem possibly include water conservation and recycling; urban sewage treatment; and water diversion projects.
Currently, the water tariff is about US $0.12–0.18/m³, while the production costs for constructing urban sewage treatment and water diversion projects are roughly US $0.1–0.15/m³ and US $0.3–0.48/m³, respectively. Therefore, a state subsidy is needed for such projects.

Some sea water desalination installations in China already produce fresh water, mainly for the industrial sector and for those power plants that require purified process water. The total capacity of these desalination installations is generally 37 700 m³/d, the largest individual facility producing 6235 m³/d. The sources to be treated are sea water, brackish water and urban sewage water, and the technologies include reverse osmosis (RO), multi-effect distillation (MED) and multi-stage flash (MSF), mainly introduced from the United States of America, Japan and Italy. China is also developing its own technology for this purpose, but the capacity is rather low.

At present, sea water desalinization in certain regions of China has been shown to be economically viable.

1.1. Urban water polluted areas

In some areas of China, such as the Pearl River Delta and the Yangtze River Delta, the rivers have been highly ramified, therefore the water is subject to more pollution and cannot be drunk without first being disinfected. In particular, the cadmium ion concentration in the water is very high. With the growth in the local economy, people have begun to demand better quality potable water; even though the price is higher, it still appears to be acceptable. For example, high quality water supply stations that subject fresh water to the process of filtration and disinfection have been established in some residential areas of Shanghai; the water is priced at US $25/m³. These supply stations have now been developed into potable water utilities.
1.2. Islands and islets

There is a chain of 6500 islands and islets off the coast of China where the population has long suffered from fresh water shortages. Where these occur, water has to be shipped from the nearby mainland to such islands, some of which have a population of 350 000. Shipment costs are generally about US $2.5–3/m$^3$.

2. PROSPECTS FOR NUCLEAR SEA WATER DESALINATION

The coastal areas of China are densely populated and economically more developed, but they lack both fresh water and energy resources. In China, coal is a major component of the energy supply, but the coal producing regions are generally 600–1000 km from the southeastern coastal areas. Building a railway infrastructure would need huge capital investment, and haulage costs would be very high. In addition, massive coal combustion would also cause serious environmental pollution. For these reasons, the Chinese Government has formulated a strategy for developing nuclear power in these regions. However, owing to lack of consideration of the possible connection with sea water desalination, the sites selected for the nuclear power plants are located far from the fresh water demand areas. Thus, top priority should be given to the development of safer small and medium sized nuclear reactors coupled to sea water desalination facilities.

While developing nuclear power in China, non-electric application of nuclear energy was established. In the northern cities, a significant amount of coal is consumed each year for space heating in winter. This has resulted in severe urban environmental pollution and increased pressure on the railway system. Therefore, nuclear heating reactors (NHRs) are being considered as a possible replacement for coal. Owing to the limited distances that heat can be transported, NHR sites should be located close to residential centres, and severe accident consequences should be limited to the reactor itself, without the need for evacuation. The 200 MW NHR [2] (NHR-200) designed by the Institute of Nuclear Energy Technology, Tsinghua University, Beijing, could meet such requirements. Besides providing space heating, this type of reactor could also be developed for sea water desalination by coupling it to MED. The technological process is shown in Fig. 2, and the main design parameters are given in Table I.

Furthermore, the heat production costs of the NHR-200 have been shown to be economically viable compared with the technology of other major energy sources in China, e.g. coal; they are 25–45% lower than those of coal boilers, and more or less the same as those of coal generation.

It is assumed that the NHR-200 will be constructed and operated in China, with basic investment costs of US $360/kW(th); the payback period is 20 years, the
FIG. 2. Schematic diagram of the NHR-200 nuclear desalination plant.
TABLE I. MAIN DESIGN PARAMETERS OF THE NHR-200 COUPLED TO MED

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactor power</td>
<td>200 MW(th)</td>
</tr>
<tr>
<td>Outlet/inlet temperature of core</td>
<td>213/154°C</td>
</tr>
<tr>
<td>Outlet/inlet temperature of intermediate circuit</td>
<td>163/135°C</td>
</tr>
<tr>
<td>Outlet steam temperature</td>
<td>130°C</td>
</tr>
<tr>
<td>Maximum temperature of the brine water</td>
<td>120°C</td>
</tr>
<tr>
<td>Unit capacity of the MED process</td>
<td>48 000 m³/d</td>
</tr>
<tr>
<td>No. of units</td>
<td>4</td>
</tr>
<tr>
<td>Gained output ratio</td>
<td>20.76</td>
</tr>
<tr>
<td>Maximum product water</td>
<td>156 000 m³/d</td>
</tr>
<tr>
<td>Water production costs</td>
<td>US $0.7–1.0/m³</td>
</tr>
</tbody>
</table>

discount rates are 5, 8 and 12%, and the heating costs US $2.16, 2.5 and 3/GJ, respectively. It is also assumed that the technology for MED desalination will be imported from abroad but that the equipment will be manufactured in China. Thus, the investment costs for a MED desalination plant could be reduced by 30%. The water production costs of the NHR-200 coupled to MED are estimated to be US $0.7–1.0/m³, making them economically competitive with the options of fossil energy MED and RO but more costly than most of the urban sewage treatment and fresh water diversion projects in China. Therefore, large scale development is impossible in the near future. However, in certain regions of China such development appears to be economically viable; the cost comparisons are given in Fig. 3.

*FIG. 3. Water production cost comparisons (US $/m³).*
3. DEVELOPMENT AND ACTIVITIES OF NUCLEAR SEA WATER DESALINATION

3.1. Nuclear sea water desalination experiment [3]

In 1989, a 5 MW(th) test heating reactor (HR-5), developed by the Institute of Nuclear Energy Technology was put into operation. The design of the HR-5 is similar to that of the NHR-200. Both are vessel type LWRs with an integrated primary loop, full natural circulation and passive residual heat removal. The HR-5 has three circuits, the pressure of the intermediate circuit being higher than that of the primary loop to avoid radiation leakage and contamination of the third circuit. The operating pressure in the primary loop is 2.5 MPa, and the outlet temperature is 213°C. The HR-5 has been successfully operated for six winter seasons, with an availability factor of 98%.

A series of experiments to provide safe performance, including accident transit without scram of the heat load loss, has been carried out, and the HR-5 has demonstrated satisfactory safety and practicability.

The HR-5 is coupled to the MED process, with a maximum brine temperature of 120°C, through an evaporator connected to the third circuit for thermal and hydraulic performance experiments; the experimental water flow is 240 t/d.

3.2. Demonstration of the NHR-200

The Chinese Government has decided to build a demonstration NHR-200 in Daqiang, a booming town in the northernmost Heilongjiang Province, to provide space heating for local residents. The National Nuclear Safety Administration of China has completed evaluation of the preliminary safety analysis report, and issued a construction licence to the owner, who plans to start the project in 1997. Operation of this reactor will demonstrate the use of nuclear power for urban space heating during winter, and will also provide valuable experience on its economic performance for sea water desalination.

3.3. Application of the HTGR

The HTGR was chosen for its favourable safety features and its ability to provide high reactor outlet coolant temperatures for efficient power generation and high quality process heating for industrial applications. The initial modular HTGR development activity within the Chinese High Technology Programme, a 10 MW helium cooled test reactor, is currently under construction on the site of the Institute of Nuclear Energy Technology to the northwest of Beijing. This plant is a pebble bed
helium cooled reactor, with initial criticality anticipated in 1999. There will be two phases of high temperature heat utilization from the HTGR-10. The first will utilize a reactor outlet temperature of 700°C, with a steam generator providing steam for a steam turbine cycle that operates on an electrical/heat co-generation basis. The second is planned for a core outlet temperature of 900°C to investigate a steam cycle/gas turbine combined cycle system, with the gas turbine and the steam cycle being independently run in parallel with the secondary side of the plant. The potential uses of the HTGR for non-electric applications in China also include sea water desalination by co-generation.

Sea water desalination coupled to HTGR co-generation could show the following advantages: (1) favourable safety features; (2) optimization of hybrid desalination; (3) a small unit of 200 MW(th) for economy of scale because of the modular design.

3.4. Feasibility study of the nuclear sea water desalination projects

As mentioned previously, in certain more economically advanced areas with water shortages, the population has begun to press for the supply of high quality drinking water, and can afford the higher price.

Because of this situation, the feasibility study on some nuclear sea water desalination projects is now under way to investigate the market potential and the application prospects. For example, Changdao County, an island near the northern coast of Shandong Peninsula, has proposed that a pilot small scale 5 MW heating reactor be built with a water production capacity of 3500 m³/d for purposes of technical demonstration, training and the supply of water to local residents.

Dalian, a very important port on the Liaodong Peninsula that has long suffered from fresh water shortages, is planning to build a demonstration project, with a capacity of 150 000 m³/d, based on the technology of the NHR-200 coupled to the MED process. At present, this project is at the pre-feasibility study stage.

3.5. R&D of sea water desalination technology

Some research institutes in China have been working on the development of technology for sea water desalination, including RO and MED, and are exploring the possibility of technology transfer from foreign equipment vendors.

REFERENCES


Abstract

NATIONAL PROGRAMMES AND ACTIVITIES ON NUCLEAR DESALINATION IN INDIA.

India receives about 4000 km\(^3\) of rain annually, but nearly three-quarters is lost as runoff to the sea and only one-fourth is stored as ground and surface water sources. Current water consumption for irrigation and domestic and industrial needs is about 750 km\(^3\), but this is likely to increase with rapid industrialization and urbanization. Many parts of the country, however, face chronic water shortages because of scanty rains. These include coastal Tamil Nadu, Andhra Pradesh, Saurashtra (Gujarat) and western Rajasthan. Desalination and water reuse has been suggested to augment sources in the coastal areas where water is scarce. The desalination plants are generally located at thermal power stations because steam and electric power are required. The thermal power stations in these areas obtain coal from far distances. Nuclear power coupled to desalination plants is therefore considered to be more useful. The Bhabha Atomic Research Centre has been engaged in R&D work on desalination for the past 15–20 years. The salient details of these activities are discussed. A number of pilot plants have been designed, manufactured and operated at the centre over the past few years. Utilizing the design and operational experience of these plants, a 6300 m\(^3/d\) combined multi-stage flash (MSF)–reverse osmosis (RO) nuclear desalination demonstration plant has been designed, and it is proposed that it be set up at the PHWR, Madras Atomic Power Station, Kalpakkam, Tamil Nadu. The combined MSF–RO plant has a number of advantages: (1) part of the high purity product water from the MSF plant will be used as makeup water for the power station; (2) blending of the product water from the RO and MSF plants will provide requisite quality drinking water; (3) during power station shutdown, the RO plant will continue to be operated in order to provide the minimum quantity of water essential for drinking purposes; and (4) the reject stream of the RO plant will be utilized as part of the feed for the MSF plant. The layout and scheme of the desalination plant are presented and discussed in detail. The process flow sheets of the MSF and RO plants are discussed and their technical specifications presented. Mention is also made of the progress being made with project activities.

1. INTRODUCTION

Large coastal areas of India, especially in the States of Tamil Nadu and Gujarat, and a few inland areas, in Rajasthan and Andhra Pradesh (Fig. 1), are experiencing a
FIG. 1. Map of India showing the desalination and treatment plants, and highlighting the water scarce areas.
severe shortage of potable water. Chennai City has faced severe shortages of water on many occasions because of monsoon failure. Even for the most essential needs, water has had to be transported long distances using tankers, and at an exorbitant cost. The Kutch and Saurashtra regions of Gujarat and part of western Rajasthan face chronic water shortages.

Conventional water supply schemes (dams, lakes, canals, piped water) involve a huge capital outlay (US $1–2 × 10^9) for water supplies of 9000–22 500 m^3/d. Further, such schemes lead to the submergence of vast land areas, the uprooting of large populations and the destruction of forests. In general, there is strong public opinion against such schemes.

Desalination of sea water is one of the methods that can be used to enhance the availability of good quality water. A number of private companies in Tamil Nadu and Gujarat have already set up or are considering sea water desalination plants through imports. It has been estimated that a desalination capacity of 150 000–200 000 m^3/d is immediately required in the States of Tamil Nadu and Gujarat.

For economic reasons, large desalination plants are generally coupled to large power plants. Conventional power plants using fossil fuels emit a large amount of gaseous pollutants and fly ash. Further, fossil fuels (coal, oil, etc.) are needed for the important chemical and metallurgical industries in the country. It would be unwise to consume these resources for large scale power generation or desalination. Therefore, if large scale sea water desalination is to be planned, it should be based on the coupling of desalination plants to nuclear power plants, since sufficient quantities of nuclear fuel are available indigenously. This would avoid the additional requirement of fossil fuels for desalination plants. Also, the emission of greenhouse gases would be restricted.

2. R&D WORK ON DESALINATION

The Bhabha Atomic Research Centre (BARC) has been conducting R&D work in the field of evaporative and membrane desalination technologies for more than a decade. A 425 m^3/d multi-stage flash (MSF) plant has been designed, manufactured, installed and successfully operated. The plant uses recirculation brine flow through 30 heat recovery stages and three heat rejection stages. The top brine temperature is around 121°C with blowdown at 44°C. It is based on a long tube design, for ease of fabrication, and utilizes acid dosing to control alkaline scale. A performance ratio of 8 was considered for the design of this plant. The flash chambers are made of carbon steel and the heat transfer tubes of aluminium brass and cupronickel (90:10).

A number of reverse osmosis (RO) demonstration plants have been set up in rural areas to provide safe drinking water from the available brackish water sources. A few plants have also been set up for the treatment of industrial effluents and water
reuse, as well as a pilot plant for sea water RO desalination. Thus, sufficient experience has been accumulated in recent years to set up commercial RO desalination plants based on the data obtained from these plants.

3. 6300 m³/d COMBINED MSF–RO PLANT AT THE MADRAS ATOMIC POWER STATION (MAPS), KALPAKKAM

The combined MSF–RO plant has a number of advantages: (1) part of the high purity product water from the MSF plant will be used as makeup water for the power station; (2) blending of the product water from the RO and MSF plants will provide requisite quality drinking water; (3) during power station shutdown, the RO plant will continue to be operated in order to provide the minimum quantity of water essential for drinking purposes; and (4) the reject stream of the RO plant will be utilized as part of the feed for the MSF plant. Figure 2 provides a schematic flow diagram of the proposed nuclear desalination demonstration plant. Steam will be taken from a suitable
tapping point and lowered to the required pressure for use in the brine heater of the MSF plant. Steam for the ejectors will be taken from a separate source to avoid contamination. The sea water pressure inside the tube of the brine heater of the plant will be slightly higher than that of the steam pressure to rule out any possibility of contamination. The MSF plant will use the process sea water outfall stream as feed, since there is a constraint on the amount of sea water that can be taken from the inlet stream of the reactor. For the RO plant it is proposed that condenser cooling sea water be used as feed, at a temperature of around 35–36°C. This will result in a higher permeate output than at ambient temperature operation. An energy recovery system will be deployed for the reject stream of sea water (at high pressure) to reduce the energy consumption of the RO plant. The total energy (including steam and power) used for the desalination plant will be around 4 MW(e).

3.1. MSF plant (4500 m³/d)

The technical specifications of the 4500 m³/d MSF plant are given in Table I, and the process flow sheet in Fig. 3. The capital investment for this plant has been estimated, taking into consideration the latest manufacturing costs and those for equipment and materials, including piping, the civil and electrical infrastructures, and

<table>
<thead>
<tr>
<th>TABLE I. TECHNICAL SPECIFICATIONS OF THE 4500 m³/d MSF PLANT</th>
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<tbody>
<tr>
<td>(A) Product water output</td>
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<tr>
<td>(B) Product water salt content</td>
</tr>
<tr>
<td>Sea water requirements</td>
</tr>
<tr>
<td>(A) Total (cooling)</td>
</tr>
<tr>
<td>(B) Makeup feed (part of A)</td>
</tr>
<tr>
<td>Maximum recirculation brine temperature</td>
</tr>
<tr>
<td>Blowdown temperature</td>
</tr>
<tr>
<td>Concentration ratio of blowdown brine</td>
</tr>
<tr>
<td>Steam consumption</td>
</tr>
<tr>
<td>(A) Heating in the brine heater</td>
</tr>
<tr>
<td>(B) Steam jet ejectors</td>
</tr>
<tr>
<td>Performance ratio (kg water production per kg steam input to the brine heater)</td>
</tr>
<tr>
<td>Power consumption</td>
</tr>
</tbody>
</table>
instrumentation. In India, the cost of steam is high because of the high fuel costs, therefore it is desirable to achieve a higher performance ratio. This requires a larger heat transfer area, adding to the capital investment. Taking into consideration the relatively low manufacturing costs in India, the increased cost for a larger heat transfer area could be absorbed. It should be noted that the capital costs for this plant are about 25–30% lower than international costs.

The makeup sea water is first sent to a chemical pretreatment system, where acid treatment is administered to suppress the formation of alkaline scales inside the tubes of the heat transfer equipment. It is then de-aerated to reduce the dissolved oxygen and carbon dioxide in order to minimize corrosion and heat transfer. The makeup feed is mixed with recycled brine and preheated at the heat recovery stages. It is further heated in the brine heater and then subjected to a flashing process at the heat recovery and heat rejection stages, which are maintained at successively lower pressures. The vapour produced during flashing gives its latent heat to the incoming brine flowing inside the condenser tubes at the heat recovery stage. The condensate is collected as product water.

3.2. RO plant (1800 m³/d)

The technical specifications of the 1800 m³/d RO plant are given in Table II. The plant is based on advanced thin film composite membranes that are capable of desalting sea water to produce less than 500 ppm total dissolved solids (TDS) product
water. These membranes can withstand a temperature of 36–38°C during their entire life (3–4 years). An energy recovery system is to be installed in the reject stream to recover energy so that the overall energy consumption is reduced by 30%. The permeate water (500–700 ppm TDS obtained from the RO plant) will be blended with the product water from the MSF plant to give an overall TDS of 250 ppm, which is suitable for drinking purposes.

The flow sheet of the RO plant is shown in Fig. 4. Sea water normally contains about 35 000 ppm dissolved solids besides suspended and biological matter. Shock injection of chlorine is carried out to maintain the residual chlorine at a level of 2–3 ppm to prevent marine growth. It is passed through a clarifier and a pressure sand filter to remove the suspension and colloidal particles from the sea water, and then through activated carbon filters to remove the organic materials. Dechlorination of the sea water is achieved using NaHSO₃. Acid dosing is done to minimize carbonate scaling. Cartridge filters are installed in line to remove the fine particles (5 μm and above) before they reach the high pressure pumps and RO modules. The RO system pumps the pretreated sea water (at about 50–70 bar) through RO modules. Part of the water (30–40%) permeates through the membrane as product water of potable quality. The remaining concentrated sea water emerges as water to the sea. Part of the energy is recovered from the reject sea water by the energy recovery turbine, reducing the specific energy consumption. After degassing, the product water is dosed with soda ash or lime to adjust the pH.

<table>
<thead>
<tr>
<th>TABLE II. TECHNICAL SPECIFICATIONS OF THE 1800 m³/d RO PLANT</th>
</tr>
</thead>
<tbody>
<tr>
<td>(A) Product water output</td>
</tr>
<tr>
<td>(B) Product water quality</td>
</tr>
<tr>
<td>(A) Sea water requirements</td>
</tr>
<tr>
<td>(B) Sea water TDS</td>
</tr>
<tr>
<td>% recovery</td>
</tr>
<tr>
<td>Membrane element</td>
</tr>
<tr>
<td>Average salt rejection</td>
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<tr>
<td>Operating pressure</td>
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<tr>
<td>Operating temperature</td>
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<tr>
<td>Energy consumption</td>
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</table>
4. SCHEDULE AND PROGRESS OF WORK ON THE PROJECT

A project site has been selected and a plot (200 × 200 m²) earmarked in the northeastern corner adjoining MAPS at Kalpakkam. It was decided to couple the desalination plant to the 2 × 170 MW(e) PHWR at the power station. Arrangements will be made to tap the required amount of steam for MSF from both the reactor systems to ensure continuous plant operation. Provision will be made to regulate the steam supply and to isolate the system as and when required. The sea water requirements for MSF will be met from the seal wells of the process sea water system of MAPS, where the temperature is about 3°C higher than the ambient temperature of the sea water. The feed sea water for RO will be taken from the condenser seal well of this power plant. The electric power requirements will be met by installing a transformer (33 kV–415 V) for power supply (415 V) to the desalination plant.

The total costs of the plant, including the civil infrastructures at the site, will be approximately US $8 × 10^6, which will be met from our own resources. Construction of the plant is likely to commence in January 1998 and to be completed by the year 2000.
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THE REPUBLIC OF KOREA’S R&D PROGRAMME AND ACTIVITIES FOR NUCLEAR DESALINATION

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Abstract

THE REPUBLIC OF KOREA’S R&D PROGRAMME AND ACTIVITIES FOR NUCLEAR DESALINATION.

Since its introduction in the late 1970s, nuclear energy has been one of the major sources of energy required to support the ambitious and successful economic development and industrialization of the Republic of Korea. Naturally, a strong national desire to achieve self-reliance in nuclear energy technology has developed, and various integrated efforts have been pursued intensively in the domestic nuclear field. The long term national effort has resulted in the firm establishment of associated technologies. These technologies will be further advanced and improved through related R&D programmes and through application to various areas other than electricity generation. Among the various applications of nuclear energy technology, energy supply for sea water desalination has received much favourable attention. Fresh water shortage problems are occurring in certain regions of the country, some of which are expected to become more severe from around the year 2006 unless well planned countermeasures are taken. When combined, the firmly established nuclear energy technology and the desalination technology could be a promising solution to the expected water shortage problems. A feasibility survey on nuclear desalination was carried out, resulting in the establishment of a special R&D programme that started in November 1996. Major efforts are being concentrated on developing a 330 MW(th) co-generation reactor and associated systems to be used for the desalination of sea water for demonstration purposes. An integrated nuclear desalination system will also be developed. The programme will continue for 5 years, until the basic design and development are completed. A summary is given of the status and development programme for nuclear energy technology, the prospects for fresh water demand and supply, the desalination technology established in the Republic of Korea, the specific R&D programme for developing a 330 MW(th) nuclear co-generation reactor, and some related R&D activities that have already been performed.

1. INTRODUCTION

A natural consequence of the advances and improvements made in the national economy is the increase in energy demands. Lack of natural energy resources in the Republic of Korea has led to the utilization of nuclear energy for industrial
development. Since the successful introduction of nuclear energy in the late 1970s, nuclear energy has been acknowledged as the most important energy resource in the country. This high regard for nuclear energy emanated, in part, as a result of the long term national effort made to achieve self-reliance in nuclear energy technology.

The prime objective for introducing nuclear technology in the Republic of Korea was to generate electricity, therefore use of nuclear energy and its associated technology has focused mainly on this area. However, nuclear power generation is not the sole area in which nuclear energy technology can be applied, and much interest has been shown in a wide range of applications to various non-electric areas in order to promote the peaceful uses of nuclear energy and to advance the technology. Well established nuclear associated technology and infrastructures now provide firm and sufficient bases to realize the various interests and requirements of nuclear application.

The Republic of Korea used to have abundant fresh natural water resources, but these have continued to dwindle for various reasons, including drastic increases in water usage as a result of rapid industrialization, an increase in population, the pollution of natural water and the problem of drought. Localized regions have already faced severe shortages of potable and process water supplies. The water shortage problems are expected to become a major issue in the near future unless well planned countermeasures are taken. Of these countermeasures, sea water desalination using nuclear energy presents the most favourable solution. A national R&D programme to develop a nuclear co-generation reactor and associated systems for sea water desalination has been established and is currently under way in response to the reasons and motives for introducing nuclear desalination, as well as the gradually increasing interest being shown in this technology.

The paper presents the on-going R&D programme and activities, together with a review of nuclear energy and desalination technology, the water supply and demand environment, and the related R&D activities that have already been performed.

2. NUCLEAR ENERGY TECHNOLOGY

Since its first implementation in the Republic of Korea, nuclear energy has become an essential energy source for the development of the country, and its demand continues to grow. In the light of heavy dependence on the import market for the nation’s energy resources, a strong desire has developed within the government and nuclear societies to achieve self-reliance in nuclear energy technology. To realize this, much effort has been made to localize nuclear energy technology and to enhance the design and manufacture of nuclear fuel, the nuclear steam supply system, the balance of plant (BOP), and the nuclear components and equipment. Initially, these efforts were pursued in the form of a joint design through which successful technology
transfer from the reference technology supplier was accomplished, followed by independent design efforts. In parallel with the assimilation of this technology, various independent R&D programmes have also been carried out to further advance and improve these technologies. All these endeavours have resulted in successfully achieving the initial goal of self-reliance in nuclear technology. In 1995, the level of self-reliant technology for large scale PWR system designs was assessed as 95%. Further efforts will be made to enhance and improve both the capability and the technology. Considering the achievements attained so far, the final goal of fully establishing the country's own capability is deemed to be reachable within the near future. Figure 1 summarizes the strategy for developing nuclear power technology in the Republic of Korea.

Well established nuclear energy technology and its infrastructures provide a firm base for advancing towards the application of nuclear technology to areas other than the generation of electricity. As shown in Fig. 1, development of the nuclear reactor and its associated technology for co-generation purposes will be pursued, while efforts will continue to be made to improve the power reactor technology. The primary purpose of the co-generation reactor is to provide energy to the sea water desalination system and to produce energy. Since this reactor is based on PWR technology, the currently available PWR technology in the country can and will be widely utilized. The R&D programme for developing the co-generation reactor is described in detail in Section 5.

FIG. 1. Strategy for developing nuclear power technology in the Republic of Korea.
3. WATER DEMAND AND SUPPLY

The country used to have an abundance of natural fresh water resources, with sufficient water from rivers, reservoirs and precipitation to meet the demand for potable water, and for agricultural and industrial usage. Annual precipitation, which is the major fresh water resource, is still 1.3 times higher than the world’s average. However, because of the wide variations in water effluence from the rivers, as well as in the regional and seasonal precipitation rates, managing the water reservoirs is a very difficult task. As a result, only 24% of the annual precipitation is available for use. Furthermore, the increase in population and industrialization has caused severe pollution of fresh water resources such as lakes and rivers, resulting in a large reduction in the usable water resources. Another major factor that has caused difficulties in water supply and management is the severe drought situation that has arisen owing to the abnormal weather which the country has experienced over the past several years. Some localized regions are currently faced with severe shortages of potable and process water supplies. Notwithstanding the water problem, population and industry, which are the main sources of water demand, are expected to increase continuously. It is foreseen that, if no action is taken, all these social and environmental conditions will definitely cause a severe fresh water shortage problem within a decade. Table I shows the prospects for the water demand and supply until the year 2011 [1].

The government is considering various measures to cope with the prospect of the water supply deficit shown in Table I. Of these, exploitation of underground water and construction of multi-purpose dams are considered to be favourable as practical means. Although small scale exploitation of underground water will be helpful locally, large scale exploitation is limited because this would cause other geological and environmental problems. Hence, the option of exploiting underground water should be limited to emergency use only. A more practical and effective way of dealing with the water shortage problem would be to construct multi-purpose dams. The Republic of Korea is currently in the process of constructing several dams, and many more are planned. According to these plans, the government has ensured that future

<table>
<thead>
<tr>
<th>Year</th>
<th>1994</th>
<th>2001</th>
<th>2006</th>
<th>2011</th>
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<tbody>
<tr>
<td>Water demand</td>
<td>29 901</td>
<td>33 640</td>
<td>34 991</td>
<td>36 652</td>
</tr>
<tr>
<td>Water supply</td>
<td>32 219</td>
<td>34 290</td>
<td>34 541</td>
<td>34 655</td>
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<tr>
<td>Deficit</td>
<td>—</td>
<td>—</td>
<td>450</td>
<td>1997</td>
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water demands will be met, with a reliable level of reserve water supplies for a certain
time period. Continuous construction of dams may, however, be impeded by factors
such as the difficulty in finding sites, the long construction period and opposition by
residents against the loss of their land or environment. Thus, other countermeasures
are also under consideration. These include sea water desalination, artificial rain,
improvement in the weather forecast capability, active water quality control of rivers
and reservoirs, etc. Since the Republic of Korea is surrounded by the sea, and thus has
a plentiful supply of sea water, the sea water desalination approach is currently
receiving the most favour for the long term security of fresh water resources.

4. DESALINATION STATUS AND TECHNOLOGY

Rapid industrialization, the increase in population and its urbanization are con­
sidered to be the key factors causing the fresh water shortage problems in the coun­
try. At present, these problems are limited to certain regions, but it is expected that
they will expand to the national scale and become much more severe in the near future
unless some countermeasures are taken. However, some problems resulting from
adverse social environmental changes can be mitigated, regulated or even overcome
through human endeavours, for example, the precautions being taken against the
expected water shortage problems. The sea water desalination approach is one of the
more attractive ways of overcoming the expected fresh water shortage problems of
the country.

Industry recognized the necessity for desalination early on because many indus­
trial complexes have to produce their own process water. In 1993, it was reported that
43 desalination plants provide process water to industrial complexes [2]. The reverse
osmosis (RO) technology is widely employed for the desalination process of these
plants. They do not, however, desalt the sea water directly, but produce the required
process water from brackish or low quality groundwater. The capacity of most of these
plants is very low, mostly around 200 t/h, but the total combined capacity reaches
around 175 000 t/d. The largest plant is located at the Daesan Oil Chemistry complex,
with a capacity of about 70 000 t/d. This plant takes brackish water from a lake and
produces water for industrial purposes using the RO process. As yet, no desalination
plant that produces fresh water directly from sea water has been constructed or
operated. There are a few plans to construct sea water desalination plants, on a very
small scale, to provide fresh water to localized regions such as an island. However,
such cases are considered exceptional. No firm plan for constructing a large scale sea
water desalination plant has been established either by the government or by industry.

The Republic of Korea is one of the countries that has very advanced and well
established technologies for certain desalination processes. For example, the Korea
Heavy Industries and Construction Company (KHIC) is a world renowned
desalination technology company with design, engineering and manufacturing capabilities. A few other heavy industries are also striving to fully build up the desalination technology. So far, these industries have concentrated on the export market because there has been no domestic demand.

The technology establishment was started in the early 1970s with technical cooperation and technology transfer from advanced overseas industries. After establishing the technology base, domestic industry has made a tremendous effort to further develop and advance the associated technology, which has resulted in the present highly regarded capability. Several R&D programmes and efforts with the same aim are being pursued by the relevant research institutes, universities and industries. From the industrial point of view, industry has now reached the stage of developing a technology that is distinct from other overseas technologies. Three major desalination technologies, multi-stage flash (MSF), multi-effect distillation (MED) and RO, are readily available from domestic industries. The associated industries are now considering technology transfer to countries willing and ready for co-operation. This advanced domestic technology base in the desalination area is one more favourable incentive for the country to move ahead with nuclear sea water desalination. The technology will be ready for implementation when the nation sets up a firm plan.

5. R&D ACTIVITIES FOR NUCLEAR DESALINATION

As described in previous sections, the environment and the required technologies are considered to be ready for implementing the development of nuclear sea water desalination. Full recognition of the necessity for nuclear desalination remains the precondition for advancing its development. However, even in such a case, the major factor that should be taken into consideration is the energy source, i.e. the nuclear reactor. All the nuclear reactors currently in operation, under construction or in the planning stage are large scale power plants utilized solely for generating electricity. Taking energy from these nuclear reactors for use in non-electric generation purposes is currently considered to be uneconomical. For the purpose of demonstrating nuclear desalination, it is considered better to develop a small or medium sized co-generation nuclear reactor so that integration of the reactor with the desalination plant is easier. This approach is consistent with the intention and willingness of the nation to expand the peaceful uses of nuclear energy and to advance the technology associated with a nuclear reactor.

In response to the reasons, backgrounds and motives laid out in previous sections, an R&D programme to develop a nuclear co-generation reactor for the purpose of demonstrating sea water desalination using nuclear energy has been established and is currently under way. Some R&D activities for developing the technology for a small co-generation reactor have been carried out since the late 1980s. In the
following subsections a brief description is given of the relevant R&D activities previously carried out and the current on-going R&D programmes.

5.1. Design technology for a co-generation reactor

This R&D activity was performed in 1987 with the purpose of studying the technical feasibility of understanding and developing the technology associated with a 50 MW(th) co-generation reactor. The programme was carried out jointly by the Korea Atomic Energy Research Institute (KAERI), the Korea Electric Power Corporation (KEPCO) and the Korea Electric Power Company (KOPEC). To investigate the required design technology and reactor concepts, the SECURE-P(PIUS) reactor was chosen as the reference conceptual design. Along with various evaluations of the design and safety concepts of the SECURE-P reactor, a wide range of investigations were carried out on the development status and technologies of a similar advanced reactor. These investigations and evaluations concluded with the identification of numerous advanced design features and technologies that had to be further studied and developed with a view to their implementation in a small co-generation reactor. This study also recommended the key design and safety technologies that should be considered in developing a practical advanced co-generation reactor.

5.2. A nuclear district heating reactor

In 1990, a wide range of preliminary studies were carried out on the prospects and development status of nuclear district heating reactors; these continued into 1991. The R&D programme aimed at establishing a preliminary design concept for a 10 MW(th) nuclear district heating reactor and at studying the techno-economic feasibility of developing a nuclear district heating reactor with advanced design features such as passive and inherent safety concepts. Along with economic evaluations, the concept of a pool type reactor and its associated technologies was studied and evaluated to establish a reference reactor for development. This study concluded by identifying numerous R&D activities relating to the environmental and social safety goals of the nuclear district heating reactor. It also recommended further R&D efforts to develop a nuclear reactor from which heat is utilized.

5.3. R&D of a nuclear co-generation reactor for sea water desalination

In 1995, KAERI carried out an in-depth survey on the feasibility of developing a demonstration co-generation reactor for sea water desalination. The survey led to the establishment of a programme to develop a 330 MW(th) reactor with integral configuration of its major components. This capacity was chosen under the assumption...
that potable water and electricity would be provided to a region with a population of approximately 100,000.

The initial concept for the integrated nuclear desalination system coupled to this reactor (a water production rate of about 40,000 m$^3$/d using the MSF system and the generation of approximately 100 MW(e) of electricity) is being considered. The water production rate is calculated by assuming a daily water demand of 400 L per person. The plant efficiency for electricity generation is about 30%, which is slightly lower than the efficiency typical of commercial nuclear power plants. The MSF design results in lower electricity generation because some heat (in the form of steam, which is normally fully expanded in the power plants) is extracted from the turbine and passed on to the desalination system. In addition, about 8 MW(e) of the 100 MW(e) electricity produced will be used to power the pumps used in the desalination system of MSF design. The remaining electricity will be sent to the grid, or used directly in the region. Table II summarizes the pre-design information on the integrated nuclear desalination system.

Taking into consideration the previous R&D results and recommendations, and concentrating on the implementation of passive and inherent safety technologies to enhance reactor safety and its reliability, the reactor concept was determined to be a system integrated reactor, i.e. an integral reactor. Some of these technologies have been studied and partly developed through the R&D programme for developing advanced reactor technology. The reactor concepts under development, the technologies to be implemented and other associated R&D activities have been described in Ref. [3].

This reactor development programme was started in November 1996 as a special R&D programme with the financial support of the government. Although it focuses mainly on the reactor and its related system development and design, the relevant design for the desalination systems will also be produced on the basis of current well advanced technologies. As shown in Fig. 2, the programme consists of three phases: the conceptual design phase (1996–1999), the basic design phase (1999–2002) and the

<table>
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<th>TABLE II. PRE-DESIGN INFORMATION OF THE INTEGRATED NUCLEAR DESALINATION SYSTEM (330 MW(th)) AND THE MSF PROCESS</th>
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<tbody>
<tr>
<td><strong>Pre-design information</strong></td>
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<tr>
<td>Reactor thermal output</td>
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<td>Desalination process</td>
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<td>Water production</td>
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<td>Electricity production</td>
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<td>Efficiency</td>
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<tr>
<td>Electricity to the MSF system</td>
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<tr>
<td>Electricity to the grid or for direct utilization</td>
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detailed design and construction phase. The application for licensing certification is planned to be submitted after completion of the basic design of the reactor and its associated systems. However, construction of a demonstration plant has not yet been officially decided upon, because firm consensus from society as well as industrial, social and environmental factors have to be determined beforehand. The development and design of the integrated nuclear desalination system will be carried out jointly by KAERI and a consortium of domestic industries. KAERI is responsible for programme management and the development and design of the nuclear reactor, the nuclear fuel and the related technologies. Nuclear industries will be involved in the programme for the development and design of the plant systems, including the desalination systems. Furthermore, as a way of easing and resolving any licensing or regulatory issue that may be raised on the new concepts of a nuclear co-generation reactor and nuclear desalination systems, the licensing body, the Korea Institute of Nuclear Safety (KINS), has participated in the programme from the early stages of the design phase. The licensing body will also develop the relevant rules and regulations, as well as licensing guidelines for the integral reactor, through an independent programme. The overall programme organization is shown in Fig. 3. This R&D programme, which is currently under way as a special project, will become one of the 32 second phase, long term national R&D programmes for developing nuclear technology, starting in July 1997. First phase programmes have been carried out over the past 5 years and will be completed just before the start of the second phase.

International co-operation also plays a significant role in this R&D programme. Besides technical co-operation with a foreign country for jointly developing the
design concept for an integral reactor, the Republic of Korea has also been actively involved in IAEA programmes for sea water desalination using nuclear energy, e.g. the Options Identification Programme, performed in 1995 and 1996, and other related programmes currently in progress. Further international co-operation on the development and implementation of nuclear sea water desalination within the framework of this currently on-going programme will also be considered. The latter programme is open to involvement or co-operation from any interested country and/or overseas organization, which is likely to result in mutually fruitful benefits.
6. SUMMARY AND CONCLUSIONS

Energy is an essential element of a nation's economy and industrial development, including the betterment of human life. Fresh water is another essential element. Severe global fresh water shortages are expected to occur in the near future because of the social and environmental changes taking place, e.g. the increase in population, industrialization, weather anomalies and several other artificial factors. The Republic of Korea is also expected to be in a similar situation and is already facing fresh water shortages in some regions. As a way of resolving this problem and preparing for such a prospect, interest in producing fresh water from sea water has gradually increased. The country is well known for actively utilizing and advancing nuclear energy and its technology. Furthermore, it is interested in expanding the application of nuclear energy and its technology with a view to contributing towards industrial advancement. Application of nuclear energy to sea water desalination is one such field and has become an area of particular interest. The firmly established nuclear energy technology, the associated infrastructures and the desalination technology provide a favourable and strong motive for moving ahead with nuclear sea water desalination.

The gradually increasing level of interest in the application of nuclear energy to sea water desalination has led to the establishment of a development programme for a reactor to supply energy to the sea water desalination system. In response to these interests, motives and momenta, a special national R&D programme started in November 1996 to develop a nuclear co-generation reactor for sea water desalination with the financial support of the government. The objective of this programme is to complete the basic design of the reactor and the associated plant systems, including the desalination system, by the year 2001. Once development is completed and the construction plan established, the demonstration project for desalination is expected to follow. The success of the programme will open a new era for nuclear desalination in the Republic of Korea and will help to solve the water shortage problems faced in the future. The programme is open for participation by any interested country or organization from abroad, with high expectations for the mutual benefits that will accrue.

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APPLICATION OF NUCLEAR REACTORS FOR SEA WATER DESALINATION IN THE RUSSIAN FEDERATION

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Abstract
APPLICATION OF NUCLEAR REACTORS FOR SEA WATER DESALINATION IN THE RUSSIAN FEDERATION.

A brief description is given of the results of work carried out in the Russian Federation on the technical and economic aspects of the application and practical implementation of sea water desalination using a nuclear reactor as the energy source.

1. INTRODUCTION

The rising threat of an acute deficit of fresh water in many regions of the world forced many countries in the mid-1950s to start an intensive search for economically acceptable ways of producing large amounts of fresh water through desalination of the saline and brackish waters available, primarily sea water. The former USSR was among these countries.
In the late 1950s, the main force behind the launching in the former USSR of R&D work aimed at identifying a rational approach towards sea water desalination was the construction of a large industrial complex and the City of Shevchenko on the Mangyshlak Peninsula, which is practically an arid desert located on the East coast of the Caspian Sea.

Development of the plentiful natural resources of this western region of Kazakhstan could only take place if a reliable fresh water supply was available, a problem that was resolved successfully. Within a comparatively short period of time, the Mangyshlak Energy Production Complex (now the Mangyshlak Atomic Energy Complex) (MAEC) was built in Shevchenko (now Aktau, Kazakhstan). This multipurpose facility ensures supplies of electricity, heat and fresh water for industry and municipal consumers. The MAEC comprises a fossil fuel fired power plant and the sodium cooled fast nuclear reactor BN-350, with large sea water distillation desalination facilities (about $150 \times 10^3$ m$^3$/d) coupled to the two energy sources.

Construction of the energy production and desalination facility employing the nuclear reactors in Shevchenko was preceded by a feasibility study, and a comparison was made of the various types of water supply of this prospective industrial region.

At that time, the former USSR had gained essential experience in the transportation of large amounts of water over long distances (hundreds and even thousands of kilometres) using canals. In such a way, the Karakumskij Canal ensured the fresh water supply of Ashkhabad City, the town of Krasnovodsk and other consumers located along the canal. Intake water to the canal from the Amu-Dar'ya River was $80 \text{ km}^3$/a. Water transportation from the Volga and Ural Rivers by pipeline as well as from the Amu-Dar'ya River by canal were first considered. Water transport by tankers was also taken into consideration. Furthermore, special R&D work was carried out on fresh water production through the desalination of Caspian Sea water. Fossil and nuclear fuelled power plants were analysed as the energy source options for desalination. This work was mainly done by those organizations and institutions that were involved in the former USSR's programme on utilization of nuclear power within the framework of the ministry now called the Ministry of the Russian Federation for Atomic Energy.

The development, design and construction of these commercial nuclear desalination facilities, which are still the largest in the world, should be considered as the starting point of the involvement of former USSR specialists and industry in sea water desalination using nuclear energy.

2. CONSTRUCTION OF THE ENERGY PRODUCTION AND DESALINATION COMPLEX BASED ON THE BN-350 REACTOR

As a result of a comprehensive study of the problem of energy and fresh water supply on the Mangyshlak Peninsula, the best solution appeared to be the
construction of a large complex comprising a nuclear reactor, an oil fuelled power and heat co-generation plant, and sea water desalination facilities [1, 2]. At that time, no industrial experience in large scale sea water desalination had been accumulated in the former USSR. Little use could be made of international experience because of lack of information and publications. As a result, in 1961 an R&D laboratory was founded in the region of the future City of Shevchenko to develop, evaluate and test the theoretical ideas and design solutions in desalination technology under real practical conditions. Pilot desalination units were built that used multi-effect distillation (MED), multi-stage flash (MSF), mechanical and thermal steam compression [3–5], ion exchange, electrodialysis and other processes. A large R&D programme aimed at the development and industrial application of technology for the suppression of scaling [6] and a study on the corrosion resistance of structural materials under conditions characteristic of desalination facilities were carried out. On the basis of the test results of different types of desalination technology, vertical tube evaporators (VTEs) were adopted for further upgrading and implementation in large scale commercial facilities.

The first four effect demonstration VTE unit (3800 m$^3$/d) was built in Shevchenko in 1963. Industrial (13 000 m$^3$/d) and production (14 000 m$^3$/d) facilities were constructed in 1967, 1969 and 1970. Since 1971, several serial ten effect 14 500 m$^3$/d units have been put into operation [2, 7] at the MAEC. In 1979, one unit of this type was built in the town of Krasnovodsk and in 1989 two units were constructed in Yemen [8].

Subsequently, the experience gained in the construction and operation of commercial VTEs, systematic research and the general trend in sea water desalination worldwide resulted in the decision being made to develop and construct new desalination facilities equipped with horizontal tube thin film multi-effect (HTME) distillation. Compared with the VTE, HTME is characterized by a 1.5–1.7 times lower specific energy consumption and a 3–4 times lower specific weight and construction site area. A vast amount of the R&D, testing and design work was carried out to develop and upgrade HTME technology. Since 1985, the HTME facilities have been in commercial operation in Aktau and their application for sea water desalination, brackish and sewage water processing, as well as in other areas of water clean-up and desalination, has continually increased [9]. A unified line of HTME units in the range of 240–20 000 m$^3$/d has been developed.

The desalination facilities on the Mangyshlak Peninsula have become the centre for the industrial introduction of thermal desalination, research and testing for developing and upgrading sea water desalination and potable water production technology. Comprehensive physiological control of the large population in Aktau has proved the safety of the long term utilization of artificial potable water through adding mineral ingredients to the distillate.
Construction of the BN-350, at that time the first reactor of its type in the former USSR and the largest commercial fast reactor in the world, was started in 1964. It was commissioned on 16 July 1973. The two major objectives for constructing this reactor were: (1) acquisition of the design, construction and operational experience required to determine the prospects for large sodium cooled fast reactors; and (2) apart from the fresh water supply in the region, evaluation and demonstration of the effectiveness of using nuclear reactors for sea water desalination.

Twenty-four years of successful operation of the BN-350 reactor have proved the effectiveness, reliability and safety of its coupling to desalination facilities.

The results of work on the development of equipment and technology for sea water desalination in Shevchenko were in great demand throughout the country. Thus, by the year 1991 more than 60 desalination units of various types had been built and commissioned at 41 sites. The total rated capacity of these facilities was 380 220 m³/d, including 15 desalination units with a total rated capacity of 175 840 m³/d in Shevchenko. During the period 1991–1995, 86 more desalination units (mostly HTME), with a total capacity of 338 000 m³/d, were designed, partially manufactured and assembled at 26 sites.

3. DESALINATION FACILITIES IN NUCLEAR POWERED SHIPS

The sea water desalination facilities used in nuclear powered icebreakers and the lighter carrier Sevmorput are the source of all regular internal fresh water supplies. An icebreaker of the Arktika type provides, on average, about 80 m³/d of fresh water. It comprises two (one on stand-by) desalination units (M4C-1), with a total rated capacity of 240 m³/d. Two desalination units (M3C, 60 m³/d each) are employed in an icebreaker of the Taimyr type, with one on stand-by.

The desalination facilities used in the icebreakers and the lighter carrier Sevmorput are of the MSF type. The design features of the equipment provide high quality distillation, therefore the product water meets the requirements for reactor primary coolant. Special attention was paid to the operational stability and the product water quality under conditions that disturb the evaporation process, such as the ship’s rolling, heeling and striking of ice. As a result, reliable operation of the equipment has been ensured under the following conditions: a permanent heeling to any side of up to 15°, and rolling at an amplitude of 45° for a period of 7–14 s.

The heat source for desalination is steam produced in the reactor steam generator (SG). The reactor design and the special leak tight control system, which provide automatic isolation of the failed SG section, prevent radioactivity entering the secondary steam. Having passed through the water desalination unit, the steam is condensed and pumped into the main or auxiliary turbine condenser, before returning to the SG.
The nuclear reactor does not affect the quality of the product water. Desalination units are separated and located far from the reactor. Direct contact between secondary steam and product water is excluded.

After 20 years of operating experience of the two M4C-1 units in the icebreaker Arktika it should be noted that they have already produced about 400 000 m$^3$ of fresh water and continue to be used according to their design function [10].

At present, ten M4C-1 and six M3C units are in operation in nuclear powered ships. Altogether, more than 50 M4C-1 and M3C units are operating in conventional and nuclear ships.

4. DEVELOPMENT OF NUCLEAR DESALINATION PLANTS BASED ON REACTORS OF THE KLT-40 TYPE AND SMALL AND MEDIUM SIZED REACTORS OF THE NEW GENERATION

The current desalination programme in the Russian Federation gives priority to the development of a small floating nuclear desalination complex based on the KLT-40 reactor. Originally, reactors of this type were designed for nuclear powered ships. For many years, they were used as the energy source for icebreaker propulsion, demonstrating a sound safety record and high reliability under harsh Arctic Ocean conditions.

The KLT-40 is an upgraded, modified version of the original reactor line, designed according to up to date national standards and the IAEA’s recommendations for nuclear safety. The latest nuclear ships are equipped with these reactors [11].

For commercial energy and/or fresh water production, the KLT-40 will provide the following performance characteristics:

- Thermal power: Up to 170 MW(th)
- Electric output: Up to 35 MW(e)
- Fresh water production:
  - For the reverse osmosis (RO) option: Up to 160 000 m$^3$/d
  - For the MED option: Up to 80 000 m$^3$/d

Development of the floating nuclear desalination complex is running in parallel, backed by a floating electricity and heat co-generation plant using two KLT-40S reactors and producing up to 70 MW(e) of electricity and 60 MW(th) of heat for district heating. This plant is now in the basic design stage, with planned implementation around the year 2000 in an Arctic Ocean coastal area (town of Pevek, Chukotskij Peninsula).

The design of the new generation HTME desalination unit (DOU GTPA-840) has been developed. The performance characteristics of this upgraded design are:
It is planned that these units will be used for a nuclear floating desalination plant. Two design concepts for the nuclear floating desalination plant equipped with KLT-40S and DOU GTPA-840 have been proposed: APWS-40 and APWS-80, producing 40 000 and 80 000 m$^3$/d of fresh water, respectively [12]. Both are considered to be firm options by potential users of the nuclear desalination system. However, there is room for detailed optimization of the technical characteristics and performance of the nuclear desalination system employing the KLT-40S reactor as an energy source with respect to user requirements and local conditions.

Taking into account the promising sea water desalination market in many countries of the world, practically all the small and medium reactors (SMRs) under development in the Russian Federation have been considered and evaluated with respect to coupling with desalination systems. The technical characteristics of some SMRs for nuclear desalination are presented in Table I [11, 13–16].

5. INTERNATIONAL CO-OPERATION

After Resolution GC(XXXIII)/RES/515 was passed at the Agency’s General Conference in 1989, the IAEA’s activities in the field of nuclear desalination were resumed. The Agency held many meetings and organized studies and programmes on various aspects of the utilization of nuclear reactors as an energy source for sea water desalination facilities. Organizations and experts from the Russian Federation took an active part in this work. One IAEA meeting on nuclear desalination was held in the country (a Technical Committee Meeting on Floating Nuclear Energy Plants for Seawater Desalination, 29–31 May 1995, Obninsk), and contributions were made to an IAEA review of the work being done on nuclear desalination [8] (Options Identification Programme for Demonstration of Nuclear Desalination [17]), and on others. As shown in IAEA-TECDOC-898 [17], the KLT-40S reactor was found to be a practical option for demonstrating nuclear desalination.

The Canadian company CANDESAL Inc. and design organizations and institutions in the Russian Federation have started a joint project on a floating nuclear desalination complex comprising KLT-40S reactors and Canadian RO desalination technology with sea water preheating [18].
### TABLE I. TECHNICAL CHARACTERISTICS OF SMRs FOR NUCLEAR DESALINATION [11, 13–16]

<table>
<thead>
<tr>
<th>Reactor</th>
<th>Type</th>
<th>Thermal power (MW(th))</th>
<th>Electric output (MW(e))</th>
<th>Fresh water production (10^3 m³/d)</th>
<th>Current status</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATE-150</td>
<td>Integral PWR/natural circulation of primary coolant [11]</td>
<td>536</td>
<td>Up to 180</td>
<td>Up to 250</td>
<td>Conceptual design</td>
</tr>
<tr>
<td>AST-500</td>
<td>Integral heating PWR/natural circulation of primary coolant [11]</td>
<td>Up to 600</td>
<td>Not relevant</td>
<td>Up to 300</td>
<td>Licensed detailed design, construction experience</td>
</tr>
<tr>
<td>VPBR-600</td>
<td>Advanced integral PWR/forced circulation of primary coolant [11]</td>
<td>1800</td>
<td>Up to 600</td>
<td>Up to 800</td>
<td>Basic design under way</td>
</tr>
<tr>
<td>LMR</td>
<td>Integral lead–bismuth LMR [15]</td>
<td>100</td>
<td>12</td>
<td>40</td>
<td>Conceptual design</td>
</tr>
</tbody>
</table>

6. **SCIENTIFIC, TECHNOLOGICAL AND INDUSTRIAL POTENTIAL FOR NUCLEAR SEA WATER DESALINATION IN THE RUSSIAN FEDERATION**

In the course of the development and practical implementation of nuclear power and nuclear desalination, highly qualified enterprises have been founded and developed that are capable of carrying out all the activities required during the lifecycle of a nuclear power plant and desalination facility, including:

1. Workforce, educational institutions, universities, specialized technical schools;
2. Operation and maintenance, personnel training and skills, upgrading of centres;
3. R&D laboratories and institutes;
(4) Nuclear island systems and equipment designers;
(5) Balance of plant and architectural designers for land based, underground and floating nuclear plants;
(6) Industrial enterprises and companies that manufacture systems, equipment, instrumentation and other special items;
(7) Central, regional and local maintenance and repair services;
(8) Governmental and local safety, quality and reliability regulatory and control bodies;
(9) Institutions and bodies that ensure contacts with foreign buyers and partners.

Relying on this potential, the Russian Federation has been able to carry out feasibility studies on the application of nuclear desalination facilities at various sites, to develop detailed designs and to manufacture, construct and operate such facilities. SMRs designed in the Russian Federation [11], including floating ones, might prove to be the solution to problems of fresh water supply in various arid regions of the world, particularly in North Africa, where a regional study on the utilization of nuclear desalination was carried out with IAEA support [19].

REFERENCES


PERSPECTIVES OF SEA WATER DESALINATION IN ALGERIA
The Oran desalination project

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Algiers, Algeria

Abstract

PERSPECTIVES OF SEA WATER DESALINATION IN ALGERIA: THE ORAN DESALINATION PROJECT.

An analysis is made of the water resources, requirements and supplies in Algeria, with emphasis placed on Oran and its surrounding area. Large quantities of water are required in many regions of the country, mainly for domestic, industrial and agricultural purposes. The growth in population and in industrial and agricultural development has created an ever increasing need for potable water, which cannot be covered by Algeria’s natural water resources. In the past, the specific cost of product water, the capital investment cost and the competitiveness of interregional water transfers have been the main barriers to implementing any large scale desalination programme to counteract the approaching water crisis in Algeria. To face the water deficit situation, Algeria has decided to carry out feasibility studies within the framework of a planned sea water desalination programme based on a desalination potential estimated to be as high as 600 000 m³/d for the northern coast by the year 2005. A description is given of the Oran area from the point of view of its geographical location, meteorology, rainfall, sea water quality, water demand, availability or lack of resources, and the daily water requirements. This information is given in terms of current data and forecasts up to the year 2020 for the entire Oran area. The capacity of the desalination plant was calculated to be the difference (which cannot be satisfied by dams, drilling, water transfers, water springs and other natural resources) between the available resources and the demand in the year 1997. Of the nine coastal locations in the Oran area identified as being possible candidate sites for the desalination plant, Bethioua (Port-aux-Poules) was selected as the reference site, and a complete feasibility study was carried out. Some of the output data related to this feasibility study are presented, including the criteria that led to the selection of MSF technology as the suitable desalination process.

1. NATURAL WATER RESOURCES IN ALGERIA AND THE POTENTIAL FOR SEA WATER DESALINATION

Rainfall is the main source of natural fresh water resources (surface and groundwaters) in Algeria. The average precipitation varies from 1500 mm/a in the
northeastern part of the country to less than 100 mm/a in the southern desert. The corresponding rates of evaporation are 1200 and 2500 mm/a, respectively.

The surface water resources consist of rain water runoff in valleys, the total (theoretical) potential of which is estimated to be about $13.5 \times 10^9$ m$^3$/a, distributed in the following basins: the Mediterranean Basin ($12 \times 10^9$ m$^3$/a); the High Atlas ranges ($0.75 \times 10^9$ m$^3$/a); and the desert basin ($0.75 \times 10^9$ m$^3$/a).

Only $5.7 \times 10^9$ m$^3$/a of the above mentioned potential can be utilized if 100 regulation and compensation dams are built. However, because only a small number of dams already exist, a large amount of rain water is lost to the sea. There are two major problems facing the Algerian plans to develop surface water resources through the construction of dams to intercept rain water: the high rate of silt carried away by runoff, estimated to be 200 000–600 000 ppm; and the irregularity of the rainfall with respect to the time of the year and/or the location.

At present, $1.8 \times 10^9$ m$^3$/a are utilized through 40 dams and four deviation facilities. Another 13 dams are under construction; these will add $1.1 \times 10^9$ m$^3$/a to the existing resources.

Rechargeable aquifers are concentrated in the north of the country. The average recharge rate is estimated to be $1.7 \times 10^9$ m$^3$/a. There is also a large amount of fossil water stored in aquifers in the south, which could be exploited at a rate of $2 \times 10^9$ m$^3$/a. However, only 25% of this potential is currently being utilized.

The potential for sea water desalination in Algeria (a production capacity that cannot be met economically through dams, aquifers, springs and other conventional resources) is estimated to be 600 000 m$^3$/d for the entire country, including the Oran agglomerations (towns with a population of more than 20 000). The national projections for sea water desalination in the future are partly based on this potential.

2. DESCRIPTION OF THE ORAN AREA

Oran is the second largest town in Algeria and is located on the Mediterranean Sea, 440 km to the west of the capital City of Algiers (see Fig. 1). The coastline comprises cliffs and small, gently sloping hills at an altitude of about 100 m. The climate is typically Mediterranean, with an average temperature of 17°C (Table I). Annual rainfall is about 400 mm, mainly occurring during the winter; summer rainfall is negligible (Table II). The hydrological resources of the Oran area are very low; in fact, the capacity of the region's surface water resources is not enough to provide Oran and the surrounding population with potable water of an adequate standard. Local aquifers satisfy only 9% of the total distributed water, while 91% is provided by pipelines and transfer from nearby areas (Table III).
TABLE I. AVERAGE TEMPERATURE IN THE ORAN AREA (°C)

<table>
<thead>
<tr>
<th>Year</th>
<th>Maximum annual temperature</th>
<th>Minimum annual temperature</th>
<th>Average annual temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>1974</td>
<td>39.9</td>
<td>-1.5</td>
<td>16.9</td>
</tr>
<tr>
<td>1975</td>
<td>29.5</td>
<td>5.2</td>
<td>16.5</td>
</tr>
<tr>
<td>1976</td>
<td>33.8</td>
<td>0.2</td>
<td>16.7</td>
</tr>
<tr>
<td>1977</td>
<td>33.8</td>
<td>0.2</td>
<td>17.2</td>
</tr>
<tr>
<td>1978</td>
<td>42.3</td>
<td>-2.1</td>
<td>17.2</td>
</tr>
<tr>
<td>1979</td>
<td>-</td>
<td>-</td>
<td>17.6</td>
</tr>
</tbody>
</table>

TABLE II. ANNUAL RAINFALL IN THE ORAN AREA

<table>
<thead>
<tr>
<th>Year</th>
<th>Annual rainfall (mm)</th>
<th>Rainy days in the year (d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1974</td>
<td>427</td>
<td>74</td>
</tr>
<tr>
<td>1975</td>
<td>457</td>
<td>8</td>
</tr>
<tr>
<td>1976</td>
<td>424</td>
<td>93</td>
</tr>
<tr>
<td>1977</td>
<td>317</td>
<td>64</td>
</tr>
<tr>
<td>1978</td>
<td>263</td>
<td>62</td>
</tr>
<tr>
<td>1979</td>
<td>430</td>
<td>89</td>
</tr>
</tbody>
</table>
TABLE III. POTABLE WATER RESOURCES IN THE ORAN AREA

<table>
<thead>
<tr>
<th>Year</th>
<th>Resource</th>
<th>Flow rate (L/s)</th>
<th>Cumulated flow rate (L/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1880</td>
<td>Bredeah aquifer</td>
<td>150</td>
<td>150</td>
</tr>
<tr>
<td>1952</td>
<td>Beni Behdel Dam</td>
<td>750</td>
<td>900</td>
</tr>
<tr>
<td>1973</td>
<td>Fergoug Dam</td>
<td>300</td>
<td>1200</td>
</tr>
<tr>
<td>1991</td>
<td>Transfer from the Tafna River</td>
<td>350</td>
<td>1550</td>
</tr>
<tr>
<td>1993</td>
<td>Transfer from the Cheliff River</td>
<td>170</td>
<td>1720</td>
</tr>
</tbody>
</table>

3. WATER DEMAND, SUPPLY AND DEFICIT IN THE ORAN AREA

In spite of the water distribution network and the efforts being made by the government to provide the region with potable water, in 1995 the estimated deficit of the Oran area was reported to be as high as 142,046 m³/d (Table IV).

In 1995, to estimate the water demand, it was assumed that the specific water requirements corresponded to 160 L/person per day. Projections for the period 1995–2020 were based on the assumption that specific water consumption would increase by 1% annually up to the year 2020; thereafter, it would remain constant at 205 L/person per day. It was also assumed that the population of the area would grow from 1,116,394 persons in 1995 to 1,653,414 in the year 2020. These projections were also based on a planned decrease in the leakage ratio in the distribution network (from 38% in 1995 to 25% in the year 2020).

The deficit is expected to increase to 172,991 m³/d in the year 2000, and then to decrease to 80,633 m³/d in the year 2010 (with the introduction of a new 1722 L/s, 1400 mm diameter and 150 km long pipeline from Gargar) and to 27,497 m³/d in the year 2020 (when another 1500 L/s, 1000 mm diameter and 150 km long pipeline from Bougrara will be in service). However, these two new water networks from nearby regions (at a distance of 150 km) are in economic competition with sea water desalination projects.

The gross water requirements for the Oran area will increase from $109 \times 10^2$ m³/a in 1995 (Table V) to $176 \times 10^2$ m³/a in 2020 (Table VI).
<table>
<thead>
<tr>
<th>Year</th>
<th>Population (P) (No. of persons)</th>
<th>Demand per person per day (N) (L/person per day)</th>
<th>Demand (D) (D = P × N) (m³/d)</th>
<th>Leakage ratio (L) (%)</th>
<th>Supply (X) (X = D/1 - L/100) (m³/d)</th>
<th>Other requirements (Y) (m³/d)</th>
<th>Total demand (Z) (Z = X + Y) (m³/d)</th>
<th>Available resources (W) (m³/d)</th>
<th>Deficit (M) (M = Z - W) (m³/d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1995</td>
<td>1 116 394</td>
<td>160</td>
<td>178 623</td>
<td>38</td>
<td>288 101</td>
<td>P × M</td>
<td>288 101</td>
<td>146 055</td>
<td>142 046</td>
</tr>
<tr>
<td>2000</td>
<td>1 234 405</td>
<td>168</td>
<td>207 380</td>
<td>35</td>
<td>319 046</td>
<td>P × M</td>
<td>319 046</td>
<td>146 055</td>
<td>172 991</td>
</tr>
<tr>
<td>2010</td>
<td>1 453 427</td>
<td>186</td>
<td>270 337</td>
<td>28</td>
<td>375 468</td>
<td>P × M</td>
<td>375 468</td>
<td>294 835</td>
<td>80 633</td>
</tr>
<tr>
<td>2020</td>
<td>1 653 414</td>
<td>205</td>
<td>338 949</td>
<td>25</td>
<td>451 932</td>
<td>P × M</td>
<td>451 932</td>
<td>424 435</td>
<td>27 497</td>
</tr>
</tbody>
</table>
TABLE V. DAILY WATER REQUIREMENTS IN THE ORAN AREA (1995)

<table>
<thead>
<tr>
<th>Population (No. of persons)</th>
<th>1 116 394</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of houses</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>183 039</td>
</tr>
<tr>
<td>No. of houses with courtyard and garden</td>
<td>46 995</td>
</tr>
<tr>
<td>Occupation rate (average No. of persons)</td>
<td>6</td>
</tr>
<tr>
<td>Water endowment (average)</td>
<td></td>
</tr>
<tr>
<td>Domestic (L/person per day)</td>
<td>120</td>
</tr>
<tr>
<td>Administration (L/person per day)</td>
<td>18</td>
</tr>
<tr>
<td>Commercial (L/person per day)</td>
<td>10</td>
</tr>
<tr>
<td>Industrial (L/person per day)</td>
<td>12</td>
</tr>
<tr>
<td>Total (L/person per day)</td>
<td>160</td>
</tr>
<tr>
<td>1995 endowment (L/person per day)</td>
<td>160</td>
</tr>
<tr>
<td>Water requirements</td>
<td></td>
</tr>
<tr>
<td>Net water requirements (m³/d)</td>
<td>188 134</td>
</tr>
<tr>
<td>Gross water requirements (m³/d)</td>
<td>297 851</td>
</tr>
<tr>
<td>Gross water requirements (10² m³/a)</td>
<td>109</td>
</tr>
</tbody>
</table>

TABLE VI. DAILY WATER REQUIREMENTS IN THE ORAN AREA (1995-2020)

<table>
<thead>
<tr>
<th></th>
<th>1995</th>
<th>2000</th>
<th>2010</th>
<th>2020</th>
</tr>
</thead>
<tbody>
<tr>
<td>Population (No. of persons)</td>
<td>1 116 394</td>
<td>1 234 405</td>
<td>1 453 427</td>
<td>1 653 414</td>
</tr>
<tr>
<td>Water endowment (L/person per day)</td>
<td>160</td>
<td>168</td>
<td>186</td>
<td>205</td>
</tr>
<tr>
<td>Net water requirements (m³/d)</td>
<td>188 134</td>
<td>219 308</td>
<td>287 092</td>
<td>362 082</td>
</tr>
<tr>
<td>Gross water requirements (m³/d)</td>
<td>297 851</td>
<td>337 403</td>
<td>425 323</td>
<td>482 774</td>
</tr>
<tr>
<td>Gross water requirements (10² m³/a)</td>
<td>109</td>
<td>123</td>
<td>155</td>
<td>176</td>
</tr>
</tbody>
</table>

4. SIZE OF THE DESALINATION PLANT

Figure 2 shows the method used to determine the capacity of the desalination plant. The difference between the total water demand and the available water resources corresponds to the annual water deficit to be satisfied by a desalination plant. In 1994, the expected deficit for 1997 was 152 000 m³/d, therefore the capacity of the desalination plant was assumed to be 150 000 m³/d.
5. COSTS AND SELECTION OF CANDIDATE SITES

The final costs of the desalinated water provided to consumers cover three principal components: the capital and operation and maintenance costs; the energy cost; and the costs of water storage, transport and distribution to consumers.

The share of each component in the final water costs depends on many factors, among which are the site characteristics. One-third of these cost components is fundamentally site dependent. Nine possible coastal locations for the siting of the desalination plant have been identified in the Oran area (see Fig. 3).
The siting process used to select the reference site consisted of successive screening and cross-comparative evaluations of the nine candidate sites, taking into account the following considerations and criteria: the meteorology; sea conditions; electricity grid and supply; water distribution network; construction area;

TABLE VII. SEA WATER QUALITY IN THE ORAN AREA

<table>
<thead>
<tr>
<th>Elements</th>
<th>Average value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ca</td>
<td>351 mg/L</td>
</tr>
<tr>
<td>Mg</td>
<td>1359 mg/L</td>
</tr>
<tr>
<td>Na</td>
<td>11960 mg/L</td>
</tr>
<tr>
<td>K</td>
<td>535 mg/L</td>
</tr>
<tr>
<td>Cl</td>
<td>20 657 mg/L</td>
</tr>
<tr>
<td>SO₄</td>
<td>2460 mg/L</td>
</tr>
<tr>
<td>CO₃</td>
<td>193 mg/L</td>
</tr>
<tr>
<td>NO₃</td>
<td>1 mg/L</td>
</tr>
<tr>
<td>NO₂</td>
<td></td>
</tr>
<tr>
<td>NH₄</td>
<td>0.40 mg/L</td>
</tr>
<tr>
<td>Others</td>
<td>0.113 mg/L</td>
</tr>
<tr>
<td>Electrical conductivity</td>
<td>518 mg/cm</td>
</tr>
<tr>
<td>Total dissolved solids (110°C)</td>
<td>39 010 mg/L</td>
</tr>
<tr>
<td>pH</td>
<td>8.25</td>
</tr>
<tr>
<td>Dissolved O₂</td>
<td>7.7 mg/L</td>
</tr>
<tr>
<td>Total dissolved solids</td>
<td>5.3 mg/L</td>
</tr>
<tr>
<td>Temperature</td>
<td>20°C</td>
</tr>
</tbody>
</table>
TABLE VIII. ALGERIAN STANDARDS FOR EFFLUENT QUALITY IN THE ORAN AREA (pH = 5.5–9.0)

<table>
<thead>
<tr>
<th>Elements</th>
<th>Maximum admissible discharge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total dissolved solids</td>
<td>120 mg/L</td>
</tr>
<tr>
<td>(after 2 hours of decanting, followed by filtration)</td>
<td></td>
</tr>
<tr>
<td>Elements in suspension</td>
<td>100 mg/L (average for 2 h)</td>
</tr>
<tr>
<td>Oil and total grease</td>
<td>20 mg/L</td>
</tr>
<tr>
<td>Volatile phenol</td>
<td>5 mg/L</td>
</tr>
</tbody>
</table>

transportation conditions; effects of the site on the desalination plant (geology, hydrology, topography, seismology and person induced effects); impact of the plant on the site (population distribution, land use around the site, chemical effluents, impact of extreme events, environmental considerations, and the socioeconomic and cultural aspects); and the existence of a qualified workforce.

As a result of this comparative study, Bethioua (Port-aux-Poules) was selected as the reference site.

TABLE IX. METEOROLOGY PARAMETERS IN THE ORAN AREA

<table>
<thead>
<tr>
<th>Month</th>
<th>Atmospheric pressure (mbar)</th>
<th>Atmospheric temperature (°C)</th>
<th>Humidity (%)</th>
<th>Rainfall (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>1019.0</td>
<td>10.2</td>
<td>82</td>
<td>70</td>
</tr>
<tr>
<td>February</td>
<td>1018.5</td>
<td>11.0</td>
<td>80</td>
<td>54</td>
</tr>
<tr>
<td>March</td>
<td>1015.8</td>
<td>13.3</td>
<td>78</td>
<td>35</td>
</tr>
<tr>
<td>April</td>
<td>1015.1</td>
<td>15.4</td>
<td>76</td>
<td>33</td>
</tr>
<tr>
<td>May</td>
<td>1015.2</td>
<td>18.3</td>
<td>72</td>
<td>19</td>
</tr>
<tr>
<td>June</td>
<td>1015.6</td>
<td>21.8</td>
<td>72</td>
<td>7</td>
</tr>
<tr>
<td>July</td>
<td>1014.8</td>
<td>24.5</td>
<td>74</td>
<td>1</td>
</tr>
<tr>
<td>August</td>
<td>1014.0</td>
<td>25.1</td>
<td>72</td>
<td>3</td>
</tr>
<tr>
<td>September</td>
<td>1015.3</td>
<td>22.9</td>
<td>75</td>
<td>16</td>
</tr>
<tr>
<td>October</td>
<td>1017.0</td>
<td>18.4</td>
<td>78</td>
<td>43</td>
</tr>
<tr>
<td>November</td>
<td>1017.5</td>
<td>14.2</td>
<td>81</td>
<td>46</td>
</tr>
<tr>
<td>December</td>
<td>1018.4</td>
<td>11.1</td>
<td>82</td>
<td>67</td>
</tr>
</tbody>
</table>
6. DESALINATION PLANT

The following are the planned design parameters of the plant:

Capacity: 150,000 m$^3$/d
Site: Bethioua
Scope: sea water intake and rejection, desalination units and connecting installations with existing water distribution networks
Desalinated water quality: according to Algerian standards
Sea water quality: see Table VII
Effluent quality: according to Algerian standards (see Table VIII)
Meteorology parameters: see Table IX
Fuel: natural gas: 9400 kcal/Nm$^3$; pressure: 4 bar

7. SELECTION OF THE DESALINATION PROCESS

Despite the competitiveness of the reverse osmosis (RO) process, multi-stage flash (MSF) technology was selected because of:

(1) The negative experience made by Algeria in implementing a 30,000 m$^3$/d RO desalination project for industrial purposes; it was felt that MSF technology has been better proved;

FIG. 4. Route of the water pipeline in the Oran area.
(2) The better adaptability of the MSF process to a large desalination plant (150 000 m$^3$/d);
(3) The better opportunities offered by MSF for local participation and manufacture.

In 1994, when the project was reviewed, the multi-effect distillation (MED) process was not taken into consideration, although a preliminary cross-comparison made between the three processes (MED, RO and MSF) had shown MED to be competitive.

8. CONCEPTUAL DESIGN OF THE 150 000 m$^3$/d MSF DESALINATION PLANT

The basic specifications are:

Process: MSF — Distillation through instant vaporization by successive expansion of the long tubes
Capacity: Five units of 30 000 m$^3$/d each
Sea water intake: 1 248 000 m$^3$/d
Potable water production: 150 000 m$^3$/d
Water effluent: 1 098 000 m$^3$/d
Production ratio: 8
Natural gas consumption: 58 500 m$^3$/h
Installed electric power: 2.2 MV·A
Consumption of scale inhibitor: 73 kg/h
Consumption of other chemical products: 392 kg/h
Required surface area: 10 ha
Operating staff: 70 persons
Construction time: 30 months
Estimation of the desalinated water cost: Algerian dinar (DA) 9/m$^3$ (US $1.5/m$^3$)
Availability: 330 d/a

9. CONNECTION WITH EXISTING WATER DISTRIBUTION NETWORKS

The route to be taken by the water pipeline is shown in Fig. 4. This pipeline connects the potable water tanks inside the desalination plant with the distribution water installations in the Gambetta area (Oran). The parameters of the pipeline are: diameter: 1200 mm; material: steel tube coated with epoxy; total length: 40 km; pipeline pump: centrifuge, 350 hm, 1.6 MV·A; and number of pumps: five in normal service, with one in reserve.
The sea water desalination option is being seriously considered by planning and
decision making engineers in Algeria. Oran is likely to be the first town in the country
where future domestic and other water requirements will be met by sea water
desalination.

To date, the desalination projects have competed with interregional water
distribution projects, but the increasing length of these transfers and the overall
reduction in the water resources in the country will make the desalination projects
competitive in the year 2005, in particular those for Oran and its surrounding area.

A 40 000 m³/d desalination project, using MSF technology and located in
Arzew (near Oran), is to be launched soon with the purpose of supplying the indus­
trial and domestic water requirements of the region. The MSF desalination units
planned within the framework of this project will be coupled to a combined cycle (gas
and steam turbines) power plant.

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THE PROSPECTIVE NUCLEAR DESALINATION MARKET IN EGYPT

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Abstract

THE PROSPECTIVE NUCLEAR DESALINATION MARKET IN EGYPT.

In view of the unavoidable decline in the per capita share of the more or less constant natural fresh water resources in Egypt, water desalination is expected to play an increasing role in mitigating a future deficit in potable water supply, particularly in remote desert areas. In the present study, an attempt was made to quantify the evolution of potable water supply, demand and deficit, as well as the portion to be covered by sea water desalination. The future potable water supply was determined as the difference between the projected total renewable fresh water supply and the projected combined demand of the other consuming sectors. To project the future demand of potable water, the history of past consumption was studied and correlated with the population and gross domestic product. Three scenarios were contemplated for economic development, reflecting low, medium and high economic growth rates. The difference between potable water supply and demand is the deficit that has to be compensated for. Part of the future deficit may be covered through various means other than sea water desalination. Therefore, it was assumed that sea water desalination will cover only 10% of the deficit in potable water supply. It is concluded that there will be a demand for an additional desalination capacity of a sufficiently large magnitude around the year 2012 and beyond that will support the installation of desalination facilities larger than 100 000 m³/d. Desalination plants in this range coupled to nuclear power plants could be competitive with fossil fired plants.

1. INTRODUCTION

An adequate supply of electric energy and potable water for domestic as well as industrial and public use is one of the fundamental conditions for development in Egypt, and indeed one of the major challenges. In view of the limited primary energy and fresh water resources, and the possible role of nuclear energy in generating electricity and/or providing energy to desalination plants, research on Utilization of Nuclear Technology in Sea Water Desalination was started. The present study includes estimation of: (1) the present and future renewable fresh water resources;
(2) the future potable water supply, demand and deficit; and (3) the future desalination market.

2. FRESH WATER RESOURCES

Egypt is a very arid country, with an average annual rainfall that seldom exceeds 200 mm. The area of greatest rainfall is the North coast, where the mean annual rainfall is 175–200 mm. Annual rainfall declines rapidly towards the interior, with 50 mm occurring 80 km inland, and less than 5 mm over much of the remaining country. Rainfall on the North coast and in the Sinai contributes to the irrigation of a narrow strip of cultivated land. It also collects in the so-called Roman wells that are used for drinking water in rural areas. In Egypt, fresh water is classified into surface and groundwater resources. These are discussed in Sections 2.1 and 2.2, respectively, based on several extensive studies [1–4].

2.1. Surface water resources

The River Nile is the only significant source of surface water in Egypt. The Nile Waters Agreement of 1959 clearly defines the division of the river’s water between...
Egypt and the Sudan. The Agreement was based on the average flow of the Nile during the 1900–1959 period. The average flow at Aswan at this time was $84 \times 10^9$ m$^3$. The average annual evaporation and other losses in Lake Nasser were estimated at $10 \times 10^9$ m$^3$, leaving a net usable annual flow of $74 \times 10^9$ m$^3$. Under the Agreement, this amount of water was allocated in proportion to the population of the two countries: $55.5 \times 10^9$ m$^3$ for Egypt and $18.5 \times 10^9$ m$^3$ for the Sudan [5].

There is a potential for increasing the Nile flow at Aswan if the Jonglei Canal can be constructed. The project was expected to canalize the river channel in the Sudd region of the Sudan, and thus reduce the substantial evapotranspiration losses. The construction of phase I of the canal was started in 1976, but had to be abandoned in 1983 because of political unrest and the resulting security problems in the southern Sudan. Even under an optimistic scenario, the Jonglei Canal is unlikely to be completed until well into the 21st century at the earliest. Therefore, Nile water cannot exceed the $55.5 \times 10^9$ m$^3$/a fixed by the 1959 Agreement with the Sudan. In the present analysis it is assumed that any future plans for conservation of the Upper Nile water will not affect the surface water supply in Egypt before the year 2017, i.e. the surface water resources are assumed to remain constant at $55.5 \times 10^9$ m$^3$/a, as shown in Fig. 1.

2.2. Groundwater resources

Groundwater utilization in Egypt dates back to ancient times. Sources mention the use of shallow wells to supplement Nile water for irrigation in the ancient capitals of Memphis and Thebs. Groundwater is found virtually everywhere in the sandy and gravelly layers (aquifers) underneath the Nile flood plain and adjacent desert areas, as well as in the deep aquifers underlying the western desert.

The Nile Valley and Delta aquifer is continuously recharged by irrigation water. The groundwater reservoir, therefore, cannot be considered as a resource in itself, since the pumped water is replenished by surface water or intruding sea water in the northern part of the Delta. The thick aquifer in the Nile Valley and Delta is in fact a large storage reservoir. The total amount of fresh water stored in the aquifer amounts to $500 \times 10^9$ m$^3$, which is about four times the storage capacity of Lake Nasser. Groundwater in inland desert areas is characterized by the absence of direct recharge. The huge amount stored in the Nubian sandstone basin ($200 \ 000 \times 10^9$ m$^3$) is mainly fossil water and mostly available at great depth. Pumping of groundwater from this basin will result in a continuous lowering of the water table (mining).

The 1990 extraction of $2.6 \times 10^9$ m$^3$/a can be increased to $4.9 \times 10^9$ m$^3$/a (annual recharge) without causing salt intrusion in the Nile Delta. In the present analysis, groundwater extraction was assumed to increase linearly from $2.6 \times 10^9$ m$^3$/a in 1992 to $4.9 \times 10^9$ m$^3$/a in 2002, and to remain constant up to the year 2017, as shown in Fig. 1.
2.3. Reuse of agricultural drainage water

Agricultural drainage water in Upper Egypt is returned to the River Nile. This increases the salinity of the river water from 200 ppm at Aswan to 350 ppm at Cairo. The drainage water in the Nile Delta is of a lower quality, and accordingly is collected through an extensive drainage network for disposal into the Mediterranean Sea. With the delays in implementing the Upper Nile Basin conservation projects, drainage reuse became a major source for increasing the water supply.

In 1992, the annual average reuse of drainage water in Egypt was $6.8 \times 10^9$ m$^3$, of which $4.7 \times 10^9$ m$^3$ are in the Nile Delta and $0.95 \times 10^9$ m$^3$ in Fayoum, with $1.15 \times 10^9$ m$^3$ returned to the Nile in Upper Egypt. Currently, plans are being made to gradually increase the annual use of drainage water within the Nile Delta to $7 \times 10^9$ m$^3$ by the year 2000. In the context of this study, linear increase was assumed over the period 1992–2002, and to remain constant thereafter, as shown in Fig. 1. It should be emphasized, however, that there is a real danger that land salinity could increase steadily over the years. Therefore, water quality issues may seriously affect the agricultural drainage reuse programmes [6].

3. ESTIMATION OF THE FUTURE POTABLE WATER SUPPLY

In view of the limited renewable water resources in Egypt and the unavoidable decline in the per capita share of natural fresh water resources, desalination will play an increasing role in mitigating the future deficit of potable water, particularly in polluted or salty areas along the Nile and Delta banks and in remote desert areas. In the following subsections, an attempt is made to quantify the evolution of the potable water supply, which could be used to identify the possible deficit in potable water and the share of desalination in filling the gap between supply and demand. This has been done in two steps.

The first was to estimate the future renewable fresh water supply up to the year 2017. In the second step, the evolution of fresh water demand for consuming sectors, other than the municipalities, was explored and estimated on the basis of the available limited information [1–3, 7]. According to these assumptions, the projected total renewable water supply will increase linearly to reach $67.4 \times 10^9$ m$^3$ in the year 2002, and remain constant thereafter.

To estimate the future potable water supply, likely development of fresh water demand in other consuming sectors is needed, including irrigation, industrial needs (other than those supplied by the municipalities) and other needs (e.g. navigation, power and regulations). Subtracting the demand of consuming sectors other than the municipalities from the total renewable water supply provides an estimate of the
available potable water supply. Estimation of the demand of various sectors is provided in the following subsections.

3.1. Irrigation

The cultivated area in the Nile Valley and Delta was estimated at the end of 1988 to be $7.2 \times 10^6$ feddans [3], compared with $6.02 \times 10^6$ feddans in 1963.\(^1\) This estimate is based on satellite images, aerial photographs and a ground survey. The National Land Master Plan identified a possible $2.8 \times 10^6$ feddans that could be reclaimed and irrigated with Nile water, provided that the Upper Nile Basin projects are carried out.

With the delays in implementing these projects, the reclaimed land would hardly exceed $1.0 \times 10^6$ feddans [5]. Each feddan will require about 20 m\(^3\)/d (7300 m\(^3\)/a). In the present analysis it is assumed that the cultivated land will increase linearly from $7.2 \times 10^6$ feddans in 1992 to $8.2 \times 10^6$ feddans in 2002, and remain constant thereafter. In terms of water demand, this will be $59.86 \times 10^9$ m\(^3\)/a in 2002 and beyond (Fig. 2).

\(^1\) 1 feddan = 4200 m\(^2\) = 0.42 ha.
3.2. Industry

In 1985, the industrial water demand was estimated to be $2.9 \times 10^9$ m$^3$/a, or 62 m$^3$ per capita per year. In 1992, the industrial water demand by the year 2000 was estimated to be $6.1 \times 10^9$ m$^3$/a [7]. However, owing to a slowdown in economic growth and, hence, industrial growth, the industrial demand for fresh water is not expected to be high, at least up to the year 2002. Therefore, it is assumed that the industrial demand will increase linearly from $2.9 \times 10^9$ m$^3$/a in 1985 to $6.1 \times 10^9$ m$^3$/a in 2017 (Fig. 2).

3.3. Navigation, regulation and other uses

A feasible water management programme is to minimize fresh water spilling into the sea, mainly during the closure period. Through construction of the new Nag-Hammadi navigation lock, construction of the new Esna Barrage, and improvements in the river navigable channel, spilling of fresh water into the sea will be restricted to $70 \times 10^6$ m$^3$/d during the closure period of about 3 weeks every year (January–December). It is proposed that an annual amount of $1.5 \times 10^9$ m$^3$ from the total spillings (estimated at $1.8 \times 10^9$ m$^3$ annually) be stored in one of the northern lakes [6]. Environmentalist groups, however, are strongly opposing the storage of fresh water in these lakes on the basis of the potential impact on fish and bird life in the lake area. In this study it is assumed that the water requirement for this sector will be reduced linearly over the period 1992–2002, and remain constant thereafter (Fig. 2).

3.4. Available municipal supply

The municipal water supply can be determined as the difference between the total renewable water supply and the demand of the other consuming sectors (Fig. 2). According to these assumptions, the potable water supply will decrease linearly by $220 \times 10^6$ m$^3$/a in the period 1992–2002, and by $100 \times 10^6$ m$^3$/a in the period 2002–2017, to be only $1.14 \times 10^9$ m$^3$/a in 2017.

Even with zero growth in future potable water consumption, a deficit will develop around the year 1997, as can be seen when comparing the projected supply values and the 1992 consumption of $3.7 \times 10^9$ m$^3$/a.

4. ANALYSIS OF THE POTABLE WATER DEMAND

The history of Egypt has centred on the development and use of its only river, the Nile. The potable water demand is met by municipalities through the establishment of treatment plants for the purification and filtration of raw water obtained from the Nile or deep wells. In rural areas, where potable water production is poor, water
obtained from shallow aquifers through hand pumps constitutes a large percentage of the fresh water used by the rural population. In 1984, the Research Institute for Groundwater [2] estimated the water produced by hand pump operations to be $375 \times 10^6$ m$^3$ or 40 L per capita per day (LCD).

Over the period 1972–1992, the total potable water consumption in urban centres increased from 958 to $3224 \times 10^6$ m$^3$/a [8]. The specific water consumption of urban areas increased from 179 LCD in 1972 to 365 LCD in 1992, with an average annual growth rate of 3.6%. Rural consumption of potable water in 1972 was $88 \times 10^6$ m$^3$/a, i.e. about 8% of the total consumption. In 1992, rural consumption increased to $471 \times 10^6$ m$^3$/a, representing about 13% of the total.

The average share of the urban and rural consuming sectors in the periods 1972–1977 to 1987–1992 is shown in Table I. As indicated in the table, the largest consuming sector in urban centres is the domestic/commercial sector, whose average share increased from 46.7% in the period 1972–1977 to 61% in the period 1987–1992. The share of rural domestic consumption increased from 10.5% in the period 1972–1977 to 57.7% in the period 1987–1992, reflecting the increase in the number of households connected to potable water networks in rural areas. This is also confirmed by the decrease in the share of free posts over the same period, from 75.1% in 1972–1977 to 22.8% in 1987–1992.

To project the future demand of potable water, the history of past consumption was studied and correlations were obtained between potable water consumption and other independent variables. It is expected that the total consumption of potable water will depend on the population and the gross domestic product (GDP). Therefore, a multiple regression analysis was carried out on historical data obtained from the World Bank [9]. The resulting correlation was:

$$\text{Water consumption} = -1.5 + 0.07 \times \text{POP} + 0.03 \times \text{GDP}$$  \hspace{1cm} (1)

where water consumption is in $10^9$ m$^3$/a, population (POP) in $10^6$ and GDP in constant US $10^9$ (1987). Three scenarios were considered for GDP growth: (1) extrapolation of present trends; (2) modest acceleration of economic growth; and (3) ambitious acceleration of economic growth. Other trend extrapolation models such as sectorial development, regional development and specific consumption models were also considered. However, the results of these models were similar and generally bracketed by the GDP scenarios. Therefore, projections of potable water demand were based on the above three scenarios, as outlined in the following subsections.

4.1. Scenario A: Extrapolation of present trends

The historical population and GDP data in the period 1972–1992 were correlated using a curve fitting computer program. The resulting correlation is given by:
<table>
<thead>
<tr>
<th>Period</th>
<th>Urban sectors</th>
<th>Rural sectors</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Domestic</td>
<td>Industrial</td>
</tr>
<tr>
<td>1972–1977</td>
<td>46.7</td>
<td>6.2</td>
</tr>
<tr>
<td>1977–1982</td>
<td>48.2</td>
<td>6.1</td>
</tr>
<tr>
<td>1982–1987</td>
<td>55.0</td>
<td>8.8</td>
</tr>
<tr>
<td>1987–1992</td>
<td>61.0</td>
<td>9.3</td>
</tr>
</tbody>
</table>
$\text{POP} = 32.8 + 1.1 \times t$ \hspace{1cm} (2)
$\text{GDP} = 6.5 \times t^{0.6}$ \hspace{1cm} (3)

where POP is in $10^6$, GDP is in constant US $10^9$ (1987) at factor cost, and $t$ is the year (1972).

This scenario represents the worst possible future for Egypt and assumes that the previous trend will continue to the year 2017. Hence, the GDP growth rate will continuously decrease, from 3.1% in 1992 to 1.3% in 2017.

In this scenario, future population and GDP were calculated using Eqs (2) and (3), respectively. According to this scenario, the potable water demand will increase from $3.2 \times 10^9$ m$^3$/a in 1992 to about $5.7 \times 10^9$ m$^3$/a in 2017 at an average annual growth rate of about 2.3%. The corresponding average growth rate of the specific water demand is about 0.7%/a.

4.2. Scenario B: Modest acceleration of economic growth

The basic assumption of this scenario is that the current GDP growth trends (Eq. (3)) will continue until the end of the present 5 year plan (1992–1997). In the following 20 years (1997–2017), the population will increase according to Eq. (2) and the GDP will increase at an average annual growth rate of 3%. In this scenario, potable water consumption will be slightly higher than that predicted in scenario A ($6.2 \times 10^9$ m$^3$/a in 2017). The average growth rate of potable water demand will be about 2.6%/a. The corresponding growth rate of specific water demand will be about 1.0%/a.

4.3. Scenario C: Ambitious acceleration of economic growth

Egypt must reverse the trend apparent in the last 5 year plan (1987–1992) of slowing economic growth (2.3% average). The ambitious and true challenge would be the return to the 9.7% rate of growth that prevailed during the decade 1972–1982. However, taking into consideration domestic problems and the world recession that resulted in industrialized countries having an average growth rate of 2–4%, a realistic goal would be an average economic growth rate of about 6% up to the year 2017 [10]. The basic assumption of this scenario is that the current GDP growth trends given in Eq. (3) will continue into 1997. In the following two decades, the GDP will increase by 6% annually. According to scenario C, the demand for potable water will increase at an average annual growth rate of 3.7% during the period 1992–2017, to reach about $8.0 \times 10^9$ m$^3$/a by the year 2017. The corresponding average growth rate of specific water demand will be about 2.2%/a.
5. ESTIMATION OF THE FUTURE SEA WATER DESALINATION MARKET

Analysis of potable water supply (Section 3.4) indicated that it might be as low as $1.14 \times 10^9 \text{ m}^3/\text{a}$ in 2017, compared with $4.84 \times 10^9 \text{ m}^3/\text{a}$ in 1992. The three demand alternatives contemplated in Section 4 project low, medium and high demands of 5.7, 6.2 and $8.0 \times 10^9 \text{ m}^3/\text{a}$, respectively, in 2017, as shown in Fig. 3. The corresponding deficit, i.e. the difference between demand and supply, will be $4.6 \times 10^9 \text{ m}^3/\text{a}$ for the low alternative, $5 \times 10^9 \text{ m}^3/\text{a}$ for the medium alternative and $6.8 \times 10^9 \text{ m}^3/\text{a}$ for the high alternative.

It is expected that part of the future deficit will be covered through: (1) redirection of part of the irrigation water, probably by changing the crop pattern and/or utilizing sewage water for irrigation; (2) rationalization of potable water consumption and a reduction in distribution losses; and (3) desalination of brackish water. Therefore, it is reasonable to assume in the present analysis that sea water desalination will cover only 10% of the deficit in potable water supply.

Until now, the sea water desalination market in Egypt has grown in a situation of an overall surplus in potable water supply. In this environment, the sea water desalination inventory increased from 200 m$^3$/d in 1971 to 25 673 m$^3$/d in 1993, according to the International Desalination Association [11], i.e. at an average annual growth rate of about 25%. Over 80% of these units are used to provide potable water.
in remote and desert areas in order to satisfy the needs of the indigenous population and tourists [11].

Recently, a study was carried out for the IAEA [12] to forecast the expected evolution of installed capacities up to the year 2015 by individual countries, regions and globally. The projections were based on historical records of the installed sea water desalting capacity [11], known orders for new capacities to be installed over the next few years, and the experience of specialists. In the case of Egypt, extrapolation of historical data, based on similar assumptions to that study, could only be true if the overall surplus pattern prevails. Therefore, the results may be considered an optimistic scenario, where no deficit in potable water supply is foreseen.

The projections of the optimistic scenario and the pessimistic scenario, corresponding to 10% of the deficits calculated using the low, medium and high demand alternatives, are shown in Fig. 4. In these scenarios, whenever there was a surplus in potable water supply, or where the calculated desalination inventory was less than that given by the optimistic scenario, the values given by the optimistic scenario were used.

On the basis of the projections shown in Fig. 4 it can be concluded that there will be a demand for an additional desalination capacity of a sufficiently large magnitude around the year 2012 and beyond that will support the installation of desalination facilities larger than 100 000 m$^3$/d. Desalination plants in this range, coupled to nuclear power plants, could be competitive with fossil fired plants [13].

![FIG. 4. Projection of future desalination inventory.](image)
6. CONCLUSIONS

(1) All economic indicators, including GDP per capita, declined in the decade 1982–1992. To reverse this trend, Egypt should resume economic growth up to at least twice its population growth rate, with particular emphasis placed on manufacturing. Any significant and steady GDP growth will require more energy and water.

(2) Three scenarios were contemplated for Egyptian economic growth: (a) extrapolation of the current economic trends; (b) modest economic growth; and (c) ambitious economic growth. The projected potable water demands in the year 2017 are 5.7, 6.2 and 8.0 x 10⁹ m³/a, respectively, in comparison to the 1992 consumption of 3.7 x 10⁹ m³/a.

(3) For the most part, Egypt lies within the temperate zone, and the bioclimate varies from arid to extremely arid. The River Nile is the main source of renewable fresh water. Owing to a halt in Upper Nile conservation projects, Nile water cannot exceed the 55.5 x 10⁹ m³/a fixed by the 1959 Agreement with the Sudan, at least in the foreseeable future.

(4) Increasing groundwater abstraction, internal conservation projects and reuse of drainage water could increase the total renewable water resources from 62.8 to 67.4 x 10⁹ m³/a. The fresh water supply to municipalities is expected to decline from 4.84 x 10⁹ m³/a in 1992 to 1.14 x 10⁹ m³/a in 2017. As a result, even if the 1992 consumption of 3.7 x 10⁹ m³/a is maintained, a deficit will develop around the year 1997.

(5) Sea water desalination could cover part of the deficit in potable water supply. The sea water desalination market in the year 2017 could be between 1.2 and 1.9 x 10⁶ m³/d. This would support the installation of desalination facilities larger than 100 000 m³/d. Desalination plants in this range, coupled to nuclear power plants, could be competitive with fossil fired plants.

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NATIONAL PROGRAMMES AND ACTIVITIES FOR NUCLEAR DESALINATION IN INDONESIA

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Abstract

NATIONAL PROGRAMMES AND ACTIVITIES FOR NUCLEAR DESALINATION IN INDONESIA.

The annual population and industrial growth of Indonesia (1.57 and 7%, respectively), which are unevenly distributed, cause some damage to the environment and the hydrological cycle. The need for potable water for industry and households, as well as use of hydropower, are increasing. Many provinces with a high population such as West Java, Central Java and East Java, as well as the eastern parts of the country with low levels of rainfall such as Sumatra Island, Kalimantan and Lombok, suffer from serious water shortages, especially in the dry season (March–August). One industrial project for increasing the economic value of natural resources is to produce methanol from natural gas containing CO₂ at Natuna but this process would require large amounts of high purity water per day. Another concept is to develop agriculture and its associated industries in the eastern parts of the country such as West Nusatenggara, East Nusatenggara and East Timor, as well as fisheries in Maluku. Water demands can be divided into four categories: category A: direct potable water; category B: raw drinking water; category C: fisheries water; and category D: agricultural (irrigation), city (household) and industrial waters, and use of hydropower. Indonesia has many types of water resources such as rivers, lakes and dams, rainfall and groundwater. However, according to the balance of water demand and supply, some areas have a negative value in the dry season. The ways of improving the water supply include construction of dams to store water during the rainy season and sea water desalination. Almost half the country suffers from water shortages in the dry season; these will increase by the year 2015. Most of these areas are surrounded by the sea, therefore sea water desalination is considered to be a suitable method for overcoming the deficit in water. On the basis of its geographical location and the number of people living in isolated areas of the country, a small nuclear power plant with a long term fuel cycle is considered to be an appropriate source of electricity and energy for desalination.
1. INTRODUCTION

Indonesia is located between two oceans and two continents, and has a wet tropical climate. It is a country of archipelagos and consists of thousands of large and small islands distributed along the equator from Sabang to Merauke, with many volcanoes and mountains. The rainfall in the eastern part of Indonesia is lower than that in the West. There is a natural lack of water in the dry season and abundant water in the rainy season. Ironically, most of the people who live in the coastal areas also suffer from inadequate fresh water supplies.

Industrial and population growth (7 and 1.57% per year, respectively), which are unevenly undistributed, also have an impact on the rising water demand and environmental damage [1, 2]. Many of the water resources such as rivers, groundwater, lakes or dams have been polluted, and therefore cannot be used as potable water. In the northern part of Jakarta, Medan, Semarang, Surabaya and Ujung Pandang, intrusion of sea water has become a serious problem. Besides, groundwater wells and septic tanks are not located sufficiently far apart from each other, resulting in contamination by coliform bacteria in the residential areas of Jakarta. The Indonesian Government also promotes the use of domestic energy resources, such as coal, geothermal energy and natural gas, instead of oil. One of the natural gas resources found in Indonesia is Natuna, the largest gas field in the world, containing 71% CO₂. Conversion of natural gas into automobile fuel or methanol is considered to be an appropriate way of increasing its economic value, but this process would require large amounts of high purity water per day.

Because of this situation, an alternative method for producing fresh water at a high production rate has to be considered. In a similar manner to the Middle East and North Africa, Indonesia also has abundant sea water with various concentrations of salt. Therefore, sea water desalination, possibly coupled to a small nuclear power plant, has been taken into consideration.

A preliminary report is given on water supplies, the current water shortage problems, and the possible coupling of a desalination installation to a small nuclear power plant.

2. WATER SUPPLIES

The water resources in Indonesia arise from rainfall, rivers, groundwater, lakes, dams and sea water. They all form part of the hydrological cycle, where moisture rises from the land and sea water surfaces into the air, and then returns to earth as a result of heat from the sun [3]. Rainfall is the primary source of water. The country has many rivers, lakes and dams (53 water reservoirs were built between 1914 and 1992, with a total volume of 9171.8 million m³, almost all of which are located on Java
Island (7807 million m$^3$)), which serve as secondary water resources. These dams are very useful as fresh water resources for irrigation, industry, fisheries and electricity, and to prevent flooding. Almost the entire country, especially the residential areas, uses shallow groundwater or surface water as fresh water.

3. PROBLEMS

3.1. Rainfall level

The amount of rainfall per month or year causes drastic changes in the water resources in some parts of Indonesia: the dry season (March–August) becomes very dry and the rainy season (September–February) is very wet, causing flooding and, consequently, a great deal of damage. There are various rainfall levels in Indonesia (Fig. 1). It is clear from the figure that almost one-third of Indonesia has a low rainfall level, particularly in the dry season.

3.2. Industrial and population growth

The population of Indonesia is almost 120 million, 50% of whom live on Java Island and use groundwater wells for domestic purposes. During the last dry season, which was relatively long, these groundwater wells dried out; this could lead to the intrusion of sea water. The northern part of Jakarta already suffers from such intrusion, and surface land has also subsided.

Human activities also affect the balance of the hydrological cycle, leading to a decrease in the groundwater level. Uncontrolled air pollution from industry (NO$_x$ and SO$_x$ compounds), resulting in difficulties with pollution abatement and high converter installation costs, will cause emission of these compounds into the air and their return.
to earth as acid rain. This effect only seems to occur in industrial areas, not in most of the country, and especially in the eastern parts of Indonesia (because of the low rainfall).

Because Jakarta is a large city, industrial and domestic pollution are increasing year by year. As the number of industrial facilities is also growing, the quality of river water is being lowered. The government has already implemented PROKASIH (Clean River Programme) to manage waste water from industry; however, the water pollution concentrations are still the main problem because of the domestic waste water contribution [2, 4, 5]. One important aspect that should be covered is the high concentration of organic waste water and the toxic components therein. Currently, PDAM JAYA (Water Supply Enterprise, Jakarta) uses river water as its main water resource and traditional purification methods such as precipitation.

The fresh water supply, especially in residential areas, e.g. in Jakarta, mostly originates from shallow groundwater wells. Since there is no sewerage system in Jakarta, utilization of a septic tank in each house is a serious problem. As the level of pollution of river water worsens, the water quality in lakes and dams, where swamp and lake water resources are the source of the groundwater aquifer, is being lowered. The result is lower quality groundwater. Recently, use of shallow groundwater wells has become inappropriate because of their position side by side with septic tanks in which there is an increasing amount of coliform bacteria. Thus, without decontamination the shallow groundwater is useless. Recent data show that of 252 shallow groundwater wells (1–30 m depth), more than 45% have already been contaminated by organic pollutants and 100% by coliform bacteria. Besides shallow groundwater wells, deep groundwater wells (> 30 m deep) have also been used. Such usage should be stopped immediately, since it will cause land subsidence and damage to many buildings and roads (e.g. in Bangkok and northern Jakarta). Also, in the future excess use of deep groundwater wells will accelerate sea water intrusion. It is planned to inject waste water into wells near the coastline. However, this method of groundwater recharge is questionable because of the soil structure (silt clay). The most suitable place for groundwater recharge is on the slopes of mountains, therefore protection of these locations is very important.

From these descriptions of environmental damage it can be concluded that instead of applying expensive recycling or reuse of water, it would be better to seek an alternative water resource such as sea water. Therefore, in the near future it is believed that a desalination process would be suitable method, not only for Jakarta as the capital city but also for all of Indonesia, especially the eastern parts.

3.3. Isolated area problems

Indonesia consists of five large islands and thousands of smaller islands. Most have areas that are located far from major cities, therefore their infrastructure is not
good and electricity has yet to be installed, making them undeveloped, arid areas. REPELITA (Five Year Development Programme) VI has developed a rural district electricity programme in 18,619 areas (79% of the total rural districts) [6]. The remaining areas will receive electricity in the REPELITA VII programme. Besides electricity, an agricultural development programme has also been introduced. This will certainly entail use of increased amounts of water for irrigation, etc. in those areas where the programme will be implemented and where dependence on rainfall is already a problem.

4. WATER DEMAND

According to Indonesian Law No. 20, 1990 [3], water demands can be divided into four categories: category A: direct potable water; category B: raw drinking water; category C: fisheries water; and category D: agricultural (irrigation), city (household) and industrial waters, and use of hydropower.

The total production capacity of drinking water (category B) for domestic and industrial use is 56.2 m$^3$/s; 64% comes from surface water and 36% from groundwater. This shows the dependence of potable water on the surface water deficit, which is influenced by seasonal fluctuations and water quality, particularly in the dry

![Water demand in 1990 and projected levels for the years 2000 and 2015 (cities and rural areas on and outside of Java Island)](image)

FIG. 2. Water demand in 1990 and projected levels for the years 2000 and 2015 (cities and rural areas on and outside of Java Island) [3].
Since the population in Jakarta is greater than that in the rural districts, the water demands there are also higher. In fact, they are five times higher than in the cities outside of Java Island (Fig. 2). In the year 2000, the water demands are likely to be double those in 1990 (almost 200 m$^3$/s).

4.1. Irrigation

Irrigation plays a dominant role in Indonesia (more than 4.5 million hectares), especially on Java Island (more than half of the total hectares under agriculture). The water demand for irrigation in the year 2015 is likely to be 150% higher than that of the present decade.

4.2. Fisheries

Besides agriculture, fisheries are also a dominant occupation. In 1986, the area under dam fisheries was five times greater than that in the water basin, and four times greater than that in rice fields. To develop fisheries by the year 2000, a 10% increase in water will be required, with 25% in 2015, which is around 4856.9 x 10$^6$ m$^3$ /a.

4.3. Hydropower

The hydropower potential is 75624 MW, but only 1743.9 MW has been installed on Java Island. Maintaining the water level is a problem, especially in the dry season, because instead of being used for hydropower, water in dams has to be distributed for domestic, fishery, irrigation and other purposes.

On the basis of the water supply from rivers, rainfall, dams and groundwater the average water availability per year can be determined (Table I); the water supply during the dry season is also shown. It can be seen that there is a tendency for the water demand to increase, although it varies between provinces and depends on population and industrial growth.

4.4. Metropolitan use

In 1996, the number of residents in Jakarta that lived in fresh water serviced areas was around 8.2 million, of which 4.5 million received services. Conditions vary between zones, with Central Jakarta and part of North Jakarta having the largest population in the serviced areas (2.4 million people).

The estimated production will have an impact on the projected operating costs for producing fresh water as a result of the consumption of pure water, electricity, etc. In practice, the projected operating costs will depend on the quality of the pure water to be processed, the climate, the type and system of processing, and the capacity.
## TABLE I. CURRENT AND PROJECTED WATER BALANCE IN INDONESIA

<table>
<thead>
<tr>
<th>Province</th>
<th>Availability Average (10^6 m³/a)</th>
<th>Availability Dry season (10^6 m³/month)</th>
<th>Water demand 1990 (10^6 m³/month)</th>
<th>Water demand 2000 (10^6 m³/month)</th>
<th>Water demand 2015 (10^6 m³/month)</th>
<th>Water balance 1990 (10^6 m³/month)</th>
<th>Water balance 2000 (10^6 m³/month)</th>
<th>Water balance 2015 (10^6 m³/month)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DI Aceh</td>
<td>87 024</td>
<td>725</td>
<td>199</td>
<td>328</td>
<td>297</td>
<td>526</td>
<td>487</td>
<td>428</td>
</tr>
<tr>
<td>North Sumatra</td>
<td>105 558</td>
<td>880</td>
<td>377</td>
<td>440</td>
<td>526</td>
<td>503</td>
<td>440</td>
<td>254</td>
</tr>
<tr>
<td>West Sumatra</td>
<td>93 643</td>
<td>780</td>
<td>212</td>
<td>234</td>
<td>263</td>
<td>568</td>
<td>547</td>
<td>517</td>
</tr>
<tr>
<td>Riau</td>
<td>128 953</td>
<td>1 075</td>
<td>35</td>
<td>124</td>
<td>260</td>
<td>1 040</td>
<td>950</td>
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<tr>
<td>Jambi</td>
<td>76 385</td>
<td>637</td>
<td>56</td>
<td>90</td>
<td>141</td>
<td>581</td>
<td>546</td>
<td>496</td>
</tr>
<tr>
<td>South Sumatra</td>
<td>149 087</td>
<td>1 242</td>
<td>87</td>
<td>237</td>
<td>458</td>
<td>1 155</td>
<td>1 005</td>
<td>785</td>
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<tr>
<td>Bengkulu</td>
<td>51 150</td>
<td>426</td>
<td>62</td>
<td>72</td>
<td>88</td>
<td>364</td>
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<tr>
<td>Lampung</td>
<td>46 238</td>
<td>385</td>
<td>174</td>
<td>199</td>
<td>231</td>
<td>212</td>
<td>186</td>
<td>154</td>
</tr>
<tr>
<td>DKI Jakarta</td>
<td>440</td>
<td>4</td>
<td>50</td>
<td>71</td>
<td>88</td>
<td>-47</td>
<td>-67</td>
<td>-84</td>
</tr>
<tr>
<td>West Java</td>
<td>81 413</td>
<td>678</td>
<td>1 293</td>
<td>1 409</td>
<td>1 561</td>
<td>-615</td>
<td>-730</td>
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<tr>
<td>Central Java</td>
<td>56 188</td>
<td>468</td>
<td>1 172</td>
<td>1 255</td>
<td>1 356</td>
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<td>-786</td>
<td>-888</td>
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<tr>
<td>DJ Jogjakarta</td>
<td>2 903</td>
<td>24</td>
<td>77</td>
<td>84</td>
<td>88</td>
<td>-53</td>
<td>-59</td>
<td>-64</td>
</tr>
<tr>
<td>East Java</td>
<td>46 277</td>
<td>386</td>
<td>1 339</td>
<td>1 415</td>
<td>1 502</td>
<td>-953</td>
<td>-1 030</td>
<td>-1 116</td>
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<tr>
<td>Bali</td>
<td>5 454</td>
<td>45</td>
<td>132</td>
<td>138</td>
<td>144</td>
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<td>92</td>
<td>-99</td>
</tr>
<tr>
<td>West Nusatenggara</td>
<td>12 774</td>
<td>106</td>
<td>204</td>
<td>215</td>
<td>229</td>
<td>-97</td>
<td>-106</td>
<td>-122</td>
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<tr>
<td>East Nusatenggara</td>
<td>28 798</td>
<td>240</td>
<td>86</td>
<td>99</td>
<td>116</td>
<td>154</td>
<td>141</td>
<td>-124</td>
</tr>
<tr>
<td>East Timor</td>
<td>12 907</td>
<td>108</td>
<td>8</td>
<td>20</td>
<td>37</td>
<td>99</td>
<td>87</td>
<td>70</td>
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<tr>
<td>West Kalimantan</td>
<td>326 083</td>
<td>2 717</td>
<td>131</td>
<td>190</td>
<td>277</td>
<td>2 586</td>
<td>2 527</td>
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<tr>
<td>Central Kalimantan</td>
<td>307 826</td>
<td>2 565</td>
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<td>163</td>
<td>313</td>
<td>2 503</td>
<td>2 403</td>
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<td>48 766</td>
<td>406</td>
<td>53</td>
<td>144</td>
<td>278</td>
<td>354</td>
<td>263</td>
<td>128</td>
</tr>
<tr>
<td>East Kalimantan</td>
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<td>204</td>
<td>2 696</td>
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<tr>
<td>North Sulawesi</td>
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<td>322</td>
<td>67</td>
<td>75</td>
<td>85</td>
<td>255</td>
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<td>81 907</td>
<td>683</td>
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<td>555</td>
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<td>521</td>
<td>585</td>
<td>674</td>
<td>221</td>
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<tr>
<td>Southeast Sulawesi</td>
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<td>310</td>
<td>40</td>
<td>52</td>
<td>70</td>
<td>270</td>
<td>258</td>
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<td>Maluku</td>
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<td>47</td>
<td>941</td>
<td>857</td>
<td>825</td>
<td>778</td>
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<tr>
<td>Irian Jaya</td>
<td>876 309</td>
<td>7 303</td>
<td>5</td>
<td>332</td>
<td>823</td>
<td>7 298</td>
<td>6 970</td>
<td>6 480</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>3 220 977</td>
<td>26 842</td>
<td>6600</td>
<td>8159</td>
<td>10 363</td>
<td>20 242</td>
<td>18 683</td>
<td>16 478</td>
</tr>
</tbody>
</table>
In principle, development of a fresh water supply system in Indonesia, and especially in Jakarta, will continue to increase because the need for fresh water will rise in parallel with the growing standard of living of the community. At present, the PDAM JAYA water utility owns 12 fresh water treatment installations with a total capacity of 12 230 L/s, and one spring water installation in Ciomas Bogor with a capacity of 150 L/s.

The capability of PDAM JAYA to produce the maximum amount of fresh water will influence various supporting factors such as the pure water, electricity power, chemicals, equipment and all the treatment machinery itself. At present, fresh water, being the basic supply of PDAM JAYA, comes from different surface water wells: the Jatiluhur Dam, Tarum Barat Canal, Ciliwung River, Krukut River, Pesanggrahan River and the secondary Bekasi Canal [4, 5].

5. WATER BALANCE

The water balance is defined as the difference between water demand and supply. Table I shows the water balance in the years 1990, 2000 and 2015 in many provinces of Indonesia [3]. Because of the water demand, the water balance is decreasing yearly. Particularly in the highly populated islands of Java (including DKI Jakarta and DI Jogjakarta) and several eastern islands (such as Bali and Nusatenggara), there is a negative water balance in the dry season. It should be noted that these values are based on the constant availability of water without taking into consideration the environmental damage that could affect the water quality.

Clearly, there is an increase in the negative water balance with time, especially in Jakarta, which covers an area of 650 km². West Java, Central Java and particularly East Java have a high water deficit compared with the provinces located outside of Java Island.

The water needs in Jakarta are five times higher than the water supply in the dry season. This is a serious problem. With a view to making Jakarta a ‘serviced city’, improvements in the fresh water supply should be continuously encouraged by PDAM JAYA.

Owing to the shortage of fresh water in the DKI Jakarta area, besides building new facilities many efforts are also being made to buy fresh water from areas outside of Jakarta such as from the Cisadane treatment installation, which is managed by PDAM Tangerang. This installation has a capacity of 3000 L/s (currently 2800 L/s), while the Buaran installation supplies 5000 L/s. The total supply capacity of PDAM JAYA will rise to 18 292 L/s. This figure does not take into account the capacity of various mini-installations, amounting to 630 L/s.

To handle the increasing water demands in Jakarta, PDAM JAYA has been developing and implementing the System Improvement Project. Completion of the
project is scheduled for the year 2000. It is expected to be able to serve 5.7 million inhabitants out of a total population of 8.9 million. Improved piping, a good team and ample experience are required.

The long range programme will not be successful unless every effort is made to reduce the water losses and to improve the fresh water services to the population of Jakarta, both quantitatively and qualitatively.

6. INCENTIVES FOR TAKING UP THE NUCLEAR DESALINATION OPTION

The electricity demands of Indonesia will be around 28.8 GW in the year 2005. Almost 50% comes from coal, and the rest from water, natural gas, etc., but none from the nuclear industry. The government is planning to develop a small electric power plant of 30 MW for isolated areas on Java Island, and another of less than 15 MW for outside of Java Island. More than 50% of these costs are expected to be funded by a private company. The government's contribution will decrease from 61.6% (PELITA I) to 13% (PELITA V) [6]. To lower the costs, multi-purpose electric power is being considered.

On the basis of a comparative study, nuclear power plants do not emit heavy metals, NO\textsubscript{x}, SO\textsubscript{x}, etc. If a nuclear power plant is compared to a coal plant with de-SO\textsubscript{x} and de-NO\textsubscript{x} equipment, the cost of producing electricity would be comparable. Earlier use of nuclear power will provide more time for technology transfer and for a non-depletion strategy to be formulated for the fossil energy source. In accordance with electric power, Indonesia also has two desalination installations located in northern Jakarta, both of which are multi-stage flash (MSF) units that can produce around 1000 m\textsuperscript{3}/d.

In principle, the energy used for the desalination process is thermal or mechanical power. All the desalination processes need pumping and electricity for the auxiliaries and services. For this reason, coupling a multi-purpose, small nuclear power plant to a desalination installation (thermal desalting, reverse osmosis, multi-effect distillation and MSF) is considered to be a suitable method for Indonesia [7–11].

An important consideration in choosing a desalination plant is evaluation of the financial costs [12]. For the long term, the type of desalination process, the type of energy source and the required output are factors that will affect the costs.

The costs of a desalination facility coupled to a nuclear power plant (depending on the technology used) [12], with clean water produced by PDAM JAYA, are competitive (US $0.7–2/m\textsuperscript{3}) [2]. The costs of both methods are still lower than those of mineral water (aqua) produced by a private company (US $467.25/m\textsuperscript{3}).
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PROGRAMMES AND ACTIVITIES ON NUCLEAR DESALINATION IN MOROCCO

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Abstract

PROGRAMMES AND ACTIVITIES ON NUCLEAR DESALINATION IN MOROCCO.

The various development plans envisaged for water resources and the opportunities for planned water transfer indicate that some hydrographical regions will show a shortage by the year 2020. Sea water desalination could solve the future deficit in water supply. Studies carried out by the IAEA have revealed that use of nuclear energy for sea water desalination is technically feasible and can compete with fossil energy. Within the framework of co-operation between China and Morocco, and with the assistance of the IAEA, both parties have decided to perform a joint pre-project study on nuclear desalination.

1. INTRODUCTION

Planning of water resources in Morocco has been designed within the framework of studies on guide schemes for different hydrographical regions that concentrate on evaluating the water needs of various users and on examining the opportunities for mobilizing conventional water resources to meet these needs in the long term.

At present, the various development plans envisaged for water resources and the opportunities for planned water transfer indicate that some hydrographical regions will show a shortage by the year 2020.

Moreover, the repeated drought cycles experienced since the end of the 1970s and the severity of those that took place at the beginning of the 1990s have reduced to a great extent those water resources that have already been harnessed. These resources appear to be limited in both time and space, and to be shared out in an unbalanced way. Besides, they are not located near the centres of water demand,
which continue to increase. This situation, together with the pressure exerted by the users of water resources, have urged Morocco to study the possibility of utilizing unconventional water resources on a large scale, mainly desalinated water; gradually this appears to be inevitable. Existing and potential sites for sea water desalination are given in Table I.

Development of water desalination relies not only on the evolution of desalination techniques but also on the source of energy used (fossil, renewable and nuclear). Both have to be taken into consideration when making an economic analysis of the

**TABLE I. DATA RELATING TO EXISTING AND POTENTIAL SITES FOR SEA WATER DESALINATION IN MOROCCO**

<table>
<thead>
<tr>
<th>Sites</th>
<th>Existing data</th>
<th>Projected data</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Capacity (m³/d)</td>
<td>Saturation point (year)</td>
<td>Capacity (m³/d)</td>
</tr>
<tr>
<td>Laayoune</td>
<td>7000</td>
<td>2000</td>
<td>14 000</td>
</tr>
<tr>
<td>Boujdour</td>
<td>800</td>
<td>2020</td>
<td>—</td>
</tr>
<tr>
<td>Agadir</td>
<td>—</td>
<td>45 000</td>
<td>2030</td>
</tr>
<tr>
<td>Tan–Tan</td>
<td>—</td>
<td>8000</td>
<td>2020</td>
</tr>
<tr>
<td>Essaouira</td>
<td>—</td>
<td>13 000</td>
<td>2020</td>
</tr>
</tbody>
</table>
production costs of desalinated water; the energy costs can be up to 40% of the water production costs.

2. SCOPE OF THE PRE-PROJECT FEASIBILITY STUDY

Studies carried out by the IAEA have revealed that use of nuclear energy for the desalination of sea water is technically feasible and can compete with fossil energy. Therefore, Morocco plans to carry out a specific study on the Tan–Tan site, which will require 8000 m$^3$/d of desalinated water by the year 2000. To this end, and within the framework of co-operation between China and Morocco, both parties, with the assistance of the IAEA, have decided to perform a joint pre-project study on a multi-effect distillation (MED) plant coupled to a 10 MW(th) heating reactor. Such a project has been recommended for demonstration in the IAEA's Options Identification Programme for Demonstration of Nuclear Desalination [1].

To launch this project, the two parties have drawn up the following documents:

1. An agreement between the Moroccan Ministry of Energy and Mines and the Chinese State Science and Technology Commission for co-operation in the pre-project study;
2. A proposal for the pre-project study.

The agreement was signed on 20 September 1996 in Rabat, Morocco.

The objectives of a demonstration plant are to build up technical confidence in the utilization of a nuclear heating reactor for the desalination of sea water; and to establish a database for reliable extrapolation of the water production costs for a commercial nuclear desalination plant (200 MW(th), 140 000 m$^3$/d).

The capacity and costs of producing drinking water are as follows: the production capacity of the demonstration facility will be approximately 8000 m$^3$/d; the water production costs of the demonstration plant have to be estimated and extrapolated for a commercial nuclear desalination plant; and the water production costs for a commercial nuclear desalination plant have to be competitive with fossil options.

The technical and economic aspects of the demonstration plant include: coupling of a nuclear reactor to a desalination plant; safety features; maintainability of the facility; and its economic competitiveness, providing elements for economic analyses.

Within the scope of this agreement, the obligations of each side are as follows:

(a) The Moroccan side is the co-ordinator of the pre-project study and is responsible for: the user's requirements for the nuclear desalination plant; the necessary data and information for a preliminary site assessment, and analysis of the
environmental impact; the related local economic parameters necessary for eco-
nomic analysis of the plant; and the data on local infrastructures, including
plant power, supply, service water system and other auxiliary systems.

(b) The Chinese side is responsible for: studies related to the reactor system and
estimation of the investment costs; studies on the sea water desalination system
and estimation of the investment costs; coupling of the reactor to the desalina-
tion plant; technical co-ordination with the vendor of the desalination equip-
ment; preliminary site evaluation and assessment of the environmental impact;
and economic analysis of the water production costs.

The agreement period is 18 months. When the agreement was signed, the
study started immediately. The Moroccan side has formed a committee composed of
some local firms, and the requests submitted by IAEA experts have been sent for
approval.

3. PROGRESS OF THE PRE-PROJECT STUDY

3.1. Site

One site has been chosen at Tan-Tan. This coastal site is located 330 km to the
south of Agadir City. Collection of data and information related to the technical, envi-
ronmental and economic aspects of the site has been launched. The first meeting on
the siting of the nuclear desalination plant is planned for July 1997.

3.2. Reactor study

The design of the proposed 10 MW(th) heating reactor is based on the
5 MW(th) version. The features and design of the proposed reactor are still being
studied by the Chinese side. Calculation of the neutron physics and thermal
hydraulics related to the 5 MW(th) reactor has been undertaken by the Moroccan
committee.

3.3. Desalination system

The MED process has been adopted by both Morocco and China because it has
a lower energy consumption and is less sensitive to corrosion. The first mission of
IAEA experts is expected to establish the terms of reference for the desalination plant
in June 1997. To date, all the necessary conditions have been met for implementing
the pre-project.
ACKNOWLEDGEMENT

The authors would like to thank the IAEA for its technical assistance.

REFERENCE

PANEL 1
Panel 1

THE CHALLENGES OF INTERNATIONAL CO-OPERATION

Chairperson: S.B. Abdel-Hamid (Egypt)

Members:
- J. Kupitz (IAEA)
- L. Awerbuch (International Desalination Association)
- E. Jankel (Middle East Desalination Research Center)
- M.F. Barakat (Arab Atomic Energy Agency)
- A.H. Nazemi (UNIDO)
- Joon Keuk Chung (Republic of Korea)

The panel was convened to address the challenges and opportunities afforded by international co-operation. A distinguished panel of experts from agencies and organizations whose role is to promote international co-operation, shared their views and experience.

One of the major themes expressed by panellists, and echoed by participants in the ensuing discussion, was that international co-operation can optimize the use of resources. In return, the benefits are shared by all. Pooling of resources encompasses both personnel and funds. However, the issue that must be addressed is how best this can be effectively and efficiently achieved, and with the necessary speed.

International co-operation can take place at many levels, including at the task, programme and project levels. The necessary agreements required to implement such co-operation may include bilateral and multilateral agreements among governments, and between governmental and non-governmental organizations (NGOs).

United Nations organizations can provide an umbrella for international co-operation. With its responsibility for the application of nuclear energy, the IAEA plays a leading role in nuclear desalination. Nevertheless, other UN organizations, such as the United Nations Industrial and Development Organization, can assist countries to enhance their level of industrial development.

NGOs can also play a significant role in creating opportunities for international co-operation, and in promoting co-operation and R&D, technology transfer, information exchange and technical training. They also provide a mechanism for overcoming some of the barriers to effective international co-operation, since they can often make decisions more quickly and, in some cases, may offer the opportunity for creative, non-traditional approaches that cannot be achieved in somewhat more traditional governmental institutions.

Regional co-operation among neighbouring countries is another important mechanism for pooling resources and sharing experience. Co-operation between
regional and international organizations can assist in establishing effective and efficient international co-operation. In particular, interaction between regional users and international suppliers can be beneficial.

Finally, it was noted that the question of public acceptance is an important consideration in international co-operation. Gaining public acceptance is one of our most important tasks, and to do so we must understand public attitudes and the social impact of our projects. International co-operation can promote the sharing of experience and the establishment of an effective information network that leads to better communications with the public and the media, drawing on techniques that have proved effective elsewhere.

The session closed with lively discussion from the floor. Suggestions for areas of future co-operation included the development of tools to improve both comparison of options and decision making on projects; an increase in the level of South–South co-operation; educational activities to enhance the level of public acceptance; sharing of databases and other technical information; development of safety regulations; and development of non-power options.

There is a strong belief in and support for nuclear desalination. Demonstration and implementation of nuclear desalination projects face many real challenges. International and regional co-operation provides a means of sharing information and resources such that these obstacles can be overcome and the dream of nuclear desalination realized.
TECHNICAL ASPECTS

(Session 3)

Chairpersons

Si Hwan KIM
Republic of Korea

L. AWERBUCH
International Desalination Association

Moon Hee CHANG
Republic of Korea
INTEGRATION OF NUCLEAR ENERGY AND DESALINATION SYSTEMS

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Abstract

INTEGRATION OF NUCLEAR ENERGY AND DESALINATION SYSTEMS.

As an international, intergovernmental organization, the IAEA encourages and assists research on and development and practical application of atomic energy for peaceful uses in order to accelerate and enlarge the contribution of nuclear energy to peace, health and prosperity throughout the world. Over the past 8 years, the IAEA has studied, with the cooperation and participation of many Member States, the feasibility of using nuclear energy for obtaining potable water through sea water desalination, which is an energy intensive process. On the basis of recent studies and the experience accumulated over the past years, the IAEA, in its recent study, the Options Identification Programme, has reviewed state of the art technologies that can be readily available in the near future. Amongst a variety of technological options, the study has explored sets of practical options for demonstrating nuclear desalination. These options foresee the use of well proven water cooled reactors for combining desalination processes. The programme has also identified the issues to be addressed for implementing demonstration and commercial deployment projects. The demonstration project will be helpful in building confidence and confirming the specific characteristics of a nuclear desalination facility. Nuclear desalination is an important option for solving the potable water supply problem.

1. INTRODUCTION

The growing demand for potable water in recent decades has raised interest in the use of nuclear energy for sea water desalination. The IAEA has therefore been studying the technical and economic feasibility of using nuclear reactors for this purpose [1].

Taking into consideration the study results at the time and in response to the increasing interest being shown in nuclear desalination¹, expressed at the 1993 session

¹ ‘Nuclear desalination’ is taken here to mean the production of potable water from sea water in an integrated complex in which both the nuclear reactor and the desalination system are located on a common site, the relevant facilities and services shared, and the energy used for the desalination process is produced by the nuclear reactor.
of the General Conference, the IAEA convened an Advisory Group Meeting (AGM) in 1994. The main conclusion of this meeting was that there was a need to establish a programme for identifying a practical\(^2\) set of options from which one or more demonstration facilities with well defined objectives might be chosen. Accordingly, it was recommended that the IAEA should undertake an Options Identification Programme (OIP). With the endorsement of the AGM's recommendation at the General Conference in its 1994 session, the 2 year programme was initiated in order to identify and define a set of practical options for the demonstration of nuclear desalination.

The objective of the OIP was to identify candidate reactor and desalination technologies that could serve as practical demonstrations of nuclear desalination, supplementing existing expertise and experience. To carry out the OIP, a Working Group was established that consisted of representatives from interested Member States and IAEA staff. The Working Group carried out its activities through a combination of periodic meetings and individual work assignments. The group called upon the services of a variety of specialists, as required, to address specific issues. Throughout the duration of the programme, peer review meetings were convened by the IAEA, through the mechanism of Advisory Group and Technical Committee Meetings. Because of the support provided by a number of Member States, in the form of expertise, relevant information and financial resources, the OIP was completed in mid-1996 with the publication of a technical document [2] that describes the main findings and conclusions.

2. PRACTICAL NUCLEAR DESALINATION OPTIONS FOR DEMONSTRATION

In the course of identifying practical options for demonstration, the list of available reactors was reviewed. A set of screening criteria based on design status and licensing status was used as a filter. Applying these criteria, the reactor technologies currently available or those that might become available within the next 10 years were identified (Table I).

Additional screening factors were then considered, including:

\(^2\) For an option to be practical, the following conditions should be fulfilled:

(1) There is no technical impediment to implementation, and a suitable site exists;
(2) It is technically feasible to be implemented on a certain predetermined schedule;
(3) The investment cost can be estimated within an acceptable range;
(4) The nuclear and desalination technologies used have promising prospects for future commercial application;
(5) The design and performance characteristics would be representative of commercial production facilities.
## TABLE I. SCREENED REACTORS

<table>
<thead>
<tr>
<th>Reactor name</th>
<th>Reactor type</th>
<th>Capacity (MW(e))</th>
<th>Criteria A: design status</th>
<th>Criteria B: licensing status</th>
<th>Screened value</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABWRA</td>
<td>BWR</td>
<td>1356</td>
<td>2</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>BWR 600</td>
<td>BWR</td>
<td>600</td>
<td>2</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>BWR 800</td>
<td>BWR</td>
<td>800</td>
<td>2</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>BWR 90</td>
<td>BWR</td>
<td>720</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>SBWR</td>
<td>BWR</td>
<td>600</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>AGR</td>
<td>GCR</td>
<td>610</td>
<td>2</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>GCR</td>
<td>GCR</td>
<td>555</td>
<td>2</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>MHTGR</td>
<td>GCR</td>
<td>$4 \times 173$</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>BN-350</td>
<td>LMR</td>
<td>90</td>
<td>2</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>BN-600</td>
<td>LMR</td>
<td>600</td>
<td>2</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>BN-800</td>
<td>LMR</td>
<td>800</td>
<td>2</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>PHENIX</td>
<td>LMR</td>
<td>250</td>
<td>2</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>SUPER-PHENIX</td>
<td>LMR</td>
<td>1240</td>
<td>2</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>CANDU 3</td>
<td>PHWR</td>
<td>450</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>CANDU 6</td>
<td>PHWR</td>
<td>660</td>
<td>2</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>PHWR 220</td>
<td>PHWR</td>
<td>220</td>
<td>2</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>PHWR 500</td>
<td>PHWR</td>
<td>500</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>PHWR 700</td>
<td>PHWR</td>
<td>700</td>
<td>2</td>
<td>1</td>
<td>2</td>
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<tr>
<td>PHWR 900</td>
<td>PHWR</td>
<td>915</td>
<td>2</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>AP 600</td>
<td>PWR</td>
<td>600</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>KLT-40</td>
<td>PWR</td>
<td>35</td>
<td>2</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>NHR 200</td>
<td>PWR</td>
<td>200</td>
<td>2</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>PWR</td>
<td>PWR</td>
<td>600</td>
<td>2</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>PWR</td>
<td>PWR</td>
<td>900/1000</td>
<td>2</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>PWR</td>
<td>PWR</td>
<td>1200/1500</td>
<td>2</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>QP 300</td>
<td>PWR</td>
<td>300</td>
<td>2</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>SES 10</td>
<td>PWR</td>
<td>10</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>WWER 1000</td>
<td>PWR</td>
<td>1000</td>
<td>2</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>WWER 440</td>
<td>PWR</td>
<td>440</td>
<td>2</td>
<td>1</td>
<td>2</td>
</tr>
</tbody>
</table>

*Note: Screening criteria — A: design status 2: in operation or under construction. 1: detailed design. 0: conceptual or basic design. — B: licensing status 1: licensed or in licensing. 0: not submitted for licensing.*
(1) Various reactor designs that are not commercially offered were screened out;
(2) LMRs and HTGRs are unlikely to be commercially available in the near term;
(3) Large reactors are unlikely to fit the electric grids of most water short countries;
(4) Small reactors currently appear to be economically less competitive; however, they may be feasible at sites with a low water demand and where alternative systems for potable water production are also expensive;
(5) BWRs are likely to require installation of additional systems in order to prevent radioactive release to the heat recipient systems.

Consideration was also given to those desalination technologies that are suitable for coupling to a nuclear reactor. Desalination of sea water using the reverse osmosis (RO) and multi-effect distillation (MED) processes appears to be the most promising option because of the relatively low energy consumption and investment costs of these processes, as well as their high reliability. Originally, the multi-stage flash (MSF) process was also taken into consideration. However, MED has a lower energy consumption and appears to be less sensitive to corrosion and scaling than MSF. Also, its partial load operability is more flexible. Therefore, MSF has been excluded because it shows no inherent advantages over MED.

The desalination processes for demonstration need not be of large scale commercial production capability. Two or three trains or units could provide design and operational performance characteristics that are fully representative of larger scale production facilities, since larger plants are simply multiple trains or units operated in parallel.

When combining a nuclear reactor and a desalination process to form an integrated facility, their compatibility was taken into account in the selection procedure. The scheduling, infrastructure and investment requirements were also considered for their significance in identifying the practical options for demonstration.

As a result of the above screening, three options were identified as being practical candidates for nuclear desalination demonstration. These options use well proven water cooled reactors and desalination technologies.

Option 1: RO desalination in combination with a nuclear power reactor being constructed, or in an advanced design stage with construction expected in the near term. The preferred capacity of the reactor is in the medium sized range. Two or three RO trains, up to 10 000 m$^3$/d each, would provide suitable demonstration. A newly constructed reactor offers the best opportunity to fully integrate the RO and reactor systems, including feedwater preheating and system design optimization. Such demonstration could readily be extrapolated to larger scale commercial production facilities.

There are about 12 power reactors under construction at the sea, one of which, in the Republic of Korea, is a medium sized PHWR. Other reactors are in an advanced
design stage, and their construction is expected to start in the relatively short term, including some medium sized PHWRs and PWRs.

Option 2: RO desalination, as above, in combination with a currently operating reactor. Some minor design modifications to the periphery of the existing nuclear system may be required. The advantages include a short implementation period, a broad choice of reactor sizes and the availability of nuclear infrastructures. A reactor in the medium sized range is preferred, as it provides a system that is similar to the one which would most likely be used in commercial production facilities.

Nearly 70 nuclear power plants are operating at the sea worldwide. Most are multi-unit stations covering a wide range of sizes. Several reactors suitable for demonstration could be available.

Option 3: MED desalination in combination with a small reactor, which would be suitable for demonstrating nuclear desalination with a capacity of up to 80 000 m$^3$/d.

There could be several suitable small reactors available. The Russian Federation’s power reactor originally developed for icebreakers and China’s heat only reactors may be suitable options.

The cost of power and water for the nuclear desalination options on a commercial scale was estimated with the Co-generation/Desalination Economic Evaluation spreadsheet programme developed by the IAEA. The methodology used in this programme for comparative economic evaluations is to compare the lifetime levelized unit costs of the potable water produced. This levelized cost is obtained by dividing the total expenses related to the production of water (capital charges, energy charge, operation and maintenance costs) by the total amount of water produced, where proper discounting is done using a predetermined discount rate.

As a representative example it was assumed that the nuclear desalination plants would be located on the North African coast or at other sites with similar conditions. Tables II and III summarize the levelized water costs of the nuclear desalination options with MED and RO, respectively. These values indicate the competitiveness of the water produced compared with that produced at conventional desalination plants using fossil fuel.

All the parameter and cost values adopted in the economic analysis are best estimates, or assumptions based on available information and experience. They correspond to selected reference values within reasonable ranges. Significant uncertainties result from predetermining the discount rate on a long term.
<table>
<thead>
<tr>
<th></th>
<th>Large sized PWR</th>
<th>Medium sized PWR/PHWR</th>
<th>Small sized PWR</th>
<th>Heating reactor</th>
<th>Medium sized fossil combined cycle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gross thermal power (MW(th))</td>
<td>2740</td>
<td>1940</td>
<td>2 \times 160</td>
<td>200</td>
<td>1200</td>
</tr>
<tr>
<td>Power plant net output (MW(e))</td>
<td>912</td>
<td>620</td>
<td>2 \times 36</td>
<td>196\textsuperscript{b}</td>
<td>615</td>
</tr>
<tr>
<td>Levelized power cost (US $/kW(e)-h)</td>
<td>0.042</td>
<td>0.047</td>
<td>0.096</td>
<td>N/A</td>
<td>0.042</td>
</tr>
<tr>
<td>Purchased power cost (US $/kW(e)-h)</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>MED plant capacity (m\textsuperscript{3}/d)</td>
<td>506 000</td>
<td>294 000</td>
<td>216 000</td>
<td>414 000</td>
<td>216 000</td>
</tr>
<tr>
<td>Gained output ratio (kg/kg)</td>
<td>7.6</td>
<td>4.5</td>
<td>4.5</td>
<td>18.3</td>
<td>11.5</td>
</tr>
<tr>
<td>Electricity to grid (MW(e))</td>
<td>790</td>
<td>838</td>
<td>564</td>
<td>467</td>
<td>559</td>
</tr>
<tr>
<td>Investment cost of a MED plant (US $10\textsuperscript{6})\textsuperscript{c}</td>
<td>660</td>
<td>409</td>
<td>312</td>
<td>282\textsuperscript{d}</td>
<td>617</td>
</tr>
<tr>
<td>Annual operating cost of a MED plant</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fixed capital charge, 8% for 30 years (US $10\textsuperscript{6}/a)</td>
<td>65.8</td>
<td>39.2</td>
<td>29.9</td>
<td>26.0</td>
<td>61.5</td>
</tr>
<tr>
<td>Heating charge (US $10\textsuperscript{6}/a)</td>
<td>16.7\textsuperscript{e}</td>
<td>8.2\textsuperscript{e}</td>
<td>7.4\textsuperscript{e}</td>
<td>20.6</td>
<td>32.8\textsuperscript{e} 10.7\textsuperscript{e}</td>
</tr>
<tr>
<td>Electric power charge (US $10\textsuperscript{6}/a)</td>
<td>17.2</td>
<td>12.3</td>
<td>10.1</td>
<td>6.3</td>
<td>10.3</td>
</tr>
<tr>
<td>Operation and maintenance costs (US $10\textsuperscript{6}/a)</td>
<td>14.0</td>
<td>8.6</td>
<td>6.5</td>
<td>4.9</td>
<td>6.4</td>
</tr>
<tr>
<td>Total annual water MED cost (US $10\textsuperscript{6}/a))</td>
<td>113.7</td>
<td>68.3</td>
<td>53.9</td>
<td>57.8</td>
<td>116.5</td>
</tr>
<tr>
<td>Levelized specific water cost (US $/m\textsuperscript{3})</td>
<td>0.85</td>
<td>0.88</td>
<td>0.96</td>
<td>1.52</td>
<td>0.92</td>
</tr>
</tbody>
</table>

\textsuperscript{a} Based on the average site specific condensing temperature (33.5°C).

\textsuperscript{b} Net thermal output.

\textsuperscript{c} Without interest during construction.

\textsuperscript{d} Does not include the investment cost of the energy source, which is included in the heating charge.

\textsuperscript{e} Heating charge is taken to be the revenue that would have been accrued from lost electricity generation (due to delivery of heating).
### TABLE III. LEVELIZED WATER COSTS OF AN RO PLANT

<table>
<thead>
<tr>
<th></th>
<th>Large sized PWR</th>
<th>Medium sized PWR/PHWR</th>
<th>Small sized PWR</th>
<th>Medium sized fossil combined cycle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gross thermal power (MW(th))</td>
<td>2740</td>
<td>1940</td>
<td>2 x 160</td>
<td>1200</td>
</tr>
<tr>
<td>Power plant net output (MW(e))</td>
<td>912</td>
<td>620</td>
<td>2 x 36</td>
<td>615</td>
</tr>
<tr>
<td>Levelized power cost (US $/kW(e)-h)</td>
<td>0.042</td>
<td>0.047</td>
<td>0.096</td>
<td>0.042</td>
</tr>
<tr>
<td>RO plant capacity (m³/d)</td>
<td>504 000</td>
<td>504 000</td>
<td>144 000</td>
<td>504 000</td>
</tr>
<tr>
<td>Electricity to grid (MW(e))</td>
<td>805</td>
<td>514</td>
<td>41</td>
<td>509</td>
</tr>
<tr>
<td>Investment cost of an RO plant (US $10⁶)</td>
<td>458</td>
<td>458</td>
<td>458</td>
<td>509</td>
</tr>
<tr>
<td>Fixed capital charge, 8% for 30 years (US $10⁶/a)</td>
<td>45.6</td>
<td>45.6</td>
<td>13.7</td>
<td>45.6</td>
</tr>
<tr>
<td>Electric power charge (US $10⁶/a)</td>
<td>38.3</td>
<td>42.1</td>
<td>21.9</td>
<td>38.6</td>
</tr>
<tr>
<td>Operation and maintenance costs (US $10⁶/a)</td>
<td>32.3</td>
<td>32.3</td>
<td>9.8</td>
<td>32.2</td>
</tr>
<tr>
<td>Total annual water RO cost (US $10⁶/a)</td>
<td>116.2</td>
<td>120.0</td>
<td>45.4</td>
<td>116.4</td>
</tr>
<tr>
<td>Levelized specific water cost (US$/m³)</td>
<td>0.69</td>
<td>0.72</td>
<td>0.95</td>
<td>0.70</td>
</tr>
</tbody>
</table>

*a* Based on the average site specific condensing temperature (33.5°C).

*b* Without interest during construction.
3. IMPLEMENTATION OF A DEMONSTRATION PROGRAMME

The process of identifying and characterizing demonstration candidates during the OIP required consideration of the many issues that have to be addressed for nuclear desalination and for commercial deployment.

A demonstration programme is intended to promote confidence and to confirm specific characteristics or parameters considered to be important in the design, construction, operation and maintenance of a nuclear desalination facility. A number of subjects were identified for more thorough examination and evaluation, covering technical, safety and economic issues, including:

(1) The interaction between nuclear reactors and desalination systems;
(2) The nuclear safety requirements specific to nuclear desalination systems;
(3) The impact of feedwater preheating on the performance of RO systems.

Desalination facilities connected to nuclear power plants in Kazakhstan and Japan have been producing desalted water for many years. In Kazakhstan, the liquid metal cooled fast reactor BN-350 has been operating since 1973 as an energy source for MED and MSF desalination units to produce potable water [3]. In Japan, several nuclear power plants of the electric power companies have sea water desalination systems (MED, MSF and RO) using heat and/or electricity to produce feedwater for the steam generator and for the on-site potable water supply [4]. The experience gained to date is encouraging, but it does not cover all aspects of interest to future users and designers. Consideration should be given to this valuable experience in order to determine those issues that should be specifically addressed in other ongoing or planned activities and projects on nuclear desalination.

National and bilateral activities and projects will contribute to international experience in nuclear desalination. For other interested Member States it will be important to utilize this experience. Such projects will undoubtedly be useful for commercial deployment, thus contributing towards solving the potable water supply problem in the next century.

The infrastructure requirements for nuclear desalination plants are primarily determined by what is required for nuclear facilities. These requirements are a major issue for Member States without previous nuclear power experience.

4. ISSUES FOR COMMERCIAL PRODUCTION FACILITIES

There are a number of issues related to commercial production facilities. Most of the technical aspects could be addressed through the mechanism of demonstration,
which would ultimately enhance the level of confidence in commercial deployment. The following issues are of particular importance and should be thoroughly addressed before commercial deployment:

(1) User requirements;
(2) General aspects, such as site selection and site qualification, scheduling, workforce and organizational requirements;
(3) Local and national infrastructure development.

National policies of importance to nuclear desalination are:

(a) A national development plan, including priorities for industrial and rural development;
(b) A national energy plan, including objectives for energy supply assurance, diversification and environmental protection;
(c) A national potable water supply assurance plan;
(d) Policies concerning international relations, including non-proliferation aspects and regional co-operation;
(e) Policies concerning financing, governmental involvement and promotion.

The following requirements will be essential to the success of commercial nuclear desalination deployment:

(i) A long term potable water supply deficit;
(ii) Suitable coastal site(s), within an acceptable distance to water consumption centres;
(iii) Firm governmental commitment, based on national policies and plans, and adequate international arrangements;
(iv) Economic competitiveness, with alternative supply options;
(v) Plant design, based on proven nuclear power and desalination technologies;
(vi) Regulatory issues, which should be resolved before the start of construction;
(vii) Efficient project management, with tight control of quality, costs and schedule;
(viii) Secured financing.

5. ADDITIONAL FINDINGS OF THE OIP

In response to the increasing interest shown by Member States for nuclear desalination, the IAEA performed a 2 year OIP, as requested at the 1994 General Conference. The main findings of the OIP are summarized below.
(1) *Demand for sea water desalination*

There is a clear demand for the increased use of sea water desalination, confirming the results obtained in earlier studies, both in those countries and regions that already deploy this supply option, and in others that will face a potable water shortage in the medium to long term.

According to a market survey performed within the framework of the OIP, the worldwide demand for desalination is expected to double approximately every 10 years in the foreseeable future. Most of the demand is in the Gulf and the North African regions, but this is likely to expand to other areas.

It is expected that most of the desalination plants to be built will be in three distinct sizes: small (capacity of less than 10 000 m\(^3\)/d), medium (50 000–100 000 m\(^3\)/d) and large (200 000–500 000 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.

(2) *Prospects for nuclear desalination*

Many years of successful operation have proved the technical feasibility, compliance with safety requirements and reliability of co-generation nuclear reactors supplying electric power and energy for district heating or for industrial use. 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 alternative supply options, and on adequate confidence in its application.

Should these conditions be satisfied, there appear to be sufficient incentives for nuclear desalination plants to penetrate the potable water market, in the same way as nuclear power reactors previously penetrated the electricity market worldwide. It is not reasonable to expect nuclear desalination to replace currently operating fossil fuelled desalination plants or to displace such options completely in the foreseeable future, but it could be commercially deployed in situations where new facilities are being considered. The continuing and increasing interest being shown at the IAEA's General Conference, as well as the monetary and in-kind support received by the IAEA from many Member States, are clear indications of the improving prospects for nuclear desalination.

(3) *Role of a demonstration programme*

A demonstration programme, as well as any individual demonstration project, must have the ultimate objective of facilitating and promoting commercial deployment of nuclear desalination. Therefore, the programme and the projects have to be
directed towards those issues that are relevant to commercial projects. These issues include technical, economic, financial, safety, infrastructural and institutional aspects. Demonstrations would provide very useful support for promotion and confidence building, which is a gradual process. Some issues, in particular those technical features that have a major impact on economic competitiveness and on the overall economics of nuclear desalination, need to be demonstrated to confirm assumptions and estimates.

Several countries have ongoing activities on nuclear desalination. Japan and Kazakhstan are operating nuclear desalination facilities, and Canada, China, India, the Republic of Korea, Morocco and the Russian Federation are proceeding with relevant activities or projects. All these activities serve the purpose of demonstration, and will undoubtedly contribute towards the building up of confidence in nuclear desalination, not only in these countries but also worldwide.

(4) Practical demonstration options

The main objective of the OIP was to identify suitable practical options which, if implemented, will facilitate and promote commercial deployment of nuclear desalination.

Nuclear reactors and desalination processes were selected that would need no further development at the time of project implementation and that could be combined with an integrated nuclear desalination facility. Some nuclear reactors were preferred (PWRs in the 600 MW(e) and 50 MW(e) ranges, PHWRs in the 450–600 MW(e) range, and heat only reactors of up to about 200 MW(th)). Among the desalination processes, RO and MED were selected because they were found to be the most promising processes in the medium to long term.

It has been concluded that the demonstration options described in Section 2 could be implemented if interested investors should decide to do so. The investment costs would be of the order of US $25–50 million for the RO options and US $200–300 million for the MED option, the latter including the reactor cost.

The next step towards proceeding with a nuclear desalination demonstration programme would be for one or more Member States to initiate the project related preparatory steps, including identification of user requirements, site selection and qualification, project specifications and development of the infrastructures required for project implementation. Upon request, the IAEA could assist Member States in moving ahead with these activities.

If a demonstration project is implemented in a Member State initiating a nuclear power programme, this could be a very effective and practical way of developing its nuclear infrastructure, in particular the necessary nuclear regulatory structure.
6. IAEA REACTOR SIMULATORS

All the reactors recommended within the framework of the OIP for demonstration of nuclear desalination are in the small and medium sized range. The IAEA has made available to interested Member States a training package to provide insights to and an understanding of the design and operational characteristics of various power reactor systems in this size range. A computer code is provided for a broad based audience of technical and non-technical personnel as an introductory educational tool to observe and compare the general response of different power reactor types to a variety of operational and accident conditions, in particular for developing countries interested in the utilization of nuclear power. The code can be operated on a personal computer with enhanced capabilities.

The simulation includes replication of the behaviour and performance of general design conditions for generic 600 MW(e) PWR, BWR and PHWR plants. For the PWR, plants with vertical inverted U bend steam generators, as designed in industrialized countries, and with horizontal steam generators, as designed in the Russian Federation, are covered. Simulated plant response covers normal operating conditions, startup and shutdown, power manoeuvring, abnormal and operational transients, and the corresponding sensitivity studies.

7. CONCLUSIONS

The IAEA's economic assessment has 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 other sites with similar conditions. It ranges between US $0.8 and US $1/m³, depending on the site conditions and the plant capacity of the nuclear and desalination systems. Demonstration projects will contribute towards confirming the parameters and conditions used in the assessment and promoting confidence in the economic feasibility.

Recommended sets of options in the recent OIP are based on well proven and widely operated systems: water cooled nuclear reactors and MED and RO desalination processes. For demonstration purposes, the plant capacity can be lower, thus reducing the investment and the implementation period. In most cases, nuclear reactors in the medium sized range are considered preferable. Small sized reactors can also be practical, depending on the site conditions.

On the basis of these economically and technically feasible options, nuclear desalination can certainly offer a practical choice to decision makers, thus contributing towards solving the potable water problem in water short regions worldwide. It is important to share the knowledge and experience gained among interested Member States.
REFERENCES


TECHNICAL ISSUES SURROUNDING DESALINATION PLANTS

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Abstract

TECHNICAL ISSUES SURROUNDING DESALINATION PLANTS.

The principal technologies used in desalination (multi-stage flash, multi-effect evaporation, vapour compression, electrodialysis and reverse osmosis) are based on concepts that are fairly easy to grasp by those with a modest amount of scientific training and/or technical experience. In practice, however, choice of technology, plant design and reliability in operation are usually determined by factors that might appear minor to the inexperienced. Similarly, new technologies showing great promise at the laboratory level frequently fail for reasons that were earlier overlooked or ignored as being trivial. Indeed, professional fascination with specific technical details has in some cases led researchers to remain oblivious to the inherent natural limitations of a process. A description is given of a number of such factors and how they have or have not been overcome in practice. Comments are also made on new criteria for desalination R&D support that might improve the practical return on such investment.

1. MAGNITUDE OF THE CHALLENGE

Sea water can contain 30 000 to more than 50 000 ppm of dissolved solids. This means that 1 m$^3$ may contain some 30 to more than 50 kg of solids. A competitive process today must be able to separate these constituents for about US $1 in total costs. This is a major challenge, reduced to its simplest form. The implications of this are often neglected by researchers seeking new separation methods.

For example, methods based on selective adsorption or absorption (e.g. ion exchange or aerogel absorption) must utilize comparable quantities of adsorbents or absorbents. To minimize capital investment in such reagents, cycle times for salt loading and regeneration must be very short. However, short cycle times require fast kinetics, often difficult if diffusion is relied upon for mass transfer. The trap that researchers often fall into is to fixate upon what is likely to be the low energy consumption of a process proceeding to thermodynamic equilibrium, rather than the kinetics of heat and mass transfer, allowing the design of practical equipment of modest size and cost.
2. MINOR CONSTITUENTS OF SEA WATER

2.1. Inorganics

If sea water consisted only of $\text{H}_2\text{O}$ and $\text{NaCl}$, the desalter's assignment would be considerably simplified. Unfortunately, however, sea water as it is found in nature is contaminated by many inorganic ions, with the result that many compounds are in solution at concentrations at or near their saturation levels. To worsen the situation, some of these have solubilities that decrease with increasing temperature. As a result, local conditions within operating desalination equipment frequently exceed these solubility levels.

Elaborate precautions are very often needed to prevent these materials from depositing on surfaces, where they retard the process by diminishing heat or mass transfer. Such precautions can include:

1. Pretreatment of feedwater to remove certain critical species (e.g. softening);
2. Alteration of the chemical conditions to increase solubility (e.g. addition of acid);
3. Modification of the morphology of insoluble species to prevent the formation and adherence of scale on critical surfaces (e.g. polyelectrolyte addition).

Such measures can be very successful, but inherently add capital and operating costs to the system, as well as opportunities for malfunction. They must be incorporated into the very earliest planning and design phases of any successful system.

2.2. Gases

Non-condensable gases such as nitrogen and oxygen that exist in solution may be released and form inert blanketing layers on surfaces where material or heat transfer is expected to take place. In evaporative plants, they can accumulate in the vapour space and retard the evaporation rates. They may also be introduced through ambient air leakage into systems operating at subatmospheric pressures and from the breakdown of chemical constituents. Chemically active gases such as oxygen, carbon dioxide, chlorine or hydrogen sulphide may lead to the corrosion of metals, other oxidizing problems, odour problems, changes in acidity and formation of insoluble species.

In evaporative systems, non-condensable gases are usually extracted by a vacuum system that continuously withdraws them (and a small amount of water vapour) from one or more carefully selected points in the vapour spaces of the equipment. There are associated capital and energy costs, but these are offset by the increased productivity of present day designs. However, proposed new evaporative systems frequently
overlook these venting issues and costs, or postpone their treatment until late in the development cycle, when they prove to be the undoing of the effort.

2.3. Biological activity

Living entities in raw sea water can form surface films that retard heat and mass transfer, and can grow to cause partial or complete blockage of the flow paths. Such films can also provide sites conducive to increased corrosion, or disturbances in the flow path, leading to cavitation and pitting. Some species can degrade critical plastic materials such as cellulosic membranes. The chemical and physical means of precluding these problems all bring with them attendant costs and 'side effects'. In particular, they require careful operating control, as the window for reliable operation can be very narrow.

2.4. Variability in contamination

The challenges cited above are frequently exacerbated by large variations in their occurrence in sea water, over both time and location. Sampling and analyses of the feedwater chemistries used in plant design must anticipate not only tidal and seasonal variations but also variations brought about by the effect of the plant itself on its local environment. Short term variations on an hourly or daily basis can also lead to process upset, and can best be coped with through the use of real time monitoring and feedback, where such instrumentation exists. Despite the best planning, unanticipated excursions into contamination (or operator attention) will occur, and therefore any design must contain a realistic level of forgiveness.

3. Predictability of the energy supply

A desalting plant must be able to anticipate the costs of its energy supply; the reliability of this supply is also critical. Probably the strongest reason for unscheduled down time in large dual purpose multi-stage flash (MSF) evaporators is loss of the steam supply. This can be due to operating problems on the boiler/generator side of the plant, or to reduced power demands by the grid. Coupling an evaporative plant to a steam turbine generator operating in the base load mode usually minimizes, but never completely eliminates, this problem. Other co-generation schemes must look carefully at the continuity of the steam source. The total water costs are calculated by dividing the total annual costs (including capital recovery and other fixed costs) by the total annual production, so production losses can seriously degrade the total water costs.
4. SPACE CONSIDERATIONS

When installing a desalination plant as part of a developed industrial or municipal complex, available space is frequently at a premium. Even in rural areas where space may be nominally inexpensive, a properly prepared site can be costly and is frequently not available. Thus, compactness is among the desirable features of a desalination system. Today’s reverse osmosis systems offer remarkable productivity per unit volume or footprint, but this can often be offset by the space required for extensive pretreatment of the feedwater. Evaporative plants tend to be bulkier, but require far less pretreatment.

5. CONSTRUCTION TIME

The usual system of plant feasibility study, bid preparation and award can be lengthy and is frequently drawn out further by complex negotiations and even rebidding of the project. However, when the final purchase decision is made, the customer will want the plant constructed and commissioned immediately. Lengthy construction periods tie up working capital, increase indirect construction costs and postpone the benefits to the customer of a completed plant. When other cost and performance factors are comparable, the delivery date (or projected on-stream date) is of great importance. Plants that are pre-engineered and prefabricated in a modular form for ease of transportation and on-site assembly have great advantages over plants requiring extensive on-site construction.

6. WASTE HEAT DILEMMA

Enormous quantities of low grade (low temperature) heat are frequently available from direct solar energy or spent industrial processes. Such sources of ‘free energy’ have been identified for over a century. However, exploitation of these sources has fallen short of expectations. The reason lies largely in a misjudgement of the balance between thermodynamics (the amount of energy potentially available) and kinetics (the rate at which this energy can be extracted and put to good use). When applied to desalination, it is frequently true that the kinetics can only be improved by considerable investment in the heat transfer surface area and, hence, the capital costs. Thus, for example, solar ponds are still not used in practice to power desalination, despite decades of glowing predictions for their success.

When considering the utilization of such sources of low grade energy, it is illustrative to consider a fictitious ‘free energy generator’ as a limiting case. This hypothetical machine is a completely maintenance free apparatus that will supply a
desalination plant with all the energy it requires, at zero operating cost. The key question, of course, is 'How much can one justify spending for such a thing?' Let us look at a specific example.

Suppose that a certain sea water reverse osmosis plant produces 4000 m$^3$/d of product water, 330 d/a, with an energy consumption of 4 kW-h/m$^3$. Let us also assume that the capital cost of the plant is US $5 million (US $1250-m^3-d^{-1}) and that the plant life is projected to be 20 years. We can then calculate the annual cost of energy to the plant for a range of possible energy prices. The present value of these energy costs over the life of this plant, assuming certain interest rates or costs of capital, will tell us how much we can afford to spend on this fictitious free energy generator. Table I gives these current values, reported as percentage increments to the cost of the conventional plant.

Thus, if the energy costs are US $0.10/kW-h and the cost of capital is 7.5%, one cannot afford to increase the plant cost by more than 27% (US $1.35 million in this case) to completely eliminate all energy costs forever. As the conventional plant consumes energy at a rate of 667 kW, we may also say that the free energy generator must be priced at less than US $1.35 million/667 kW or US $2000/kW. If this should be a solar powered system, this US $2000/kW must also include the cost of energy storage and conditioning to allow 24 hour operation. Such attention to the capital equivalent of energy costs is important in justifying the expenditures for energy saving improvements.

### TABLE I. COST INCREASE JUSTIFIED FOR FREE ENERGY GENERATOR

<table>
<thead>
<tr>
<th>Energy cost (US $/kW-h)</th>
<th>Annual energy cost (US $)</th>
<th>Possible interest rates (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>5</td>
</tr>
<tr>
<td>0.04</td>
<td>52 800</td>
<td>13</td>
</tr>
<tr>
<td>0.06</td>
<td>79 200</td>
<td>20</td>
</tr>
<tr>
<td>0.08</td>
<td>105 600</td>
<td>26</td>
</tr>
<tr>
<td>0.10</td>
<td>132 000</td>
<td>33</td>
</tr>
<tr>
<td>0.12</td>
<td>158 400</td>
<td>39</td>
</tr>
<tr>
<td>0.14</td>
<td>184 800</td>
<td>46</td>
</tr>
<tr>
<td>0.16</td>
<td>211 200</td>
<td>53</td>
</tr>
<tr>
<td>0.20</td>
<td>264 000</td>
<td>66</td>
</tr>
</tbody>
</table>
7. CAN THE ABOVE ISSUES BE SUCCESSFULLY ADDRESSED?

Absolutely. All the above issues are being addressed today in successful commercial plants, but they must be considered at the earliest design and planning stages. As proof that they can be dealt with, we need only point to the thousands of successful installations around the world, and to the fact that the most modern plants being put into operation at this moment are capable of converting sea water to potable water at total water costs (operating costs plus capital recovery) of not much more than US$1/m³ of product. This is a remarkable achievement, reached after decades of paying attention to details and seemingly unimportant secondary matters.

Research into new and improved desalination systems must bear in mind that it is usually 'secondary issues' such as those cited above that determine the eventual success or failure of a candidate system. Failure to realize this has led to wasted time, money and talent in the past and, given human nature, will probably continue to do so in the future.
SAFETY ASPECTS OF THE DESALINATION OF SEA WATER USING NUCLEAR ENERGY

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Abstract

SAFETY ASPECTS OF THE DESALINATION OF SEA WATER USING NUCLEAR ENERGY.

The nuclear plants for desalination to be built in the future will have to meet the standards of safety required for the best nuclear power plants currently in operation or being designed. Some specific characteristics of desalination plants such as siting and coupling require particular consideration from a safety point of view, and further safety studies will be needed when the type and size of the reactor are determined. The current safety approach, based on the defence in depth strategy, has been shown to be a sound foundation for the safety and protection of public health, and gives the plant the capability of dealing with a large variety of sequences, even beyond the design basis. The Department of Nuclear Safety of the IAEA is involved in many activities, the most important of which are to establish safety standards and to provide various safety services and technical knowledge in many Technical Co-operation assistance projects. The department is also involved in other safety areas, notably in the field of future reactors. The IAEA is carrying out a project on the safety of new generation reactors, including those used for desalination, with the objective of fostering an exchange of information on safety approaches, promoting harmonization among Member States and contributing towards the development and revision of safety standards and guidelines for nuclear power plant design. The safety, regulatory and environmental concerns in nuclear powered desalination are those that are related directly to nuclear power plants, with due consideration given to the coupling process. The protection of product water against radioactive contamination must be ensured. An effective infrastructure, including appropriate training, a legal framework and a regulatory regime, is a prerequisite to considering use of nuclear power for desalination plants, also in those countries with limited industrial infrastructures and little experience in nuclear technology or safety.

1. INTRODUCTION

Several desalination methods are technically feasible and available. Three are currently used on a large scale (multi-stage flash, multi-effect distillation and reverse
osmosis), although they have different production throughputs and require different quantities of thermal and electric energy. Reverse osmosis requires only electric power (5–7 kW·h/m³), while the other processes require electric and thermal energy (4.5–24 kW·h/m³).

Nuclear energy has proved to be a viable energy source for desalination, although the economics of the option need to be further investigated, taking into account the infrastructure necessary for nuclear power activities.

There has been a recent resurgence of interest in nuclear powered desalination in North African countries; indeed, the 1996 IAEA General Conference reaffirmed its importance and indicated that further activity was needed in this area. In the light of this interest, it is important to review recent developments in the safety of nuclear power plants and to address some general safety issues and regulatory aspects, as well as some specific safety issues pertinent to this application.

The general approach to safety of nuclear reactors supplying heat or electric power to desalination plants is equivalent to the approach used for nuclear power plants producing electricity. The nuclear plants for desalination to be built in the future will have to meet the standards of safety required for the best nuclear power plants currently in operation or being designed, and for this reason the safety aspects are common with those related to new generation reactors for which a dedicated programme exists at the IAEA. Most of the general safety considerations reported on here have been discussed and analysed during the development of this programme. Some specific characteristics of desalination plants such as siting and coupling require particular consideration from a safety point of view, and further safety studies will be needed when the type and size of the reactor are determined.

2. GENERAL SAFETY ASPECTS OF NUCLEAR POWER PLANTS

Application of the defence in depth strategy will continue to be the overriding approach for ensuring the safety of workers and the public, and for protecting the environment. This strategy is effective in compensating for human and equipment failures, both potential and actual. The concept is based on several levels of protection, including successive barriers that prevent the release of radioactive material to the environment. However, its efficacy depends on rigorous implementation. This implies a determined effort to make the defence effective at each level, particularly for accident prevention and accident mitigation. There is not a unique way to implement defence in depth, since there are different designs, different safety requirements in different countries, different technical solutions and varying management or cultural approaches. Nevertheless, the strategy represents the best general framework to achieve safety for nuclear power plants and, thus, nuclear powered desalination plants. In general, strong implementation of defence in depth requires a determined
and constant effort from the design phase to construction and operation in order to provide graded protection against a wide variety of transients, abnormal occurrences and accidents, including human error and equipment failures within the plant, and events initiated outside the plant.

2.1. Design basis approach and severe accident treatment

Operating nuclear plants are largely designed according to the design basis accidents approach. This means that the plant is deterministically designed against a set of hypothetical accident situations according to well established design criteria in order to meet the radiological targets. The current design basis approach has been shown to be a sound foundation for the safety and protection of public health, in part because of its broad scope of accident sequence considerations, but also because of its many conservative assumptions, which have the effect of introducing highly conservative margins into the design that, in reality, give the plant the capability of dealing with a large variety of sequences, even beyond the design basis. Often, probabilistic targets for core damage frequency and for containment performance are established. Experience and analysis have shown, however, that some sequences beyond the design basis (i.e. severe accidents) may need to be considered explicitly in the design, providing it with additional safety features to further prevent and mitigate such severe sequences. In this regard probabilistic safety assessment is recognized as a very efficient tool for identifying those sequences and plant vulnerabilities that require specific design features (elimination by design of the most challenging sequences to the containment). Such assessment, together with an effective containment system, including good control of potential containment bypass, ensure minimum radiological impact, with an extremely small chance of any off-site radioactive releases. For a nuclear powered desalination plant, the design basis may need to also include some transients or abnormal occurrences that might originate in the desalination unit itself.

2.2. Human error

In the past, the contribution of human error to events has been significant. Human errors are a potential source of impairment of defence in depth because human activity is involved at all levels of defence. Therefore, the objectives are that new designs be made simpler, and therefore easier to operate, and that specific design provisions be taken to make plants more tolerant to human failure, as well as to reduce the potential for human interference in initiating abnormal plant conditions.

The potential for a deterioration in defence in depth through human failure can be drastically reduced by introducing the following improvements, proposed for new reactors, to make plants more operator friendly:
(1) Major system simplification through better design and greater inherent design margins that reduce the need for overly complex control systems and procedures;
(2) A greatly improved man–machine interface, with priority given to clear and unambiguous indications of plant parameters, and simpler and more forgiving controls, with direct feedback on the results of actions taken;
(3) Prolonged grace periods by providing increased time constants for the reactor system, or by a higher degree of automation;
(4) Use of symptom based procedures to complement event based procedures for emergency/accident situations;
(5) Greater automation to prevent human error.

2.3. Shutdown and low power states

Recently, increased emphasis has been placed on consideration of non-power states. INSAG-3 and INSAG-10 state that, during normal power operation, all levels of defence should be available at all times. During other plant conditions, an appropriate number of levels have to be available in order to maintain an adequate level of safety. This is because, during certain shutdown conditions, radiological barriers may be rendered ineffective (e.g. reactor coolant pressure boundary, containment) for maintenance or other reasons. Future plants will ensure that the concept of defence in depth can be implemented appropriately under these specific shutdown conditions. Specifically, new reactor designs have explicitly addressed safety in non-power states, primarily through improved defences that reduce the probability and safety significance of loss of decay heat removal events. This is often a design specific determination.

3. SPECIFIC SAFETY ASPECTS OF DESALINATION PLANTS

Simple energy considerations based on a survey of possible sites in North Africa and for different desalination methods show that the total power (electric and thermal to supply potable water to a medium sized town) needed varies from a few to several hundred megawatts, and thus any proposed reactor falls into the small or medium sized category. Larger sizes would be required for the combined production of water and electric power.

The nuclear power plants used for water desalination have several characteristics that are similar to those power plants that are used for district heating reactors (e.g. siting, power size, possibility of combined production), and the experience gained with these plants should be considered in designing nuclear powered desalination plants.
3.1. Coupling

The overall safety of an integrated complex composed of a nuclear reactor plant coupled to a desalination plant is predominantly dependent on the safety of the nuclear reactor plant and the effect of coupling, or rather the interaction between the desalination plant and the nuclear plant. This interaction should be analysed in various coupling situations to assess its effect on the safety of the reactor and on the overall nuclear desalination system, either in normal operation or in an accident situation.

Coupling will not pose any new safety concern if desalination uses only electric power.

In thermal processes, the energy to be supplied is mainly low temperature process steam or water. Coupling is accomplished via a heat transfer circuit. Since radioactivity exists in the primary steam or hot water, the risk of contamination of product water exists and must be avoided. This can be done by adding intermediate loop(s) maintained at values of pressure such that any leakage would not produce transfer of contamination to the distributed water. These simple measures, together with appropriate instrumentation and monitoring, should be effective in preventing contamination of the distributed water. They do not seem to present any particular technical difficulty.

All the information available from the operating experience accumulated on an existing plant (Aktau, Kazakhstan) and from conventional desalination plants will also provide a valuable source of information for design and operation purposes. Operational transients in a desalination plant would have direct feedback into the reactor system. Such transients could have safety implications and need to be assessed.

3.2. Siting

For obvious reasons, the siting of a nuclear powered desalination plant raises some safety concerns, mainly because of the site selection restraints. The plant has to be built on a coastal site and near to populated areas in order to limit the cost of potable water distribution. The choice of site raises problems related to oceanography (tides, plant elevation) and very often to seismicity (frequent presence of faults on coasts).

The proximity of the nuclear desalination complex to population centres, with the implication on the design and on the emergency planning and water supply, should be examined.

If the site is in a remote area, an important aspect to consider is the availability of an adequate external electric power grid or supply for safe operation of the nuclear plant.
There are certain prerequisites for the safe utilization of nuclear power:

1. To establish a legislative and statutory framework for the regulation of nuclear facilities;
2. To establish a regulatory body that is independent of the organizations or bodies charged with the promotion or utilization of nuclear energy;
3. To ensure that this regulatory body has the responsibility for authorization (licensing), assessment, inspection and enforcement, and adequate authority, competence and resources to discharge its assigned responsibilities; no other responsibility assigned to the regulatory body should jeopardize or conflict with its responsibility for regulating safety;
4. To ensure that there is a clear delineation and separation of responsibilities between the regulatory body and the operating organization;
5. To ensure that adequate provision is made for the safe management of radioactive waste;
6. To establish governmental emergency response capabilities;
7. To ensure adequate physical protection arrangements;
8. To provide the technological infrastructure necessary to support the safety of facilities and the radiation related activities.

These basic requirements need to be established well in advance of constructing any nuclear facility, and will need considerable resource commitment from any country currently without a nuclear power plant.

In several cases, nuclear desalination plants may be proposed for countries with very little experience of nuclear technology and, in particular, of nuclear safety. The necessary creation of the infrastructure requires time, human resources and a great deal of training.

There are a large number of new designs that have been proposed for small or medium sized reactors. Although they are mainly based on existing proven technology, they include innovative solutions and systems that require a careful safety evaluation, a safety review and demonstration of licensability which, in some cases, cannot be done by the operator or the local licensing authority because of lack of experience or capability. Licensing of nuclear power plants involves considerable effort and expertise, and good communication between the nuclear authority, the operator and other national authorities. In the case of nuclear powered desalination, this will involve additional responsibilities dealing particularly with water use. Joint effort and co-ordination are envisaged between the designer, the utility and the local authorities.
5. THE ROLE AND ACTIVITIES OF THE IAEA

The Department of Nuclear Safety is involved in many activities, the most important of which are to establish safety standards, and to provide various safety services and technical knowledge in many Technical Co-operation assistance projects. The department is also involved in other safety areas, notably in the field of future reactors. The newly established Convention on Nuclear Safety was developed under the auspices of the IAEA.

The Agency produces many documents related to nuclear safety, the most important of which are those now to be included in the Safety Standards Series (SSS), formerly the Safety Series, which included the NUSS programme. The SSS will comprise three levels: Fundamentals, Requirements and Guides. They will be produced under the authority of the Advisory Commission for Safety Standards (ACSS) and its four subcommittees. These standards are written primarily for national regulatory bodies, which may wish to impose them upon licensees or other related organizations. They are, however, non-binding unless a Member State is receiving assistance or has an agreement with the Agency, in which case they are mandatory.

5.1. Safety Fundamentals (SFs)

Currently, there are three SF documents, but in the long term the aim is to combine these into a single document. These are the first documents in the hierarchy; they present basic objectives, concepts and principles to ensure safety in the development and application of atomic energy or radioactive material for peaceful purposes. The SF documents constitute the reasons why activities must fulfil certain requirements; they do not state what these requirements are, they are self-sufficient and do not include a list of references. In the SF on Safety of Nuclear Installations (SS-110), there are 25 fundamental principles grouped into four main areas related to the Legislative and Regulatory Framework, the Management of Safety, the Technical Aspects of Safety and the Verification of Safety.

5.2. Safety Requirements (SRs) and Safety Guides (SGs)

Supporting the SFs are Requirements (formerly termed Codes, Standards or Regulations). In the nuclear safety area, there will be four main areas: Siting, Design and Operation of thermal neutron nuclear power plants, and the Research Reactor Series, which has two SR documents. Previously, also Quality Assurance (QA) and Governmental Organization were included in the NUSS programme. These have been moved into a ‘general safety’ category and will be dealt with by the ACSS. All the existing NUSS codes (except QA, which was published in October 1996) are now
subject to a comprehensive revision process, which is being overseen by the Nuclear Safety Standard Safety Committee (NUSSAC). This revision will ensure that all the relevant principles in the SFs are systematically addressed, thus enabling a coherent set of documents to be produced. The SRs will set out in more detail what is required of Member States to ensure safety in a particular area, and they are governed by the content of the SFs. SRs do not generally present recommendations on or explanations of how to meet the requirements. This more detailed aspect is covered by the third level in the hierarchy, namely, the Safety Guides. The SGs present recommendations on the basis of international experience of the measures to be followed in order to meet the requirements set out in the SR documents.

The category of Safety Practice has now been abandoned and these detailed documents will form part of the new Safety Reports Series.

Safety Series documents also deal with Radiation Safety and Waste Safety; they also need to be used as references for national regulations.

5.3. Experience with existing nuclear power plants

Over recent years, the Agency has carried out many missions to operating nuclear power plants, some of which were to reactors of Eastern European countries often used for combined electric power generation and district heating. A mission was also conducted on the BN-350 plant at Aktau, Kazakhstan, which is coupled to a desalination plant.

The BN-350 is a sodium cooled fast reactor used to produce electricity and heat. The plant is operated by the Mangyshlak Power Generation Company and its output supplies a large industrial complex that is relatively isolated from the rest of the Kazakhstan electric grid.

The plant design output is 1000 MW(th), but the current operation is limited to 520 MW(th). The reactor itself is technically separated from the electricity/desalination/heat plant that takes the steam output and returns feedwater to the nuclear part of the installation.

Therefore, the nuclear safety aspects discussed during an IAEA mission carried out in March 1995 were limited to the nuclear reactor and its cooling system, and did not involve the desalination plant. The topics discussed included detection and control of sodium fires, component ageing, sodium corrosion, vessel in-service inspection, seismic safety and accident analysis.

With the independence of Kazakhstan, a new nuclear regulatory body has been created. However, the Kazakhstan Atomic Energy Authority still needs assistance in establishing a regulatory body in accordance with current international practice. The IAEA has approved a Technical Co-operation project to provide this assistance. Several nuclear plants in the world provide heat for nearby communities. This is a
common procedure in WWER plants (Bohunice, Paks, Kola) and other LWRs in cold regions.

Generally, the heated water (or steam) is generated in a separate heat exchanger using part of the steam extracted between the high pressure and low pressure turbines. The pressure in the hot water (steam) distribution system is high enough to ensure that any leaks in the heat exchanger will be into the plant system and not into the water (steam) distribution system. This provision prevents the transfer of possible contamination from the nuclear plants to the heat distribution network.

The technical decision on the amount of diverted steam for district heating purposes depends on economic factors and on the distances involved between a given plant and the nearby towns and villages. No specific safety concerns related to the district heating aspects have been raised during the safety review missions carried out by the IAEA at these plants.

5.4. **Current experience accumulated on research reactors**

Nuclear desalination plants have been proposed for various Member States, in particular, those that are located in arid areas of Africa, Asia and elsewhere. Many of these countries have no experience at all with nuclear reactors, while a few have one or more research reactors.

Reviewing the experience gained with research reactors in several developing countries, the following points can be made that may be applicable to a desalination project:

1. Experience with a research reactor facility may be quite useful, since it usually means that the country already has a nucleus of a regulatory authority; some infrastructure in radiation protection and waste effluent control related to nuclear reactors; a group of knowledgeable personnel in the areas of reactor operations and maintenance; programmes for the training of personnel; and experience with Agency sponsored projects.

2. A research reactor facility (especially a larger reactor) can be used to simulate or experiment with some of the processes associated with a desalination plant, and can also be used as a school for training the new staff needed for the new project.

3. Developing countries vary greatly in their political stability, economic wealth, technological infrastructure, logistical infrastructure, and general technical and safety related attitudes.

The following problems have been observed in various countries:

(a) The lack of ability to obtain fresh fuel or spare parts for the reactor because of political instability;
Negligence of important reactor systems that are out of order (for lack of resources, or a proper attitude, or both, in order to replace or repair them);
Lack of an adequate operating budget;
Failure to make use of Agency assistance (e.g. the equipment procured lies unused for years);
Inadequate security arrangements around the facility (even in riot prone countries);
The lack of any central inspection (e.g. licensing, radiation protection), which is in conflict with the statement made in the previous section;
Unreliable technical and logistical support (electricity, communications, general equipment and spare parts);
The inability to prepare and implement a priority based operational programme.

While gaining experience with a research reactor is expected, in general, to be useful as a first step before introducing nuclear power (or desalination), this same experience can shed light on the deficiencies that may undermine the prospects for such a project unless, in particularly serious cases, adequate international support can be provided.

5.5. IAEA activities on new generation nuclear power plants

The IAEA activities on the safety of new generation reactors, which were formally initiated after the Conference on the Safety of Nuclear Power: Strategy for the Future held in September 1991, are being carried out under the project Safety Approaches to the New Generation of Nuclear Power Plants, foreseen to continue for the next 2 years. The main objective of this project is to foster an exchange of information on safety approaches to new generation nuclear power plants with a view to promoting harmonization among Member States and contributing to the development and revision of safety standards and guidelines for nuclear power plant design. The revision is already in progress and relevant indications have been provided. It is expected that the new standards will have an impact on the design of all nuclear power plants, including those for desalination, to be constructed in the coming years.

In June 1995, following INSAG’s review and comments, the Agency published a technical document, Development of Safety Principles for the Design of Future Nuclear Power Plants (IAEA-TECDOC-801). The work tried to incorporate the lessons learned from recent operational experience, research and development, design, testing and analysis, as well as from attempts to reflect current trends in reactor safety design. It provides a basis for the development of safety objectives and principles for new generation nuclear power plants and for the revision of safety standards. The key proposal is that severe accidents beyond the existing design basis will be systematically considered and explicitly addressed during the design process for
future reactors. The design features provided to address severe accidents are not expected to meet the same stringent requirements (redundancy, diversity and conservative acceptance criteria) used for the safety features to cope with design basis accidents; however, they will be engineered in such a way as to give reasonable confidence that they are capable of achieving their design intent. The document also emphasizes the need to further lower the risk of any serious radiological consequences and to ensure that the potential need for prompt off-site protective actions can be reduced or even eliminated (good neighbour concept).

Other safety areas that are specifically addressed in TECDOC-801, and for which new or modified principles were suggested, are:

(1) **In the area of safety prevention**

   - Clarification of the use of probabilistic safety analysis;
   - Consideration of modes of operation other than full power (low power and shutdown);
   - Spent fuel handling and storage;
   - Multiple unit sharing equipment.

(2) **In the area of accident mitigation**

   - Confinement to mitigate the addressed severe accidents.

(3) **In the area of proven engineering safety practices**

   - Classification of the safety systems;
   - Standardization;
   - Consideration of the passive systems;
   - Plant security.

(4) **In the area of human factors**

   - Design to be user friendly and to avoid complexity;
   - Design to reduce dependence on operator action;
   - Consideration of operating and maintenance procedures since the design phase;
   - Plant security.

Additional effort has been made to prepare a technical document on the implementation of defence in depth for new generation nuclear power plants. The work was based on the report on defence in depth prepared by INSAG, and the main objective
was to bring together the relevant aspects of existing publications on both defence in depth and future reactor designs, and then to apply recent defence in depth formulations specifically to ongoing developments in future plant designs.

Particular attention has been focused on identifying and addressing those factors that have the potential to affect multiple levels of defence in depth. This provides high confidence that appropriate actions will be taken to ensure the effectiveness of the defence in depth concept against failures that have the potential to impact multiple levels of defence in depth (human failure, internal and external hazards, etc.).

The report provides a good general framework for a safety evaluation and also gives some indication as to how the defence of each level could be enhanced.

6. CONCLUSIONS

Use of the nuclear option as an energy source for the desalination process is feasible. The safety, regulatory and environmental concerns in nuclear powered desalination are those that are related directly to nuclear power plants, with due consideration given to the coupling process. It is important, however, to maintain a progressive approach and to take advantage of state of the art knowledge and techniques; for this reason it is expected that any reactors used for desalination purposes will be designed, constructed and operated in accordance with internationally recognized safety standards.

IAEA missions to operating nuclear power plants coupled to heat production and desalination plants have not revealed any serious specific safety concerns related to the interaction of the nuclear plant with the heat distribution plant or desalination plant, but they have shown that any safety concerns are related to the reactor itself.

Nuclear safety and environmental considerations in nuclear desalination are those that arise from the use of nuclear reactors as energy sources. Nuclear safety and regulatory actions should be based on relevant IAEA safety standards. In addition, as a specific requirement the design, operation and performance of an integrated nuclear desalination complex must ensure the protection of product water against radioactive contamination.

The most serious concern, as experience with research reactors has shown, arises from the fact that very often countries that need water are developing countries, with limited industrial infrastructures, and little experience in nuclear technology or safety. An effective infrastructure, including appropriate training, a legal framework and a regulatory regime, is a prerequisite to considering use of nuclear power for desalination plants.

Investing in safety, which includes upgrading the national infrastructure, developing competent staff, strengthening the regulatory regime and establishing a positive safety culture, is an essential requirement.
Another relevant aspect is the social and political instability of some countries, where nuclear facilities could be possible targets of external attack; the plant would require comprehensive physical protection arrangements.

With respect to existing international safety standards and guides, they also seem to be appropriate for covering desalination plants. There seems to be no need to prepare any specific guidance for the safety of nuclear powered desalination plants.

BIBLIOGRAPHY


THERMO-ECONOMIC EVALUATION OF A NUCLEAR CO-PRODUCTION PLANT FOR ELECTRICITY AND POTABLE WATER

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Abstract

THERMO-ECONOMIC EVALUATION OF A NUCLEAR CO-PRODUCTION PLANT FOR ELECTRICITY AND POTABLE WATER.

Construction of co-production plants for electricity and potable water through sea water desalination involves high capital costs. Decision makers have to take all the relevant factors into account to ensure that the best technical and economic plant configuration is selected, and that an appropriate method for costing electricity and potable water is applied. A methodology for the economic ranking of different co-production plants and a cost allocation method based on exergy pro-rating are presented. Both methodologies are illustrated for a representative site on the Arabian Peninsula. Various sea water desalination processes and designs, all with the same net water plant capacity, are considered to be coupled to a nuclear PWR of medium size. The economically best co-production plant configuration is identified. For each plant configuration, the potable water production cost, applying the exergetic cost allocation method, is determined and compared with the results achieved by implementing the usually applied power credit method.

1. INTRODUCTION

Sea water desalination is a proven and reliable industrial process. At the end of 1995, a sea water desalination capacity of about 13.6 million m$^3$/d had been installed or contracted worldwide [1]. According to world market projections, the demand for sea water desalination will continue to increase.

Most of the installed large scale sea water desalination plants are distillation plants, which require mainly low pressure saturated steam as the heat source and some electricity for the ancillary equipment (e.g. pumps). From the thermodynamic and economic points of view it is useful to combine sea water distillation plants with power stations in integrated co-production plants in which high pressure steam is used to produce electricity and low pressure exhaust steam from the turbine serves as the heat source for distillation.
Construction of such a co-production plant, particularly with large sized units that would justify consideration of nuclear energy sources, involves high capital costs. Decision makers have to take all the relevant factors into account to ensure that the best technical and economic plant configuration is selected, and that an appropriate method for costing electricity and potable water is applied. In this paper, a methodology for the economic ranking of different co-production plants and a cost allocation method based on exergy pro-rating are presented and applied for a co-production plant with a nuclear energy source.

2. METHODOLOGY FOR THE ECONOMIC RANKING OF CO-PRODUCTION PLANTS

The economic objective of single purpose plants for power generation or for desalination is to achieve the lowest possible production cost per unit. Single purpose plants can easily be compared and ranked by calculating the production cost, which is obtained by dividing the overall annual expenditures (capital charge, fuel cost, operation and maintenance costs) by the annual output. For single purpose plants of the same net output, comparison of the annual expenditures is already sufficient to identify the most economic plant.

For co-production plants that have simultaneously two final products, electricity and potable water, economic comparison and ranking are more difficult. The plant with the least annual overall expenditures $C_0$ (annual expenditures related to both electricity generation and potable water production) is not necessarily the most economic solution, since it is unlikely that all plant alternatives will have exactly the same net electricity and potable water outputs. Furthermore, the potable water production cost and the electricity generation cost vary from one co-production plant to the other, which makes comparison of different plants by these parameters difficult. A methodology has to be defined to economically assess and compare different co-production plants in which the annual overall expenditures as well as the output of the two final products, electricity and potable water, are considered.

An appropriate method for comparing co-production plants with the same potable water output and – to make a fair comparison – with similar base power plant capacities (when not supplying heat and/or electricity to the desalination plant) is to calculate the so called ‘equivalent electricity generation cost’, $c_{eq}$, where the annual net electricity supplied to the grid $E_a$ (saleable electricity) is charged with the overall annual expenditures $C_0$ [2]

$$c_{eq} = \frac{C_0}{E_a} \quad \text{(in US \$/kW(e)-h)} \quad (1)$$
In other words, it is arbitrarily assumed that the potable water production is completely subsidized by the electricity generation. The plant alternative with the lowest resulting equivalent electricity cost will be the economically optimal solution.

3. COST ALLOCATION METHOD BASED ON EXERGY PRO-RATING

3.1. Nature of the problem of cost allocation

After identifying the most economic co-production plant, a cost basis for the sale of potable water and electricity has to be established. There are several methods for allocating the annual expenditures $C_0$ to the two final products $[3]$. In general, $C_0$ can be expressed as a function of the annual electricity output $E_a$ and the annual potable water output $W_a$. Cost allocation methods correlate them linearly with their respective unit costs $c_E$ and $c_W$

\[ C_0 = c_E E_a + c_W W_a \quad \text{(in US $/a)} \]  

\[ (2) \]

**FIG. 1. Allocation of overall annual expenditures of the co-production plant for electricity and potable water (qualitative presentation).**
The line representing Eq. (2) is shown in Fig. 1. Its slope depends only on the water to electricity ratio. Modification of the cost data and the economic assumptions used for calculating $C_0$ would result in moving this line up or down parallel to itself.

Two boundary points can be determined on this line as follows. If the whole economic benefit, achieved by integrating two single purpose plants (electricity and potable water) into one co-production plant, is assigned to the cost of potable water without penalizing electricity (i.e. the power credit method using the electricity generation cost of a least cost single purpose power plant), the value of electricity is known and point A can be placed on the curve. Point B is determined in the same manner, but with the entire benefit being assigned to the cost of electricity by using a water credit, the value of which would be equal to the cost of water produced in an alternative least cost single purpose water scheme. The points on the curve that lie outside the segment AB correspond to subsidizing either potable water or electricity.

An appropriate cost allocation method should:

1. Enable assignment of the economic benefit derived from the production to both potable water and electricity, resulting in a point inside the segment AB in Fig. 1;
2. Break this benefit down in an equitable and generally applicable way.

The equitable cost breakdown depends on the objective and the environment in which the plant is built. Considering only the thermodynamic aspects, which enable establishment of a generally applicable cost breakdown, the way to achieve an equitable cost breakdown is to assess the thermodynamic value (exergy) of the energy streams to produce electricity and potable water. In this regard, a cost allocation method based on exergy pro-rating should be applied to define the formula for cost allocation (point E in Fig. 1).

3.2. Exergy

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 high temperature steam is higher than the exergy of low temperature steam of identical pressure.

Although thermodynamic analyses have been traditionally based on energy and the first law of thermodynamics, a system's performance can be more appropriately evaluated using the exergy approach. Energy can neither be produced nor destroyed, therefore it is non-depletable. During all real processes, however, some of the exergy of the associated energy is lost. When energy is converted from one form to another,
only part of its exergy is transferred to the new form; the remainder is actually lost in order to cause the change. Thus, an exergy analysis describes how the potential of a system to produce mechanical work is used and where the losses of that potential occur.

For stationary open systems, the exergy balance equation can be written in the following form

\[ \sum_{\text{inlet}} \dot{E}_i + \int \left( 1 - \frac{T_0}{T} \right) dQ = \sum_{\text{outlet}} \dot{E}_i + \dot{W} + \dot{E}_l \]  

That is, the sum of exergy \( \sum_{\text{inlet}} \dot{E}_i \) associated with matter entering the system and the exergy associated with the net rate of heat addition (indicated by the second term where \( T_0 \) represents the temperature of the reference environment) is equal to the sum of exergy \( \sum_{\text{outlet}} \dot{E}_i \) associated with the matter leaving the system, the net rate of mechanical work \( \dot{W} \) delivered by the system, and the net rate of exergy losses \( \dot{E}_l \) (a measure of process irreversibilities).

For steam power cycles, the exergy \( \dot{E}_j \) of a steam/water flow \( j \) can be calculated by

\[ \dot{E}_j = m_j \left[ (h_j - h_0) - T_0 (s_j - s_0) \right] \]

where \( h \) is the specific enthalpy in kJ/kg, \( s \) the specific entropy in kJ·kg\(^{-1}\)·K\(^{-1}\), \( T \) the absolute temperature in K, \( m \) the mass flow rate in kg/s, and 0 is the subscript that denotes the state of the reference environment, usually the ambient sea water.

3.3. Exergetic cost allocation method

In the following, an exergetic cost allocation method is described and applied to an example consisting of a co-production plant using a nuclear PWR as the energy source [2]. The overall expenditures \( C_0 \) of the co-production plant are divided into the following cost components (see also Table I):

1. Direct electricity generation expenditures \( C_{E_e} \), allocated exclusively to the generation of electricity;
2. Direct steam production expenditures for providing heat to the desalination plant \( C_{S_e} \), allocated exclusively to the production of potable water;
3. Common electricity and steam production expenditures \( C_C \);
4. Remaining water production expenditures \( C_{W*} \).

\[ C_0 = C_{E_e} + C_{S_e} + C_C + C_{W*} \quad \text{(in US $/a)} \]
TABLE I. EXERGETIC COST EVALUATION OF A CO-PRODUCTION PLANT
WITH A PWR AS THE ENERGY SOURCE

Composition of the individual cost components

<table>
<thead>
<tr>
<th>Cost Component</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_{Ee}$</td>
<td>capital charge of the PWR power plant turbogenerator equipment</td>
</tr>
<tr>
<td>$C_{Se}$</td>
<td>capital charge of incremental equipment of the PWR power plant for providing steam to the distillation plant</td>
</tr>
<tr>
<td>$C_c$</td>
<td>remaining capital charge of the PWR power plant; fuel cost of the PWR power plant; decommissioning cost of the PWR power plant; fixed and variable operation and maintenance costs of the PWR power plant</td>
</tr>
<tr>
<td>$C_{ws}$</td>
<td>capital charge of the desalination plant and the backup heat source; fixed and variable operation and maintenance costs of the desalination plant and the backup heat source; fuel cost of the backup heat source</td>
</tr>
</tbody>
</table>

Exergy analysis

$$\dot{E}_F = \text{exergy of fuel}$$

$$\dot{E}_{SG} = \text{exergy losses in the primary circuit}^a, \text{including the reactor, steam generator and reactor coolant pumps}$$

$$\dot{E}_{MSR} = \text{exergy losses in the moisture separators and steam reheaters}$$

$$\dot{E}_{Aux} = \text{electrical auxiliary loads}^b$$

$$\dot{E}_{FH} = \text{exergy losses in the feedwater heaters}$$

$$\dot{E}_{PP} = \text{exergy losses in the feedwater pumps}$$

$$\dot{E}_T = \text{exergy losses in the turbines}$$

$$\dot{E}_{Con} = \text{exergy losses in the condenser}$$

$$\dot{E}_{Ee} = \text{exergy losses in the generator and mechanical losses}$$

$$P_{net} = \text{net electrical output}$$

$$\dot{E}_{Se} = \text{exergy of the steam provided for the distillation plants}$$

^a Mainly associated with the fission process and heat transport.

^b With the exception of the feedwater pumps and reactor coolant pumps.
The common expenditures $C_C$ are allocated to electricity and steam production proportionally to the exergy flows $\dot{E}_E$ and $\dot{E}_S$, which are the shares of the exergy $\dot{E}_F$ of the fuel supplied to the PWR, required to produce electricity and low temperature steam, respectively. They consist of the exergy flows of the two product flows themselves (net electrical output and exergy of steam flow to distillation plant, respectively) and a share of the net rate of exergy losses occurring in the power plant.

The exergy flows $\dot{E}_E$ and $\dot{E}_S$ are determined by applying the exergy analysis presented in Table I. The exergy flows summarized in $\dot{E}_{Ee}$ are allocated exclusively to the generation of electricity; $\dot{E}_{Se}$ is allocated exclusively to the production of low temperature steam. The exergy flows summarized in $\dot{E}_C$, which can be assigned both to the generation of electricity and the production of steam, are allocated to the two products proportional to $\dot{E}_{Ee}$ and $\dot{E}_{Se}$. On the basis of these considerations, $\dot{E}_E$ and $\dot{E}_S$ are calculated by Eqs (6) and (7), respectively

$$\dot{E}_E = \dot{E}_{Ee} + \dot{E}_C \frac{\dot{E}_{Ee}}{\dot{E}_{Ee} + \dot{E}_{Se}}$$

$$\dot{E}_S = \dot{E}_{Se} + \dot{E}_C \frac{\dot{E}_{Se}}{\dot{E}_{Ee} + \dot{E}_{Se}}$$

The electricity generation expenditures $C_{E*}$ and $C_S$ to generate electricity and steam, respectively, are then calculated by Eqs (8) and (9)

$$C_{E*} = C_{Ee} + \frac{\dot{E}_E}{\dot{E}_E + \dot{E}_S} C_C \quad \text{(electricity)}$$

$$C_S = C_{Se} + \frac{\dot{E}_S}{\dot{E}_E + \dot{E}_S} C_C \quad \text{(steam)}$$

$C_{E*}$ is further divided into expenditures for the generation of electricity supplied to the grid $C_E$ and for the generation of electricity delivered to the sea water desalination plant $C_{Ew}$, proportional to their respective electric capacities $P_E$ and $P_W$ (Eqs (10) and (11))

$$C_E = C_{E*} \frac{P_E}{P_{net}}$$

$$C_{Ew} = C_{E*} \frac{P_W}{P_{net}}$$
$P_{\text{net}}$ is the electrical output of the power plant. The total water production expenditures $C_W$ are calculated by

$$C_W = C_{W^*} + C_{E_W} + C_S$$

(12)

The electricity generation cost $c_E$ in US $$/\text{kW(e)\cdot h}$ and the potable water production cost $c_W$ in US $$/\text{m}^3$ are then obtained by dividing $C_E$ and $C_W$ by the respective units produced.

4. THERMO-ECONOMIC EVALUATION FOR A REPRESENTATIVE SITE

The preceding thermo-economic considerations are illustrated for a representative site on the Arabian Peninsula [2]. Various sea water desalination processes and designs, all with the same net water plant capacity (288 000 m$^3$/d) are considered to be coupled to a PWR of about 600 MW(e) base net capacity (without heat and/or electricity supply to the desalination plant). The desalination plants were preselected on the basis of their favourable technical and economic characteristics, and their commercial availability. The co-production plant is assumed to be base loaded for both electricity and water production. For calculating and comparing the costs of the different plant alternatives, the constant money levelized cost methodology is used. Costs related to water storage, transport and distribution to the consumer are not covered in the evaluation. For the purpose of cost comparison, the operation reference date was assumed to be 1 January 2005, regardless of the actual period required for the planning and implementation of a nuclear power project, which may be longer. As drinking water standards, the World Health Organization standards were applied, which recommend 1000 ppm for total dissolved solids (TDS) and 250 ppm for chlorides as the ‘highest desirable level’ for potable water.

4.1. Reference co-production plants

The main technical parameters of the reference co-production plants considered are given in Table II.

As the energy source, a two loop medium sized PWR with a thermal power of 1870 MW(th) was chosen, generating steam at 53.6 bar and 268°C.

The following sea water desalination plants were considered for evaluation:

(1) Four different multi-stage flash (MSF) once through plants with a gained output ratio (GOR) of 7.5–13.5, all of modular long tube design (four units of 72 000 m$^3$/d net capacity at reference conditions).
(2) Two different high temperature-vertical tube evaporation (HT-VTE) plants with a GOR of 17 and 21, respectively, as well as four different low temperature-horizontal tube multi-effect (LT-HTME) plants with a GOR of 7.5–13.5 (eight units of 36,000 m³/d net capacity at reference conditions).

(3) An RO plant with hollow fibre membranes operated in the single stage mode (12 parallel trains of 24,000 m³/d net capacity). The recovery ratio of the RO trains is kept constantly at 35% by regulating the feedwater pressure as a function of temperature. The pumping energy in the brine blowdown is partly recovered by Pelton turbines.

When coupling the sea water desalination plants to the PWR, radioactive contamination of the potable water produced must be prevented. Coupling of the RO plant is simple, requiring only an electrical connection (preheating of feedwater in the condenser of the power plant was not considered). For the distillation plants considered, the coupling was performed by replacing one of the two condensing turbines with a backpressure turbine and by directing the exhaust of the backpressure turbine to the distillation plant. To exclude the risk of contamination of the distillation system, intermediate ‘pressurized water isolation loops’ and intermediate ‘open flash loops’ were connected between the backpressure turbine and the MSF and MED units, respectively.

4.2. Exergy analyses

In Table III, the exergy analyses of the co-production plants are given. The results are needed to calculate the exergy flows $\tilde{E}_E$ and $\tilde{E}_S$. To understand the derivation of the exergy flow breakdown in Table III, Fig. 2 serves as an illustrative example, where the exergy analysis for the coupling with the MSF-1 plant is shown.

The individual components of the power plant are divided into blocks. The numerals shown alongside the flow streamlines between, into and out of blocks represent the amount of exergy (in MW) flowing past the block. The numerals inside the blocks represent either the exergy losses occurring in this block (calculated by Eq. (3)), or the exergy flows consumed in this block. The numerals shown in parentheses are the values of exergy expressed as a percentage of the exergy of fuel supplied to the reactor. The exergy flows of the individual water/steam flows were calculated by Eq. (4), using the annual average sea water temperature (301.5 K) as the reference environment temperature $T_0$. The exergy of the nuclear fuel was equated with the thermal power of the reactor (1870 MW). In this example, 498.3 MW of exergy leave the system as electrical net output and 140.5 MW are needed to supply the MSF-1 plant with heating steam; the balance (about 1230 MW) is destructed in the system because of irreversibilities.
### TABLE II. TECHNICAL PARAMETERS OF THE REFERENCE CO-PRODUCTION PLANTS

(Sea water temperature = 24–34°C (an annual average of 28.5°C was taken as the reference temperature for evaluation); and sea water salinity = 45 000 ppm)

<table>
<thead>
<tr>
<th>PWR power plant</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Core power</td>
<td>1870 MW(th)</td>
</tr>
<tr>
<td>Fuel (reload enrichment at equilibrium)</td>
<td>UO₂ (3.55%)</td>
</tr>
<tr>
<td>Primary coolant/moderator</td>
<td>H₂O (155 bar/312/276°C)</td>
</tr>
<tr>
<td>Maximum steam temperature/pressure</td>
<td>268°C/53.6 bar</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Desalination plants (288 000 m³/d)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit size (m³/d)</td>
<td>24 000</td>
</tr>
<tr>
<td>No. of units</td>
<td>12</td>
</tr>
<tr>
<td>GOR</td>
<td>13.5</td>
</tr>
<tr>
<td>No. of stages/effects</td>
<td>1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>RO</th>
<th>MSF-1</th>
<th>MSF-2</th>
<th>MSF-3</th>
<th>MSF-4</th>
<th>HT-VTE-1</th>
<th>HT-VTE-2</th>
<th>LT-HTME-1</th>
<th>LT-HTME-2</th>
<th>LT-HTME-3</th>
<th>LT-HTME-4</th>
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<tbody>
<tr>
<td>36 000</td>
<td>36 000</td>
<td>36 000</td>
<td>36 000</td>
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<td>36 000</td>
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<td>21</td>
<td>17</td>
<td>13.5</td>
<td>11.5</td>
<td>9.5</td>
<td>7.5</td>
<td>28</td>
<td>23</td>
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<td>23</td>
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<td>18</td>
<td>15</td>
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<td>44</td>
<td>35</td>
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### TABLE II. (cont.)

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<tr>
<th></th>
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<th>MSF-1</th>
<th>MSF-2</th>
<th>MSF-3</th>
<th>MSF-4</th>
<th>HT-VTE-1</th>
<th>HT-VTE-2</th>
<th>LT-HTME-1</th>
<th>LT-HTME-2</th>
<th>LT-HTME-3</th>
<th>LT-HTME-4</th>
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<tbody>
<tr>
<td><strong>Desalination plants (cont.)</strong></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
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<tr>
<td>Maximum brine temperature (°C)</td>
<td>125</td>
<td>110</td>
<td>98</td>
<td>90</td>
<td>120</td>
<td>100</td>
<td>70</td>
<td>65</td>
<td>60</td>
<td>55</td>
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<tr>
<td>Thermal heat consumption (kW(θ)-h/m³)³</td>
<td>45.1</td>
<td>53.7</td>
<td>65.6</td>
<td>83.5</td>
<td>29.0</td>
<td>36.7</td>
<td>47.9</td>
<td>56.5</td>
<td>68.7</td>
<td>87.5</td>
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<td>Electricity consumption (kW(e)-h/m³)³</td>
<td>5.5</td>
<td>3.0</td>
<td>3.3</td>
<td>3.5</td>
<td>3.9</td>
<td>1.2</td>
<td>1.3</td>
<td>1.6</td>
<td>1.9</td>
<td>2.2</td>
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<tr>
<td>Unit sea water flow (m³/h)⁴</td>
<td>2.860</td>
<td>21 000</td>
<td>25 000</td>
<td>30 000</td>
<td>35 000</td>
<td>8 500</td>
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<td>17 000</td>
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<td>24 000</td>
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<tr>
<td>Recovery ratio</td>
<td>0.35</td>
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<td></td>
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<td></td>
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</tr>
<tr>
<td><strong>Co-production plants</strong></td>
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<td></td>
<td></td>
<td></td>
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<tr>
<td>Exhaust steam temperature of back-pressure turbine (°C)</td>
<td>133</td>
<td>118</td>
<td>106</td>
<td>98</td>
<td>129</td>
<td>109</td>
<td>79</td>
<td>74</td>
<td>69</td>
<td>64</td>
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<tr>
<td>Net electricity output (MW(e))</td>
<td>597</td>
<td>498</td>
<td>497</td>
<td>486</td>
<td>464</td>
<td>533</td>
<td>535</td>
<td>548</td>
<td>547</td>
<td>546</td>
<td>540</td>
</tr>
<tr>
<td>Net electricity to the grid (MW(e))</td>
<td>531</td>
<td>463</td>
<td>459</td>
<td>445</td>
<td>424</td>
<td>519</td>
<td>519</td>
<td>529</td>
<td>524</td>
<td>520</td>
<td>511</td>
</tr>
</tbody>
</table>

---

*a* Without steam supply for vacuum units.

*b* Excluding the electricity consumption of the intermediate loop pumps for distillation plant coupling.

*c* Related to the average feedwater pressure of 72 bar.

*d* Including the cooling water demand of a multi-stage steam ejector vacuum system of the barometric type.
### TABLE III. EXERGY ANALYSES OF THE REFERENCE CO-PRODUCTION PLANTS

<table>
<thead>
<tr>
<th></th>
<th>RO</th>
<th>MSF-1</th>
<th>MSF-2</th>
<th>MSF-3</th>
<th>MSF-4</th>
<th>HT-VTE-1</th>
<th>HT-VTE-2</th>
<th>LT-HTME-1</th>
<th>LT-HTME-2</th>
<th>LT-HTME-3</th>
<th>LT-HTME-4</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Net electrical output</strong> $P_{net}$ (MW(e))</td>
<td>597</td>
<td>498</td>
<td>497</td>
<td>486</td>
<td>469</td>
<td>533</td>
<td>535</td>
<td>548</td>
<td>547</td>
<td>546</td>
<td>540</td>
</tr>
<tr>
<td><strong>Thermal heat to the distillation plant</strong> (MW(th))</td>
<td>–</td>
<td>541</td>
<td>644</td>
<td>787</td>
<td>1001</td>
<td>348</td>
<td>441</td>
<td>574</td>
<td>678</td>
<td>825</td>
<td>1050</td>
</tr>
<tr>
<td><strong>Losses in primary circuit,</strong> including the reactor and steam generator (%)</td>
<td>56.6</td>
<td>56.6</td>
<td>56.6</td>
<td>56.6</td>
<td>56.6</td>
<td>56.6</td>
<td>56.6</td>
<td>56.6</td>
<td>56.6</td>
<td>56.6</td>
<td>56.6</td>
</tr>
<tr>
<td><strong>Net electrical output (%)</strong></td>
<td>31.9</td>
<td>26.7</td>
<td>26.6</td>
<td>26.0</td>
<td>25.1</td>
<td>28.5</td>
<td>28.6</td>
<td>29.3</td>
<td>29.3</td>
<td>29.2</td>
<td>28.9</td>
</tr>
<tr>
<td><strong>Steam provided for the distillation plant (%)</strong></td>
<td>–</td>
<td>7.5</td>
<td>7.9</td>
<td>8.6</td>
<td>10.0</td>
<td>4.7</td>
<td>5.0</td>
<td>4.4</td>
<td>4.8</td>
<td>5.2</td>
<td>5.9</td>
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<tr>
<td><strong>Losses in turbines (%)</strong></td>
<td>5.1</td>
<td>4.0</td>
<td>4.0</td>
<td>4.0</td>
<td>3.9</td>
<td>4.3</td>
<td>4.4</td>
<td>4.5</td>
<td>4.5</td>
<td>4.5</td>
<td>4.4</td>
</tr>
<tr>
<td><strong>Electrical auxiliary loads (with exception of the feedwater pumps and reactor coolant pumps) (%)</strong></td>
<td>1.1</td>
<td>1.1</td>
<td>1.1</td>
<td>1.1</td>
<td>1.1</td>
<td>1.1</td>
<td>1.1</td>
<td>1.1</td>
<td>1.1</td>
<td>1.1</td>
<td>1.1</td>
</tr>
<tr>
<td><strong>Losses in condensers (%)</strong></td>
<td>2.8</td>
<td>1.6</td>
<td>1.4</td>
<td>1.1</td>
<td>0.7</td>
<td>1.9</td>
<td>1.7</td>
<td>1.4</td>
<td>1.1</td>
<td>0.9</td>
<td>0.5</td>
</tr>
<tr>
<td><strong>Losses in moisture separators and steam reheaters (%)</strong></td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td><strong>Losses in generator and mechanical losses (%)</strong></td>
<td>0.6</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td><strong>Losses in feedwater heaters (%)</strong></td>
<td>1.2</td>
<td>1.0</td>
<td>0.9</td>
<td>0.9</td>
<td>0.8</td>
<td>1.1</td>
<td>1.0</td>
<td>1.0</td>
<td>0.9</td>
<td>0.9</td>
<td>0.9</td>
</tr>
<tr>
<td><strong>Losses in feedwater pumps (%)</strong></td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
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</tr>
<tr>
<td><strong>Exergy of fuel $E_F$ (MW)</strong></td>
<td>1870</td>
<td>1870</td>
<td>1870</td>
<td>1870</td>
<td>1870</td>
<td>1870</td>
<td>1870</td>
<td>1870</td>
<td>1870</td>
<td>1870</td>
<td>1870</td>
</tr>
<tr>
<td><strong>Exergy flows to produce electricity $E_E$ according to Eq. (6) (MW)</strong></td>
<td>1870</td>
<td>1522</td>
<td>1505</td>
<td>1470</td>
<td>1404</td>
<td>1649</td>
<td>1638</td>
<td>1664</td>
<td>1649</td>
<td>1629</td>
<td>1595</td>
</tr>
<tr>
<td><strong>Exergy flows to provide steam for the distillation plants $E_S$ according to Eq. (7) (MW)</strong></td>
<td>–</td>
<td>348</td>
<td>365</td>
<td>400</td>
<td>466</td>
<td>221</td>
<td>232</td>
<td>206</td>
<td>221</td>
<td>241</td>
<td>275</td>
</tr>
</tbody>
</table>

Proportional breakdown of exergy flows according to Table 1

BREIDENBACH
4.3. Capital and operation and maintenance costs

The capital and operation and maintenance cost estimates of the co-production plants considered are presented in Table IV. The total overnight cost assumed for the PWR power plant is based on information provided by a prospective supplier and valid for conditions prevailing in industrialized countries [4]; 10% additional costs were assumed for construction in Arabian countries. The fuel cost and operation and maintenance costs of the PWR power plant are based on data of a case study on the feasibility of small and medium power plants in Egypt [5]. The capital and operation and maintenance costs of the desalination plants are based on cost estimates by consulting engineers for construction in Arabian countries [6–8]. The cost data of the MSF units are related to an advanced MSF–OT design; these plants have a noticeably lower capital cost than current MSF brine recycle plants of cross-tube design [7]. The capital cost of the RO plant is drawn from actual experience in Arabian countries, taking into account the current low cost of membrane equipment. Gas and/or fuel–oil fired boilers were considered as a backup heat source. It was assumed that the fuel cost of the backup boilers will be governed by the world market crude oil price.

![Exergy flow diagram of the PWR power plant coupled to the MSF-1 plant.](image-url)
### TABLE IV. CAPITAL AND OPERATION AND MAINTENANCE COSTS OF THE REFERENCE CO-PRODUCTION PLANTS

**PWR power plant**

<p>| | | | | | | | | |</p>
<table>
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<th></th>
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<td>Net output</td>
<td>600 MW(e)</td>
<td></td>
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<tr>
<td>Total overnight cost(^a)</td>
<td>900 US $/kW(e) (20% for turbogenerator equipment, 80% for balance of plant)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Construction time</td>
<td>60 months</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>Annual fixed (variable) operation and maintenance costs</td>
<td>39.4 US $10^6/a (0.5 mill/kW(e)-h)</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Annual fuel cost</td>
<td>7.5 mill/kW(e)-h (no real fuel cost escalation)</td>
<td></td>
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<tr>
<td>Annual decommissioning cost</td>
<td>1 mill/kW(e)-h</td>
<td></td>
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<tr>
<th>Desalination plants</th>
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<th>MSF-1</th>
<th>MSF-2</th>
<th>MSF-3</th>
<th>MSF-4</th>
<th>HT-VTE-1</th>
<th>HT-VTE-2</th>
<th>LT-HTME-1</th>
<th>LT-HTME-2</th>
<th>LT-HTME-3</th>
<th>LT-HTME-4</th>
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<tbody>
<tr>
<td>Base overnight cost(^a) (US $10^6)</td>
<td>259.5</td>
<td>422.3</td>
<td>402.2</td>
<td>384.1</td>
<td>370.0</td>
<td>340.0</td>
<td>317.5</td>
<td>298.7</td>
<td>273.2</td>
<td>259.7</td>
<td>244.7</td>
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<tr>
<td>Intake/outfall cost(^b) (US $10^6)</td>
<td>8.8</td>
<td>21.3</td>
<td>24.9</td>
<td>29.2</td>
<td>34.1</td>
<td>17.3</td>
<td>20.1</td>
<td>25.3</td>
<td>30.9</td>
<td>35.4</td>
<td>41.4</td>
</tr>
<tr>
<td>Backup heat source cost (US $10^6)</td>
<td>–</td>
<td>27.1</td>
<td>32.2</td>
<td>39.4</td>
<td>50.1</td>
<td>17.4</td>
<td>22.0</td>
<td>28.7</td>
<td>33.9</td>
<td>41.2</td>
<td>52.5</td>
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### TABLE IV. (cont.)

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<th>Desalination plants (cont.)</th>
<th>RO</th>
<th>MSF-1</th>
<th>MSF-2</th>
<th>MSF-3</th>
<th>MSF-4</th>
<th>HT-VTE-1</th>
<th>HT-VTE-2</th>
<th>LT-HTME-1</th>
<th>LT-HTME-2</th>
<th>LT-HTME-3</th>
<th>LT-HTME-4</th>
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<tbody>
<tr>
<td>Intermediate loops cost (US $10^6)</td>
<td>—</td>
<td>25.5</td>
<td>28.0</td>
<td>31.5</td>
<td>36.2</td>
<td>19.5</td>
<td>22.2</td>
<td>25.5</td>
<td>28.0</td>
<td>31.5</td>
<td>36.2</td>
</tr>
<tr>
<td>Interest during construction (US $10^6)</td>
<td>21.5</td>
<td>39.7</td>
<td>39.0</td>
<td>38.7</td>
<td>39.2</td>
<td>31.5</td>
<td>30.5</td>
<td>30.3</td>
<td>29.3</td>
<td>29.4</td>
<td>30.0</td>
</tr>
<tr>
<td>Total (US $10^6)</td>
<td>289.7</td>
<td>535.9</td>
<td>526.3</td>
<td>522.9</td>
<td>529.7</td>
<td>425.7</td>
<td>412.3</td>
<td>408.5</td>
<td>395.3</td>
<td>397.2</td>
<td>404.8</td>
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<td>Spare parts cost (US $/m³)</td>
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<td>0.035</td>
<td>0.035</td>
<td>0.035</td>
<td>0.035</td>
<td>0.03</td>
<td>0.03</td>
<td>0.04c</td>
<td>0.04c</td>
<td>0.04c</td>
<td>0.04c</td>
</tr>
<tr>
<td>Chemicals cost (US $/m³)</td>
<td>0.06</td>
<td>0.06</td>
<td>0.06</td>
<td>0.06</td>
<td>0.06</td>
<td>0.06</td>
<td>0.06</td>
<td>0.06</td>
<td>0.06</td>
<td>0.06</td>
<td>0.06</td>
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<tr>
<td>Membrane replacement cost (US $/m³)</td>
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<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
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</tr>
<tr>
<td>Personnel cost (US $10^5/a)</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
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<td>—</td>
</tr>
<tr>
<td>Construction time (months)</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
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#### Economic parameters

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<th>Reference currency date</th>
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<tr>
<td>Operation reference date</td>
<td>= January 2005</td>
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<tr>
<td>Economic life</td>
<td>= 30 years</td>
</tr>
<tr>
<td>Discount rate</td>
<td>= 8%</td>
</tr>
<tr>
<td>Fuel cost of backup heat source</td>
<td>= US $17/barrel, 2% real escalation rate (US $4.33/GJ)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Lifetime average load factors</th>
</tr>
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<tbody>
<tr>
<td>PWR power plant</td>
</tr>
<tr>
<td>Desalination plants</td>
</tr>
<tr>
<td>Power plant as the heat source</td>
</tr>
<tr>
<td>Backup heat source of the MSF-MED plant</td>
</tr>
</tbody>
</table>

---

* Including owner's cost and contingency.
* Covering cost savings in sharing intake/outfall structures with the power plant.
* Includes US $0.01/m³ for retubing of the aluminium tubes (8% discount rate).
TABLE V. THERMO-ECONOMIC EVALUATION

<table>
<thead>
<tr>
<th></th>
<th>GOR</th>
<th>Maximum brine temperature (°C)</th>
<th>$c_{eq}$ (US $/kW(e)-h$)</th>
<th>$c_{E}$ (US $/kW(e)-h$)</th>
<th>$c_{W}$ (US $/m^{3}$)</th>
<th>$c_{W*}$ (US $/m^{3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSF-1</td>
<td>13.5</td>
<td>125</td>
<td>8.30</td>
<td>4.65</td>
<td>1.24</td>
<td>1.22</td>
</tr>
<tr>
<td>MSF-2</td>
<td>11.5</td>
<td>110</td>
<td>8.42</td>
<td>4.62</td>
<td>1.28</td>
<td>1.25</td>
</tr>
<tr>
<td>MSF-3</td>
<td>9.5</td>
<td>98</td>
<td>8.76</td>
<td>4.59</td>
<td>1.36</td>
<td>1.32</td>
</tr>
<tr>
<td>MSF-4</td>
<td>7.5</td>
<td>90</td>
<td>9.38</td>
<td>4.56</td>
<td>1.50</td>
<td>1.45</td>
</tr>
<tr>
<td>HT-VTE-1</td>
<td>21</td>
<td>120</td>
<td>6.97</td>
<td>4.68</td>
<td>0.88</td>
<td>0.87</td>
</tr>
<tr>
<td>HT-VTE-2</td>
<td>17</td>
<td>100</td>
<td>6.98</td>
<td>4.63</td>
<td>0.91</td>
<td>0.87</td>
</tr>
<tr>
<td>HT-VTE-3</td>
<td>13.5</td>
<td>70</td>
<td>6.91</td>
<td>4.56</td>
<td>0.92</td>
<td>0.86</td>
</tr>
<tr>
<td>LT-HTME-1</td>
<td>11.5</td>
<td>65</td>
<td>6.99</td>
<td>4.51</td>
<td>0.96</td>
<td>0.88</td>
</tr>
<tr>
<td>LT-HTME-2</td>
<td>9.5</td>
<td>60</td>
<td>7.13</td>
<td>4.46</td>
<td>1.02</td>
<td>0.92</td>
</tr>
<tr>
<td>LT-HTME-3</td>
<td>7.5</td>
<td>55</td>
<td>7.41</td>
<td>4.40</td>
<td>1.13</td>
<td>1.01</td>
</tr>
<tr>
<td>RO</td>
<td>N/A</td>
<td>N/A</td>
<td>6.57</td>
<td>4.70</td>
<td>0.72</td>
<td>0.71</td>
</tr>
</tbody>
</table>

$ c_{W*} = $ potable water production cost when applying the power credit method (the electricity generation cost of the PWR power plant is fixed at US $ \leq 4.72/kW(e)-h$).

FIG. 3. Breakdown of the potable water production cost.
4.4. Results

In Table V, the results of the reference co-production plants evaluated are summarized. For comparison, the potable water production cost achieved in applying the power credit method is also given. In Fig. 3, the cost composition of the potable water production cost for each co-production plant alternative applying the exergetic cost allocation method is shown.

The main results of the thermo-economic evaluation can be summarized as follows:

1. The RO process coupled to the PWR power plant yields the lowest equivalent electricity generation cost (US $6.57 kW(e)-h) and potable water production cost (0.72 m$^3$/d).
2. Of the co-production plant alternatives with distillation plants, the lowest equivalent electricity generation cost is attained by the LT–HTME-1 plant (US $6.91/kW(e)-h), and the lowest potable water production cost is provided by the HT–VTE-1 plant alternative (US $0.88/m^3$).
3. For all distillation plant processes considered (MSF, HT–VTE, LT–HTME), the potable water production cost as well as the equivalent electricity generation cost decrease either with increasing GOR or with increasing maximum brine temperature.
4. For the MSF plants, both the potable water production cost and the equivalent electricity generation cost are substantially higher than those of MED plants with the same GOR.
5. The potable water production cost achieved in applying the exergetic cost allocation method is higher than that using the power credit method. For the distillation plants considered, the difference in potable water production cost between both cost allocation methods increases with the decreasing GOR.

Use of backup heat boilers to achieve high potable water availability is an expensive measure (see cost breakdown in Fig. 3). In individual cases, it is to be examined whether an alternate source of potable water can be provided during the time when the power plant is not in operation. For LT–HTME plants, use of thermal vapour compression in the backup heat system might reduce the energy consumption of the distillation plant.

5. CONCLUSIONS

To allocate the production cost of electricity and potable water, the exergetic cost allocation method leads to a higher potable water production cost and a
somewhat lower electricity generation cost than the usually applied power credit method. While the latter method allocates all the benefits of co-production to potable water, the exergetic method distributes them to electricity and potable water according to the exergy consumption of the processes. From the thermodynamic viewpoint, this is the most equitable method for allocating costs to electricity and potable water production, since the value of the energy consumption streams is taken into account.

The exergetic cost allocation method, which is valid for any type of nuclear, fossil or renewable energy source, gives utilities an equitable basis for costing electricity and potable water, both for new and already existing plants. Tariffs established on this basis could also give a clear message to the consumers on the true value of these products, and could lead to more efficient use than a subsidized approach.

REFERENCES

THE CONCEPT OF A CO-GENERATING NUCLEAR PLANT (RUTA-TE) FOR SEA WATER DESALINATION

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Abstract

THE CONCEPT OF A CO-GENERATING NUCLEAR PLANT (RUTA-TE) FOR SEA WATER DESALINATION.

A heating reactor can be used for water desalination with multi-effect distillation and multi-stage flash or reverse osmosis processes. However, pumps and other plant equipment need electricity, which may have to be supplied by an outside network. Because remote sites may not have such a possibility, the Research and Development Institute of Power Engineering has developed the concept of a small swimming pool reactor that generates heat and electricity for the desalination plant. Electricity is generated in a small turbine island near to the reactor. The steam for the turbine is generated in modular channels, which are submerged in the reactor pool. The secondary circuit feeds all the modular channels and collects their steam. The lower parts of the modular channels surround the ordinary core of a RUTA reactor, whose fuel assemblies are positioned in the pool. Thus, the central part of the core produces heat in the form of heated water (up to 100°C). This heat is transported from the reactor pool to the desalination facility through intermediate loops. The interface between the nuclear and desalination systems consists of three separate loops: two loops of the reactor plant, and the steam generation loop of the distillation unit. The loop to loop heat is passed through the heat transfer surfaces. The high pressure loop of the turbine island is not connected to the desalination system. Preliminary economic analysis has shown the competitiveness of such a desalination plant.

1. INTRODUCTION

Nuclear energy can make a major contribution to district heating and the supply of potable water for industrial and household use. The portion of primary energy consumed by the district heating sector approaches 35% in the north of the Russian Federation, which is 25% more than that consumed in most of Europe, Asia and North America. Taking into account the increasing demand for potable water worldwide it is expected that there will be an increase in energy consumption for
fresh water production. A nuclear contribution to this market would help to equate the supply and demand of energy and lower the price level. This issue is very important for regions where the distances between fossil fuel extraction and consumption sites are long.

However, in contrast to the earlier development period, nuclear energy has become much less popular. The accidents at Three Mile Island and Chernobyl have raised the issue of nuclear safety. Some countries have had to consider cancelling or postponing their nuclear power plant programmes in the face of public opposition to the perceived risk of nuclear technology. Under these conditions, the nuclear industry needs to show a new potential for safety.

Different reactor type operating experience has shown that pool type research reactors meet, in the most complete manner, the safety requirements, often operating within town boundaries. Their role in research, a function for which substitutes are not available, has assisted in making the presence of these research reactors acceptable. The ready acceptance of these reactors offers a clue to the means by which nuclear energy could be made more publicly acceptable [1]. The atmospheric pressure in the primary circuit, the great volume of pool water and, especially, the selected reactor core neutronics make these reactors some of the safest. The thermal energy of the reactor may be used for district heating and other purposes, including sea water desalination.

The Research and Development Institute of Power Engineering is designing swimming pool nuclear reactors of 10, 20 and 55 MW(th) [2]. It should be pointed out that inculcation of this nuclear technology into existing local heating systems is carried out without any essential transformations having to be made. An example of this approach is the design of the underground RUTA nuclear heating plant (NHP) in Apatity, Murmansk region, which could supply 75-80% of the annual heating demands of the area [3]. The existing fossil fuel plant plays the role of a peak and stand-by energy source. During the first stages of reactor design considerable attention was paid to the development of inherent safety features, which means that reactor safety is ensured by natural processes. Reactor self-control, self-restriction of power and natural coolant circulation make common nuclear power plant safety systems unnecessary, therefore the reactor design is more reliable and cheap.

The modular steam generation possibility has already been proved by long term testing of the modular channels in the operating core of the first nuclear power plant in Obninsk.

2. REACTOR DESIGN

The simplicity of the reactor structure results in a more ‘flexible’ design of the reactor module. This means that the reactor core and control system, the primary heat
exchangers and the modular channels are of a rather standard design, but the arrangement of these components in the reactor pool and the structure of the reactor vessel depend on the site characteristics and requirements. The major goal is to achieve high economic indices, along with a high level of safety. As can be seen in Fig. 1, the reactor core is at the bottom of the reactor pool and the heat exchangers are at the top.

The RUTA-TE reactor core consists of two hydraulically independent parts: the central part and the circumference part. The fuel rods of the central part of the core operate under the low pressure of the water pool, while the fuel rods of the circumference part operate under the high pressure of the modular channels.

The central part of the core consists of fuel assemblies (FAs), with the fuel rods clad in two co-axial zirconium alloy claddings. This type of fuel element structure has successfully passed long term reactor testing under conditions of boiling coolant, with parameters that are higher than those of the RUTA reactor, and shown high reliability and availability. Along with well tested fuel elements, the design considers the possibility of using safer fuel elements of a new generation, so called ‘cold’ fuel elements. The fuel of such elements is of UO$_2$–Zr ceramics–metal (cer–met) and is placed in the main zirconium cladding. This type of structure creates an additional safety barrier and also enhances reactor safety. The hexagonal fuel assembly contains 54 fuel rods (3.6% enrichment of the uranium dioxide tablets) and has a seven cell arrangement for the burnable absorber, absorber rods and other purposes. In the central cell of each fuel assembly there is an absorber device that acts independently. Small absorber balls in the device can drop into the core if the outlet FA coolant temperature rises to 120°C. Shape memory material is used in the structure of the lock, which prevents balls dropping into the core.

The circumference part of the core has FAs placed in the modular channels. The modular channel is a separate high pressure water loop that is organized inside a long vertical tube. The FA is arranged at the bottom of the tube and steam generator, at the top end of the same tube. Natural water circulation inside the sealing tube provides heat transport from the FA to the steam generator. The FA of the modular channel operates under a pressure of 9.8 MPa, and each FA contains 61 fuel rods. The fuel is 6.5% enriched uranium dioxide tablets. There are 78 modular channels. Steam is generated in the secondary circuit, which feeds all the modular channel steam generators and collects the steam from all the modular channels (Fig. 2).

The reactor fuel lifetime is 9 years for the FAs of the central part and 12 years for the FAs of the circumference part. Partial refuelling of the core is required every 3 years.

The integral reactor design, with placement of the primary plate type heat exchangers in the reactor pool top and the core at the pool bottom, allows organization of the natural primary water circulation in the reactor pool. The design also considers the possibility of using forced primary water circulation, which allows
FIG. 1. 1. RUTA-TE reactor.
FIG. 2. Modular channel.
minimization of the reactor dimensions and capital costs. However, the complexity of the reactor structure and the rise in operating costs require special economic investigations when making the final decision for a possible NHP site.

Modular channels have outer thermal insulation along the tube vessel, i.e. a thin stainless steel tube with an external ceramic liner. The bottom of this tube is connected to the pool water, but the top is normally sealed off from the pool. After reactor startup, the water inside the gap between the modular channel vessel tube and the insulation tube begins to boil and steam fills the gap, providing good thermal insulation. Under emergency conditions it is envisaged that the top of the insulation tube will be sealed so that the pool water creates natural convection along the modular channel vessel tube. In this case, the modular FA heat is passed through the vessel to the pool water, so that the modular channels serve as the FA of the central part for heating the pool water. Secondary circuit channel feedwater can be cut off for an unlimited period, with the reactor remaining in the heat production mode only (without electricity production).

No large primary water pipelines leave the reactor tank, consequently the possibility of a rupture in these pipelines, with an abrupt loss of primary water, is excluded. Only two systems are arranged outside the reactor tank: the pool water purification system and the reactor gas purge system. The latter is used to support the required gas regime above the water level in the reactor and to monitor the gas radioactivity products at the same time. The pool water purification system maintains the water purity and pH of the pool within the required limits, and removes dissolved material to control the concentration of radioactivity from oxidation of the stainless steel structures and from potential fuel defects. Loss of reactor water through these systems in the event of pipeline rupture is excluded by appropriate engineering measures. Purification of the internal channel water is not required, as has been demonstrated in long term reactor testing.

Considerable loss of reactor water in the event of a sudden rupture in the reactor tank is also impossible, because of the low coolant pressure and low tension in the stainless steel reactor tank. Maximum pressure is determined by the height of the water in the pool, i.e. not more than 18 m. Possible inconsiderable water losses as a result of latent metal defects in the reactor tank do not reduce reactor safety because of the special design of the reactor tank; the primary heat exchangers remain underwater in the event of a water leak from the reactor tank. Currently, two variants of the tank design are included in the reactor design: double and single reactor tanks. In the first variant, the safeguard tank consists of a concrete vessel with a steel lining; the main reactor tank of the second variant is of the same design. The choice of final variant depends on the local reactor site safety conditions.

All the modular channels are subdivided into three independent groups, each of which has a joint gas pressurizer in the shape of a torus, which is located above the modular channel heads in the reactor pool. Pressurizers provide for thermal water
expansion in the modular channels through thin pipes that connect each modular channel with the pressurizer.

The reactor is regulated by control and protection system (CPS) rods, which are bundles of rods with absorbers (clusters). The absorber rods are shared by the control and safety shutdown systems, which are otherwise separate and independent. Only the central part of the core has such CPS rods.

Heat is transferred to the desalination plant through intermediate circuits (Fig. 3). The radiators of the secondary circuit are used to remove the decay heat from the reactor to the atmosphere without the water boiling in the reactor pool in the event of an accident. All the auxiliary systems connected to the primary coolant or cover reactor gas are arranged in the reactor hall. Equipment for the intermediate circuits, including their auxiliary systems and the monitoring and control systems, is arranged in ordinary industrial compartments.

All the modular channels generate a water–steam mixture, with an average steam content of 15% (mass). The pressure of the saturated steam in the separator is 5 MPa, and the humidity of the outlet separator steam is 0.1% (mass); the separator capacity is 23.5 t/h. The turbine is of the WWER K-220-44 prototype, which can be redesigned to a 4 MW turbine on 4.4 MPa inlet saturated steam. Other turbine island equipment is of standard design.
3. REACTOR SAFETY

One of the main principles for ensuring plant safety is defence in depth based on the use of several safety barriers:

1. A ceramic fuel matrix, whose temperature does not exceed 650°C under normal reactor operating conditions and for a short time, and 1200°C in the event of the most severe accident (for cer–met fuel, these temperatures can be much lower);
2. Double fuel rod cladding, which ensures enhanced fuel integrity, and the modular channel vessels, which provide pressurized circuit integrity;
3. A reactor tank with a leak tight lid, and heat exchange surfaces for the primary heat exchangers;
4. A leak tight reactor hall, and a waterproof concrete reactor cavity with a leak tight guard lining.

During the design process of these safety barriers, special attention was paid to increasing their reliability and permanently monitoring their integrity and leak tightness. A sufficiently high water level in the reactor tank ensures heat removal from the core in all situations.

One of the most important features of the RUTA–TE reactor is self-control against human errors and multiple failures of the automatic control system, resulting in positive reactivity insertion into the core. This feature consists of the reactor core (central part) operating in the heat removal mode, so called ‘surface boiling’, close to the point where significant volumetric boiling begins. Intensive volumetric boiling in the event of an increase in core power results in reactor self-shutdown because of the high negative steam influence on the neutron flux. Under normal operating conditions, stable functioning is ensured because of the negligible amount of volumetric coolant boiling in the core. The stability of this heat removal mode in the core has been confirmed in a series of experimental investigations. Figure 4 shows the behaviour of the reactor in a beyond basis accident, demonstrating the inherent safety features of the reactor.

The primary high pressure circuit is subdivided into small volume modular channels, so that rupture of one channel (70 L) does not significantly influence reactor safety. Only one FA operates under emergency conditions, but analysis of such a situation has shown that the temperature level of the fuel rods remains below the permissible limits. Contamination of the water pool is negligible.

An additional level of activity caused by releases under normal operating conditions is within the limit of natural background fluctuations; for all the accident scenarios taken into consideration in the design (including most beyond basis accidents), the additional equivalent dose did not exceed that of radiation exposure caused by natural background.
FIG. 4. Behaviour of reactor during fast withdrawal of the control rod without operation of a scram system (0.46% full reactivity) ((1) reactor power; (2) core outlet temperature; and (3) average core void fraction).

FIG. 5. Fresh water capacity versus total net electric power for the RUTA–TE desalination plant.
4. DESCRIPTION OF THE RUTA–TE DESALINATION PLANT

Regarding reliability, the concept envisages that on one site there would be two nuclear units, which could be located in one building (40 x 70 m), all the auxiliary reactor systems and the secondary circuits with their heat exchangers. The desalination equipment is placed near to the main building in the open air. The dimensions of the plant site are approximately 275 x 170 m, and proper physical protection has to be provided. The design also considers placing the reactors underground, so that the security provided is very high.

The desalination facility operates on the principle of thermal distillation of sea water in a horizontal film apparatus (multi-effect distillation (MED)). Desalination is effected at a water temperature of 78°C (boiling) in the first stage of the plant. Facilities of this design have shown better performance than other plants at the given level of engineering and technology. The general plan of the desalination plant is illustrated in Fig. 5.

As shown in the figure, two circuits belong to the reactor plant and the third is designed to generate the steam used as a heating agent in the distillation units. Circuit to circuit heat is transferred via the heat exchange surfaces. Even in the event of loss of leak tightness of all the heat exchange surfaces, contamination of the media in the fourth loop, which produces the final product (distillate), is avoided because of the blocking ratio of pressures in the reactor plant loops (1:3): the coolant pressure in the secondary circuit is higher than that in the reactor, and in the third circuit it is higher than in the secondary circuit. The fourth loop operates under vacuum.

Water distillation is provided in the standard desalination equipment (DOUGTPA-150), which is manufactured and completed in a factory. The vacuum inside this equipment is provided by a water ejector pump.

It is possible to apply any desalination plant design, including reverse osmosis (RO), RO with preliminary heating, and others. The final choice depends on economic issues only.

Table I presents the main characteristics of the MED plant.

5. PRELIMINARY ECONOMIC ASSESSMENT

Economic assessment has been carried out using spreadsheets (IAEA Co-generation/Desalination Cost Model) [4]. These had to be modified, since the base models presented therein do not contain independent outputs for thermal and electric power. The initial data accepted were: net electric power of one nuclear unit = 3.5 MW(e); total thermal power of one unit = 70.4 MW(th); the specific cost of power plant construction = US $11 000/kW(e) for one unit; US $7300/kW(e) for two units;
TABLE I. MAIN MED PLANT CHARACTERISTICS

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint core thermal capacity (MW(th))</td>
<td>70.4</td>
</tr>
<tr>
<td>Net reactor heating capacity (MW(th))</td>
<td>65.5</td>
</tr>
<tr>
<td>Net reactor electrical capacity (MW(e))</td>
<td>3.5</td>
</tr>
<tr>
<td>Pool water parameters</td>
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</tr>
<tr>
<td>In/out temperature (°C)</td>
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</tr>
<tr>
<td>Pressure at the core level (MPa)</td>
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</tr>
<tr>
<td>Water volume in the pool (m³)</td>
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</tr>
<tr>
<td>Modular channel water parameters (maximum)</td>
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</tr>
<tr>
<td>In/out temperature (°C)</td>
<td>274/306</td>
</tr>
<tr>
<td>Pressure at the core level (MPa)</td>
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</tr>
<tr>
<td>Water volume in the channel (m³)</td>
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</tr>
<tr>
<td>Average thermal capacity of the modular channel (MW(th))</td>
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</tr>
<tr>
<td>No. of modular channels</td>
<td>78</td>
</tr>
<tr>
<td>No. of fuel assemblies in the central part of the core</td>
<td>169</td>
</tr>
<tr>
<td>Turbine efficiency (%)</td>
<td>26.7</td>
</tr>
<tr>
<td>Temperature of the reactor hot water (°C)</td>
<td>90</td>
</tr>
<tr>
<td>Weight of dry DOU GTPA-150 equipment (t)</td>
<td>21.5</td>
</tr>
<tr>
<td>Two reactor units plus the MSF plant:</td>
<td></td>
</tr>
<tr>
<td>fresh water capacity (m³/d)</td>
<td>35 000</td>
</tr>
</tbody>
</table>

and US $6000/kW(e) for three to four units. The other initial data were taken from the spreadsheets without any changes. Calculations have been done for one, two, three and four nuclear units. Some of these results are given in Figs 5–8.

The dependence of the average daily fresh water capacity on the total net electric power for various types of desalination plant is shown in Fig. 5. In the range of power of 3.5–14 MW(e), the water capacity for MED varies from 15 700 to 62 800 m³/d, for RO from 12 000 to 60 000 m³/d, and for hybrid plants (MED + RO) from 36 000 to 84 000 m³/d. The discrete character of the points for RO corresponds to the accepted model minimum water capacity of 12 000 m³/d for the desalination unit.

In Fig. 6, the results of fresh water cost versus fresh water capacity are shown; the water cost decreases when the water capacity increases. This cost is quite
competitive when compared with the cost of water produced in fossil fuelled power plants. Thus, when the fresh water output ranges between 12 000 and 84 000 m$^3$/d, the cost of water is US $0.9–1.92/m$^3$ for MED, US $0.96–2.02/m^3$ for SARO (stand alone reverse osmosis), US $0.89–1.86/m^3$ for CRO (contiguous reverse osmosis), and US $0.92–1.89/m^3$ for MED + RO.

In Fig. 7, the results of the net saleable electric power (excessive) versus the fresh water capacity are given. It is clear that the electric capacity of the power plant is sufficient for water desalination. Excess electric energy can be used to supply other consumers. Therefore, the net saleable electric power produced at one unit is 0.68 MW(e) for MED and 0.92 MW(e) for RO; at four units, it is 4.7 MW(e) for MED and from 1.11 MW(e) (at 60 000 m$^3$/d of fresh water) to 11.4 MW(e) (at 12 000 m$^3$/d of fresh water) for RO. Only for hybrid desalination plants of one and two units is there insufficient electrical capacity. In this case, the desalination plants would have to be supplied with power from an additional electric energy source (the transmission line).

The total investment costs for power and water plants of one to four nuclear units are presented in Fig. 8. These correspond to the option 3 economic estimation given in Ref. [4].

6. CONCLUSIONS

Heating has become more expensive because of the rise in the price of fossil fuels. Burning of large quantities of fossil fuel leads to local ecological problems. The nuclear alternative seems to be reasonable, but in contrast to the earlier development
FIG. 7. Net saleable electric power versus fresh water capacity for the RUTA–TE desalination plant.

FIG. 8. Total investment costs versus fresh water capacity for the RUTA–TE desalination plant.
period it has become much less popular. A nuclear source for generating heat must be simple, cheap and safe. Pool type reactors show great potential for district heating and sea water desalination. Their simplicity and ease of maintenance and manufacture make this type of heat source attractive for those states with an undeveloped nuclear industry.

REFERENCES


ADVANCED INTEGRAL REACTOR (SMART) FOR NUCLEAR DESALINATION

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Abstract

ADVANCED INTEGRAL REACTOR (SMART) FOR NUCLEAR DESALINATION.

At present, severe fresh water shortages are occurring in some regional areas of the Republic of Korea and the problem is expected to spread throughout the country within a decade unless appropriate and timely countermeasures are taken. Of these, nuclear sea water desalination is receiving much attention because the Republic of Korea has a firmly established nuclear environment and abundant sea water resources. In addition, nuclear plants provide cleaner energy than fossil plants, which is another important beneficial factor for countries as crowded as ours. With a view to applying nuclear desalination, development of SMART (system integrated modular advanced reactor) was initiated and is currently in progress. SMART is being developed as a 330 MW(th) integral reactor with passive safety features. The design of SMART is aimed at combining the firmly established commercial reactor design with new advanced technologies. This has led to the use of industry proven Korea optimized fuel assembly (KOFA) based fuels, while radically new technologies such as a self-pressurizing pressurizer, helical once-through steam generators and a new control concept are being developed. The current development status of SMART and its application to nuclear desalination are presented.

1. INTRODUCTION

Water is an essential element of human life and its availability can dictate the quality of life. In the Republic of Korea, clean fresh water used to be found in large quantities in many rivers and streams, and the average precipitation rate used to be high enough to replenish these water resources. However, the drastic increase in water usage as well as the increase in pollution (caused by rapid industrialization) and the population are taking a heavy toll on such natural water resources. A series of droughts caused by abnormal climatic conditions over the past few years has resulted in severe water shortages in local regions. Such localized problems are having an impact on agriculture and on the operation of the large industrial complexes located in these regions. The dwindling natural water resources, coupled with increasing water demands, are expected to result in serious nationwide water shortages within a
FIG. 1. Overall schematic flow diagram of the nuclear steam supply system (NSSS).
decade unless appropriate countermeasures are taken. Of the several countermeasures under consideration, sea water desalination is receiving much attention because the Republic of Korea has an abundance of sea water from the surrounding seas.

Fossil and nuclear fuels are considered to be the main industrially proven, large scale energy sources for sea water desalination. However, for countries such as ours, which are deficient in fossil fuel resources, the nuclear energy option offers economic and political advantages for securing the local energy requirements. Without considering the adverse and serious environmental effects of, for example, global warming and acid rain resulting from the use of fossil fuel, the nuclear option will become even more of a reality as the supplies of fossil fuel are depleted in the near future.

Over the past decade, the Republic of Korea has successfully secured commercial nuclear power technology. This self-reliance in nuclear energy technology makes a notable contribution to the energy security of the country, where no oil is produced. The determination of the government to solve the energy problems has resulted in the expansion of the peaceful uses of nuclear energy to non-electrical applications.

In view of such an energy option, the Korea Atomic Energy Research Institute (KAERI) started a programme for developing a new advanced 330 MW(th) integral reactor named SMART (system integrated modular advanced reactor) to supply the energy for sea water desalination and for electric power generation. The major design requirement of SMART is passive safety features, and after studying various layouts the integral layout was selected because it provides the optimum configuration for passive safety. In addition, one of the design objectives of SMART is to combine new technologies with firmly established commercial reactor design and manufacturing technologies. For example, the fuel design for SMART will be based on the industry proven Korean optimized fuel assembly (KOFA) design, but a new advanced reactivity control technology, using a control rod and a large negative moderator temperature coefficient, will be developed to eliminate chemical shim. The design status and the issues involved in developing SMART are summarized in the following sections.

2. NUCLEAR STEAM SUPPLY SYSTEM

The major systems and components of the nuclear steam supply system (NSSS) of SMART include the primary circuit system, the secondary circuit system, the equipment cooling system, the emergency core cooling system (ECCS), the scheduled and emergency cool down system (SECS), the make-up and emergency boron injection system and the safeguard vessel. An overall schematic flow diagram of the NSSS is given in Fig. 1. The various systems are described briefly in the following subsections.
### TABLE I. MAJOR PARAMETERS OF THE PRIMARY CIRCUIT SYSTEM

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal thermal power of the reactor</td>
<td>330 MW(th)</td>
</tr>
<tr>
<td>Parameters of the primary circuit</td>
<td></td>
</tr>
<tr>
<td>Nominal pressure</td>
<td>15 MPa</td>
</tr>
<tr>
<td>Design pressure</td>
<td>17 MPa</td>
</tr>
<tr>
<td>Coolant temperature at nominal power</td>
<td></td>
</tr>
<tr>
<td>Core outlet</td>
<td>310°C</td>
</tr>
<tr>
<td>Core inlet</td>
<td>270°C</td>
</tr>
<tr>
<td>Coolant flow rate through the core</td>
<td>1556 kg/s</td>
</tr>
<tr>
<td>No. of MCPs</td>
<td>4</td>
</tr>
<tr>
<td>Main characteristics of the MCPs</td>
<td></td>
</tr>
<tr>
<td>Capacity</td>
<td>1982 m³/h</td>
</tr>
<tr>
<td>Head</td>
<td>13.5 m (0.095 MPa)</td>
</tr>
<tr>
<td>Working temperature (medium)</td>
<td>310°C</td>
</tr>
<tr>
<td>Working pressure (medium)</td>
<td>15 MPa</td>
</tr>
<tr>
<td>Rotational speed</td>
<td>3600 rev/min</td>
</tr>
<tr>
<td>Power consumption</td>
<td>128–170 kW</td>
</tr>
</tbody>
</table>

*FIG. 2. Schematic layout of the secondary circuit system.*
2.1. Primary circuit system

SMART is of integral design and most of the primary circuit system is housed within the reactor vessel. The major primary circuit components housed in the reactor include the core, four main circulating pumps (MCPs), 12 steam generator cassettes and the pressurizer. The major portion of the primary coolant circulates within the reactor vessel, and the primary circuit itself is hydraulically connected to the following systems:

1. The ECCS via three nozzles on the annular cover of the reactor;
2. The reactor overprotection system via one nozzle on the centre cover of the reactor;
3. Make-up and emergency boron injection via three trains of ECCS;
4. The nitrogen supply system via the gas pipeline of the pressurizer system;
5. The drainage and air removal system.

The major parameters of the primary circuit system are given in Table I.

2.2. Secondary circuit system

The function of the secondary circuit is to remove the heat from the primary circuit to generate superheated steam from the feedwater. A schematic layout of the secondary circuit system is given in Fig. 2. It consists of in-vessel steam generators and out-of-vessel piping with various valves. The system is divided into four independent sections arranged in such a way as to minimize the heat removal imbalance in the vessel when one section fails. The major features of the secondary circuit system are as follows:

1. The design pressure of the steam and feedwater line is 17 MPa in order to withstand the pressure increase in the event of steam generator tube rupture;
2. The steam generator tube leak monitoring system is used to identify leaky sections.

The major parameters of the secondary circuit system are given in Table II.

2.3. Equipment cooling system (ECS)

The function of the ECS is to remove the heat that is generated in the MCPs, the control rod drive mechanisms (CRDMs), the pressurizer and the internal
TABLE II. MAJOR PARAMETERS OF THE SECONDARY CIRCUIT SYSTEM

<table>
<thead>
<tr>
<th>Parameters of the secondary circuit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal steam pressure</td>
<td>3 MPa</td>
</tr>
<tr>
<td>Design pressure</td>
<td>17 MPa</td>
</tr>
<tr>
<td>Design temperature</td>
<td>350°C</td>
</tr>
<tr>
<td>Steam output</td>
<td>152.4 kg/s</td>
</tr>
<tr>
<td>Superheated steam pressure</td>
<td>3 MPa</td>
</tr>
<tr>
<td>Superheated steam temperature</td>
<td>274°C</td>
</tr>
<tr>
<td>Feedwater pressure</td>
<td>5 MPa</td>
</tr>
<tr>
<td>Feedwater temperature</td>
<td>180°C</td>
</tr>
<tr>
<td>Degree of superheating of steam</td>
<td>40°C</td>
</tr>
</tbody>
</table>

biological shielding. The feedwater supplied from the condensate pumps of the turbogenerator is used as coolant. The main characteristics of the ECS are as follows:

- Cooling water pressure: 0.5 MPa
- Cooling water temperature: 40°C
- Flow rate of the water supplied:
  - MCP: 4 × 1.2 kg/s
  - CRDM: 25 × 0.06 kg/s
  - Pressurizer: 3.5 kg/s
  - Biological shielding: 3 kg/s

2.4. Emergency core cooling system

The function of the ECCS is to mitigate the consequences of a design basis loss of coolant accident (LOCA) by means of reactor make-up to ensure core coverage with water. The postulated LOCA includes a double ended break of the largest primary circuit pipeline connected to the reactor vessel, and a leak in the base metal or the welding of the vessel. The ECCS consists of three independent trains, each of which includes an accumulator type water tank with a gas cushion connected to the reactor cover via a pipeline. The pipeline is fitted with a cut-off valve to isolate the water tank during scheduled shutdown of the reactor, a rupture disc and a check valve. There are other pipelines for filling and adjusting the water level, and for nitrogen supply and discharge. The ECCS operates passively; preliminary estimates are a volume in the water tank of about 5 m$^3$ and a pressure for the rupture disc of about 10 MPa.
2.5. Scheduled and emergency cool down system

The function of the SECS is to cool down the NSSS actively by forced circulation for normal, scheduled and maintenance cool down using a pump, and passively by natural circulation for emergency cases where the normal steam extraction or feedwater supply is unavailable. The SECS consists of four independent trains; the operation of any two trains will be sufficient to remove the decay heat. Each train consists of the following:

1. A heat exchanger/condenser placed in an emergency cool down tank filled with water;
2. A compensating tank to fill the pipeline with water as the system comes into operation;
3. Pipelines and valves.

A schematic flow diagram of the SECS is shown in Fig. 3. The capacity and size are determined on the basis of a 72 hour grace period, i.e. the system should provide a core decay removal capability for 72 hours without any operator action.
2.6. Make-up and emergency boron injection system

The function of the make-up and emergency boron injection system is to fill and make-up the primary circuit with coolant, and to bring and maintain the core into a subcritical state in the event of failure of the core protection system. The pipeline connecting the boron injection tank to the system is detachable. To avoid spurious actuation of the boron injection system, the pipeline is normally disconnected, and the system is brought into operation by connecting the pipeline manually upon receiving the order. The make-up system is composed of three independent trains, each of which consists of one high pressure pump, a tank holding the boron solution, and the piping and valves.

2.7. Safeguard vessel

The major functions of the safeguard vessel are as follows:

1. To confine the radioactive products released from the primary circuit within the design boundaries;
2. To limit and terminate the egress of primary coolant and to maintain core coverage with coolant during the 72 hour grace period in conjunction with the operation of the SECS and ECCS;
3. To protect against overpressure under beyond design basis accidents.

The safeguard vessel is designed as a leak tight metal structure and houses the integral reactor with MCPs, CRDMs, piping, valves and the pressurizer gas cylinders. To ensure isolation of the primary circuit, double cut-off valves will be installed for the make-up system, the air removal system and the pipelines, all of which are connected to the primary circuit during normal operation. The leak rate in the safeguard vessel is designed to be below 1%/d under a maximum excessive pressure of 2 MPa.

In addition, the safeguard vessel itself is completely enclosed in the containment. The safeguard vessel is to be fabricated in-shop.

3. REACTOR AND MAJOR COMPONENTS

The major components of the reactor system are a reactor vessel with covers and internal structures, a core with 57 fuel assemblies, 25 CRDMs, 12 steam generator cassettes with steam collecting and feedwater distributing chambers and pipe networks, four main circulating pumps and a self-pressurizing pressurizer.
FIG. 4. General view of the reactor vessel (1 = MCP (4); 2 = drive fastening frame; 3 = CRDM (25); 4 = thermal insulation; 5 = annular cover; 6 = pressurizer; 7 = displacers; 8 = steam generator; 9 = protection tubes; 10 = vessel; 11 = core barrel; 12 = fuel assembly (57); 13 = side screen; and 14 = partition).
3.1. Reactor vessel, covers and internals

Figure 4 provides a general view of the reactor vessel, and it can clearly be seen where all the major components of the primary circuit are housed. The reactor vessel consists of two welded cylindrical barrels forming the middle section, a semi-ellipsoidal section welded at the bottom and a flange part welded at the top. An annular cover is fixed on to the top flange by means of stud bolt joints. A centre cover is fastened to the annular cover by a flangeless joint of unique design, which allows a substantial decrease in the dimensions of the fastening unit and simplifies the dismantling and mounting procedures. The mating surfaces of the vessel to annular cover and the annular to central cover joints are made leak tight by welded torus type sealings.

The steam collecting and feedwater distributing chambers for the steam generators, four MCPs, the make-up piping nozzles with check valves embedded in the cover, and various other piping are located on the annular cover. The CRDMs and various nozzles, pipes and the pipeline are located at the top of the centre cover.

Other major structures inside the reactor vessel include displacers at various locations to reduce the water inventory, the control rod assemblies, the protection tubes, the debris combs and the side screens for radiation shielding purposes.

*FIG. 5. Reactor core and fuel assembly.*
3.2. Reactor core and fuel assembly

As shown in Fig. 5, the reactor core consists of 57 fuel assemblies (FAs) with a $17 \times 17$ fuel rod array. The fuel assembly is based on the design of KOFA. The fuel rods are arranged in rectangular lattices, as in KOFA, but the length of the FA has been reduced from 4058 to 2400 mm. Because of the reduced FA length, experimental programmes are planned to determine the pressure drop, the heat transfer and the critical heat flux characteristics. The fuel used is uranium oxide and the uranium enrichment for all the FAs is 5%. KOFA has been successfully used in several nuclear power plants in the Republic of Korea, and shown good performance.

As indicated in Fig. 5, the control rod clusters are located in 25 FAs, and the instrumentation probes are located in 28 other assemblies. The design of the control rod cluster is shown in Fig. 6. It comprises a head with 16 phalanges of various length, to which 24 absorber rods are attached. The absorber material used for the control rod is composed of TiO$_2$ and Dy$_2$O$_3$.

The water is used as both coolant and moderator, and reactivity control is achieved by an inherent large negative moderator coefficient and the operation of control rods. The design of the CRDM allows fine reactivity control by using linear step motors. Unlike large commercial PWRs that use the same type of FAs, there is

![FIG. 6. Control rod cluster.](image-url)
no liquid absorber, resulting in much simpler water chemistry control. The core is designed to have a power operation capability in the range of 20–100% nominal power. The major design parameters of the core are given in the Table III.

3.3. Steam generator

The SMART has 12 steam generator cassettes that are located around the middle section of the annulus formed between the reactor vessel and the core barrel,

TABLE III. MAJOR DESIGN PARAMETERS OF THE CORE

<table>
<thead>
<tr>
<th>(1) Operational parameters</th>
<th>(4) Control rod parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal power</td>
<td>330 MW(th)</td>
</tr>
<tr>
<td>Average coolant temperature</td>
<td>290°C</td>
</tr>
<tr>
<td>Pressure</td>
<td>15 MPa</td>
</tr>
<tr>
<td>Lifetime (refuelling period)</td>
<td>54 months</td>
</tr>
<tr>
<td>Average power density</td>
<td>62.6 kW/L</td>
</tr>
<tr>
<td>Average linear power density</td>
<td>109 W/cm</td>
</tr>
<tr>
<td>No. of control groups</td>
<td>6</td>
</tr>
<tr>
<td>No. of control rods in each group</td>
<td>CG1: 4, CG2: 8, CG3: 4, CG4: 4, CG5: 4, CG6: 1</td>
</tr>
<tr>
<td>Absorbing material</td>
<td>TiDy-205</td>
</tr>
<tr>
<td>Absorber density</td>
<td>6 g/cm³</td>
</tr>
<tr>
<td>Total worth of control groups</td>
<td>In cold state: 15.2%, In hot state: 20.1%</td>
</tr>
</tbody>
</table>

(2) Design parameters

| Effective core height | 2 m                     |
| Equivalent core diameter | 1.831 m                |
| Core volume           | 5.266 m³                |
| No. of FAs            | 57                      |
| Type of FA            | 17 × 17 square          |
| No. of fuel elements in the FA | 264 |
| Burnable poison       | Gd₂O₃                   |

(3) Fuel cycle parameters

| Fuel                  | UO₂                     |
| Uranium enrichment    | 5%                      |
| Linear UO₂ density    | 5.189 g/cm³             |
| Total uranium loaded  | 13.617 t               |
| Total U-235 loaded    | 0.681 t                 |
| Specific uranium power| 24.2 MW/t U             |
| Average burnup        | 38.8 MW-d/kg            |
| Average discharge burnup | 1.6%                  |

(5) Reactivity effects

| Supercriticality of unpoisoned reactor with or without control groups | In cold state: 11.0%, In hot state: 4.2% |
| Subcriticality of reactor in cold unpoisoned state | At beginning of life: 11.0%, At maximum reactivity: 4.2% |
| Life of prompt neutron | 2 × 10⁻³ s |
| Effective fraction of delayed neutron | 0.007 |
as can be seen in Fig. 4. The steam generator is of once-through design, with helically coiled tubes of titanium alloy (12 mm outer diameter and 1.5 mm thickness). Feedwater and steam flow inside the tubes, while the primary coolant flows over the outer surface. Each steam generator cassette is composed of 330 tubes wound around the central mandrel. The tubes in the cassettes are further grouped into six

**FIG. 7. Steam generator cassette (1 = feedwater pipe (6); 2 = feedwater chamber (6); 3 = throttling device (330); 4 = tubing plate; 5 = housing; 6 = steam chamber (6); 7 = lower plate; and 8 = throttling orifice).**
independent modules, each of which has one independent feedwater intake and one steam outlet header. The design of the steam generator cassette is shown in Fig. 7.

Because of the possible hydrodynamic instability of the parallel connected tubes, provision must be made for the hydrodynamic stability of the steam generator cassette tubes for the whole range of operating loads. Specially designed throttling devices are installed at the feedwater inlet of each helically coiled tube. Each of these devices is located in the tube sheet of the cassette module feedwater headers and designed as a sleeve with a core connected by a thread joint. Throttling orifices are also installed on the primary side of the lower part of each cassette to allow uniform primary coolant flow rates through each cassette by controlling the hydraulic resistance of the cassette shell side.

The maximum feedwater temperature is limited because of the possibility of local boiling in the throttling devices installed at the inlet of the tubes during the low power operating mode. Local boiling will be the major reason for flow instability during this mode.

The steam generator is also used as the heat exchanger for the passive decay heat removal system, which permits independent operation of this system in the hydraulic condition of the primary circuit.

KAERI has developed a computer code, ONCESG, for thermal sizing the once-through steam generator, and an analysis code for transient analysis and control logic development is currently under development. To validate the design and to verify the codes, an experimental programme using a full sized steam generator cassette is planned.

3.4. Self-pressurizing pressurizer

Another important new concept is in the pressurizer design. To reduce the out-of-reactor primary pipework and thus to lessen the severity and possibility of a LOCA, the pressurizer is housed entirely in the reactor pressure vessel. In addition, a self-pressurizer concept has been adopted to eliminate the complicated control and maintenance requirements. With the self-pressurizer, active pressure control, e.g. for the spray and heaters, is not required. However, in spite of simpler control and enhanced safety, such design raises certain engineering problems. First, the in-vessel pressurizer has a certain limit in size, and the in-vessel pressurizer, located in the upper part of the reactor where the coolant is hot, has to operate under a high temperature. Also, the temperature in the pressurizer gas–steam space changes with the reactor core outlet temperature, and the pressurizer pressure is strongly affected by the reactor core outlet temperature.

To solve problems such as the relatively large variation in pressure caused by a change in power, SMART has adopted the constant primary coolant average temperature control concept and the constant pressurizer temperature concept. In our
constant average temperature design concept, the core outlet temperature decreases by about 16°C, which corresponds to a 2.3 MPa pressure change, when the power changes from 100 to 20% nominal power. If we add the pressure change caused by the change in volume in the pressurizer gas–steam space, the total pressure drop amounts to about 3 MPa during power manoeuvring from 100 to 20% nominal power. This large pressure variation during power manoeuvring can be reduced by keeping the constant temperature of the pressurizer gas–steam space low and insensitive to the core outlet temperature variation. For this purpose, a pressurizer cooler has been installed to maintain the low pressurizer temperature, and a wet thermal insulator placed between the pressurizer and the primary circuit to reduce conduction heat transfer.

To provide high primary coolant pressure, high pressure nitrogen is used in the pressurizer gas–steam space. The solubility of nitrogen gas is dependent on the coolant temperature and pressure. It has been observed that the solubility of the nitrogen gas for water at a given coolant pressure reaches the minimum solute temperature at about 80°C; SMART maintains the pressurizer temperature at around 100°C.

3.5. Main circulation pump

SMART has four MCPs installed through the top annular cover of the reactor vessel. Each MCP is an integral unit consisting of a canned asynchronous three phase motor and an axial flow single stage pump. The motor and pump are connected by a common shaft rotating on three radial bearings and one axial bearing, which are made of specialized graphite based material; the axial bearing also performs the function of sealing. The pumps are cooled by equipment cooling water.

Gas accumulates in the upper part of the motor because of saturation of the coolant with nitrogen in the pressurizer and gas transfer into the primary circuit, and is discharged to the suction side of the pump runner (via holes drilled through the length of the shaft) because of a pressure drop between the upper cavity of the motor and pump suction.

The speed of the pump rotor is controlled by a sensor installed in the upper part of the motor. To avoid reverse rotation of the pump rotor, it is planned that an anti-reverse device be installed at the motor shaft near the middle radial bearing. The main characteristics of the MCPs are provided in Table I.

4. POWER CONTROL SYSTEM

The control concept of SMART is very different from that of a commercial nuclear power plant. In the integral reactor using a once-through steam generator, the
control system needs to be fully automated because a relatively small heat imbalance can result in water carry-over to the turbine, or evaporation of the entire water mass inside the steam generator tubes. Such problems can be alleviated by providing reliable fine control of the feedwater flow rate at the steam generator inlet for steam generator heat balance, which requires the development of new control logic and systems.

SMART does not use chemical shim; instead, it relies on the very strong moderator temperature coefficient to control the reactor power without movement of the control rods. It is envisaged that the thermal power of the nuclear core will be controlled only by regulating the feedwater flow rate to the once-through steam generator. With the variation in feedwater, the controllable power will range from 20 to 100% nominal power. Detailed control logic is under development.

The control rod drive mechanism will have the capability of fine control because of the possibility of water carry-over to the turbine or of dry-out of the entire water inside the steam generator tubes by the relatively small heat imbalance between the core thermal power and the heat removal capability of the steam generator.

Another new design concept of SMART is nuclear heating during reactor startup. Owing to the very low hydraulic resistance of the primary coolant circuit, small MCPs are sufficient for normal coolant circulation. As a result, heating of the NSSS in the startup phase using the MCPs, as practised in commercial PWRs, will take an unacceptably long time, therefore the nuclear heating method will have to be used. The detailed heatup procedure has yet to be formulated and further R&D programmes are necessary. In addition, designs or operating procedures such as a core without soluble boron, control element drive mechanisms capable of fine reactivity control and nuclear heating during reactor startup still require R&D programmes to verify the design/operation concept.

5. DESALINATION SYSTEM FOR SMART

KAERI intends to develop SMART so that it is as flexible as possible; one application is the coupling of SMART to a conventional sea water desalination plant. The heat or electricity required for sea water desalination can be supplied by nuclear sources, with few technical problems; in principle, nuclear reactors can accommodate a sea water desalination plant of any size.

In the design of SMART, most of the well known large scale water production plants are being considered. Thus, commercially available desalting processes such as reverse osmosis (RO), multi-effect distillation with vapour compression (MED–VC), multi-effect distillation (MED) and multi-stage flash (MSF) are being studied for coupling to SMART. All these processes have already been used and proven worldwide for the desalination of sea water, and all are commercially available from a variety of suppliers.
In general, the characteristics of the nuclear reactor for sea water desalination will be determined by the type of sea water desalination plant to be coupled. If the plant were to be coupled to the MED or MSF process, the nuclear reactor should be located adjacent to the sea water desalination plant and be a co-generation plant producing electricity as well as heat. However, if the nuclear reactor were to be coupled to the RO or MED–VC process, it need not be near to the sea water desalination plant and would only produce electricity.

In principle, the design of sea water desalination plants should not differ, whether a nuclear or a conventional energy source (fossil, natural gas or petroleum) is used to supply the heat. Thus, KAERI is concentrating on developing a safe and economical integral nuclear reactor for sea water desalination that will be competitive with fossil fuel. KAERI and other industrial companies in the country are currently developing the most effective design concepts for a sea water desalination plant.

6. CONCLUSIONS

With the prospect of severe water shortages, sea water desalination using a nuclear reactor is receiving much consideration as a promising countermeasure. Development of basic technology and feasibility study programmes for an integral reactor has been carried out in the past, and a government supported 10 year project for developing a nuclear desalination facility was launched in 1996. Thus, the design of SMART was initiated with a view to multi-purpose applications, including nuclear desalination.

The design of SMART is intended to meet more stringent performance and safety requirements by designing advanced features such as the passive removal of decay heat, simplification of the systems, a reduction in radioactive releases under severe hypothetical conditions, a minimum 72 hour grace period, a 48 month refuelling period, and a power change without control rod movement. The design of SMART combines the well proven technologies of current commercial reactors and many radically new and innovative technologies such as a self-pressurizer and once-through helical steam generators.

Most of the basic design concepts for SMART have been established, and current efforts are concentrated on verifying the new design concepts through experiments as well as other R&D efforts. With the successful completion of this project, including the development of SMART, KAERI will be able to provide the technology to solve the nation’s severe water shortages expected in the near future. In addition, by securing a broad range of fundamental nuclear technologies, the country’s energy security will be assured.
EVALUATION OF THE CONCEPTUAL DESIGN OF INTEGRATED PWRs AND THE CAREM 25 PROJECT

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Abstract

EVALUATION OF THE CONCEPTUAL DESIGN OF INTEGRATED PWRs AND THE CAREM 25 PROJECT.

If the potable water demands worldwide are to be met, the desalination capacities will have to be extended. The choice of nuclear energy as the electricity supply for sea water desalination plants has been studied, and several integrated PWRs have been proposed. Bearing in mind that economic potable water is required, the electricity supply provided must also be economic. Rigorous evaluation should be made of both the competitiveness of an integrated PWR and the economic production of electricity for a desalination plant. The power required usually ranges between that produced in small and medium reactors, and for this reason the size effects must be carefully studied. The competitiveness of the desalination power range was analysed using an economic evaluation and optimization programme based on integral PWR designs. Several design rules have been defined for obtaining competitive potable water supplies with these reactors. From this point of view, an outline of the Carem 25 project is given, showing that its design meets the economic criteria required for a nuclear power source for desalination in the very small power range.

1. INTRODUCTION

If the potable water demands worldwide are to be met, the desalination capacities will have to be extended. There are several reasons for the choice of a
nuclear reactor as the energy supply for sea water desalination plants. However, the availability of different types of nuclear plant demands careful selection, taking into account the specific requirements related to this application.

Within the framework of current nuclear technology, the integrated PWR appears to be an appropriate option for this purpose. This type of reactor has many inherent safety characteristics (no large loss of coolant accident (LOCA), long characteristic times in the event of transients or severe accidents because of the large coolant inventory, and the decay heat is transferred to the steam generators (SGs) by natural circulation). These factors and simple operation make the integrated PWR a realistic energy option in countries with limited nuclear development. For economic reasons, it is convenient to locate the reactor and the desalination plant near to cities; however, this is only possible if a high level of nuclear safety is provided (these requirements can be easily met by integrated reactors because of their design). On the other hand, to minimize specialized labour on the construction site, complex operations associated with reactor assembly should be reduced. In this field, integrated reactors show advantages over traditional designs in their quality control, construction schedules and costs (less difficult welding on the construction site, off-site assembly of systems, etc.).

However, a rigorous evaluation should take into account the economic competitiveness of such an option compared with other energy sources [1]. Normal integral PWR designs have not been developed with a view to being competitive with large plants because of their well known economy of scale effects. However, production of economic potable water requires a low cost electricity supply, even in the very small, small and medium power ranges.

2. REACTOR EVALUATION

2.1. Advanced evaluation model

A design analysis computer code was developed to analyse the economic performance of different integral PWR designs in order to achieve a coherent engineering design for the production of economic potable water in the very small, small and medium power ranges. The code was developed using well known PC systems so that it can be easily run by users others than those who developed the code.

This code contains several modules related to different aspects of the evaluation: various models of reactor systems, procedures for the mechanical design of the nuclear steam supply system (NSSS) and for the economic evaluation of the plant, and an optimization routine. The models are employed to predict the thermohydraulic and neutronic performance of the primary system, the efficiency of the secondary circuit, and other parameters of the NSSS, including the void coefficient and the
minimum critical power ratio. Figure 1 gives a flow chart of the modules of the design programme. A detailed explanation of the models used in the code is not included here because of its scope and length, and because a detailed paper on this subject is currently in preparation; however, Ref. [2] could be of use for further studies.

The optimization routine carries out numerous procedures to minimize the cost of the generation of electricity with respect to the design variables. Because of its

FIG. 1. Flow chart of the modules of the design programme.
TABLE I. BOUNDARY CONDITIONS, OPTIMIZED VARIABLES AND PARAMETRIZED VARIABLES USED IN THE CODE

<table>
<thead>
<tr>
<th>Boundary conditions</th>
<th>Optimized variables</th>
<th>Parametrized variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum diameter of SG tube</td>
<td>Primary pressure</td>
<td>Thermal power</td>
</tr>
<tr>
<td>Maximum burnup of fuel element</td>
<td>Temperature difference</td>
<td>Interest rate</td>
</tr>
<tr>
<td>Minimum steam overheating</td>
<td>in pressurizer</td>
<td>Height to diameter</td>
</tr>
<tr>
<td>Minimum critical power ratio</td>
<td>Flow of primary pumps</td>
<td>core ratio</td>
</tr>
<tr>
<td>Minimum void reactivity coefficient</td>
<td>Inlet temperature of SG</td>
<td>Linear heat rate of fuel</td>
</tr>
<tr>
<td>Inlet temperature of SG</td>
<td>at secondary side</td>
<td>rod</td>
</tr>
<tr>
<td>Max height of reactor pressure vessel</td>
<td>Secondary pressure</td>
<td>No. of SGs</td>
</tr>
<tr>
<td></td>
<td>Diameter of SG tube</td>
<td>Refuelling zones</td>
</tr>
<tr>
<td></td>
<td>Pitch to diameter SG</td>
<td>SG baffles in</td>
</tr>
<tr>
<td></td>
<td>tube ratio</td>
<td>liquid phase</td>
</tr>
<tr>
<td></td>
<td>Length of SG tube</td>
<td>SG baffles in</td>
</tr>
<tr>
<td></td>
<td>Pitch of fuel rod</td>
<td>vapour phase</td>
</tr>
<tr>
<td></td>
<td>Enrichment of fuel rod</td>
<td></td>
</tr>
</tbody>
</table>

Because of these design requirements, security considerations and construction limits, the optimization procedure must take into account the constraints in the design variables, e.g. the minimum diameter of the SG tubes and the maximum burnup of the fuel elements.

Table I shows the boundary conditions, the optimized variables and the parametrized variables used in the code. The power of the plant can be easily changed, therefore the economic behaviour of the design at different power ranges and the major consequences on potable water production have to be studied.

The optimization routine uses a finite difference model to compute the gradient vector and the changes in variables in a least cost direction. When the programme reaches a boundary condition, a new step has to be calculated from the gradient projection that is normal to the boundary condition vector using standard vector algebra (the Grand–Schmidt method). The step size and convergence criteria used in this routine can be changed by the user.

Figure 2 shows the evolution of several design variables (normalized to their initial values) during execution of the automatic optimization procedure.
2.2. Integral reactor design evaluation

Reviews made of the integrated PWR designs [3, 4] have shown that they use different steam generator designs, coolant circulation systems, pressurizer systems, etc. The reactor power itself varies greatly in the different designs.

The objective of this section is to apply the developed computer code to the study of the economic behaviour of these designs, using only the lowest cost option for each design. The code allows evaluation of the different SG systems and the primary and secondary pressures. Because of the strong dependence of the results on the coolant circulation system, all the optimal forced convection and natural convection designs are shown as the regions where the lowest costs were obtained. If other performance factors and parameters were used, the levelized energy costs would be higher.

An example of such regions is given in Fig. 3, which shows the optimal efficiency for both circulation systems. It can be seen that, for a thermal power greater
than 200 MW(th), the efficiency of the natural convection design is much lower than that of the forced convection design. This is because of the larger size of the reactor pressure vessel (RPV) and the temperature differences in the core of the natural convection design.

The results of another parametric study are given in Fig. 4. In the power range of 80–150 MW(e), natural convection leads to an RPV length that is longer than current nuclear RPVs. The RPV length limit does not preclude a further power increase, but it does reduce the degree of freedom needed to minimize the generation costs. Figure 5 shows that the optimal power density of forced convection is similar
FIG. 5. Optimal power density of the forced convection and natural convection designs.

FIG. 6. Relative construction costs of the forced convection and natural convection designs.

To that of natural convection at 100 MW(th) but is very different at 400 MW(th). A lower power density core implies higher initial core amortization costs but is directly related to a longer operational time between refuelling outages. Forced convection reactors can operate for approximately 300 full power days compared with 400 full power days for natural convection reactors.

The relative construction costs (US $/kW(e)) are given in Fig. 6. As can be seen in the figure, the natural convection design is not the lowest cost option for energy generation because of the differences in capital costs. When the simplification costs
for the forced convection and natural convection designs are considered, the differences are large.

### 2.3. Carem 25 reactor design

Application of this programme to the Carem 25 design [4] shows that technically it falls into the lowest cost range of the natural convection system (Figs 3–6). This is because of the similarity in the figure of merit used both in the optimization procedure of the earlier Carem design stages and in the computer program described here. The Carem design minimizes the weight and cost of the primary system components and has low relative fuel cycle to capital fuel cycle costs. Minimization of the primary system component weights is not effective at a power level greater than 100 MW(e) because the relative fuel cycle cost is not negligible and the operation and maintenance costs are high.

Therefore, Carem 25 is as an example of an economic integrated PWR in the very small power range.

### 3. CAREM 25 PROJECT: CURRENT STATUS

#### 3.1. Historical review

The Carem project, which comprises a very small nuclear power plant owned by the Comisión Nacional de Energía Atómica (CNEA), is being developed jointly by CNEA and INVAP S.E. The concept was born in the 1980s as a step towards reaching nuclear maturity in the design and construction of nuclear power plants. In a country with a medium sized economy and restricted financial resources, a nuclear reactor has to carry limited risk, therefore the focus was set on a small nuclear power plant. In addition, the plant had to be able to operate at isolated sites, where the ability of operating personnel to obtain assistance in the event of an incident/accident is limited, and where long distances separate the plant from fully developed areas. These criteria led to the design of an integrated primary system and to the use of passive systems (e.g. natural circulation cooling). Because of these innovative features, an R&D programme was set up and construction of a laboratory for thermohydraulics and a critical facility was undertaken.

#### 3.2. Engineering stage

Since 1995, much effort has been devoted to the R&D plans on the innovative areas of the Carem design (mainly related to the RPV) in order to be able to complete the detailed engineering needed to start plant construction in 1998.
In-depth studies encouraged project personnel to seek different solutions for some systems and components, therefore certain designs may still evolve (e.g., for the control rod drive mechanism, the residual heat removal system and the containment). Figures 7 and 8 show the Carem 25 primary containment layout and RPV scheme, respectively.

3.3. Experimental developments

The Circuito de Alta Presión y Circulación Natural is a rig designed mainly to verify the dynamic response of the primary circuit, including pressure control through feedback on power. It resembles the Carem primary loop, while the secondary loop only produces adequate boundary conditions for the steam generator. The operational parameters have been designed for reproducing intensive magnitudes (pressure around 120 bar, saturation temperature, etc.) and scaled for extensive magnitudes. The electric heaters may be operated by a feedback control loop on the dome pressure, including software simulation of the neutronic kinetics.

The experimental programme on dynamic tests has defined the stages of pure thermohydraulic dynamics (no feedback on power), the response of the pressure control loop and the startup operating points. The first of these stages has already been completed, showing that self-pressurized natural circulation is very stable around the operating point, including different perturbations and important deviations in the relevant parameters (primary hydraulic resistance, steam dome volume, secondary water conditions, etc.). This stage consisted of 180 transients produced by external perturbation of the steady states. At present, the recorded data are being used to improve modelling, while the rig is being prepared for the next stage of tests.

3.4. Control rod drive mechanisms and RPV internals

The Carem control rod drive mechanisms are of the hydraulic type, and located inside the RPV. The driving water circuit provides a constant flow over which positive or negative pressure pulses are produced, resulting in movement of the device. Development of these mechanisms has passed through preliminary verification, as has construction of a first prototype to determine experimentally the main operating parameters, to optimize the design and manufacturing techniques and to improve reliability. The objectives of these experiments have almost all been achieved. At present, work is being carried out on characterization under reactor conditions for water subcooling and feedline geometry, in what we call the warm rig. A final stage is foreseen on a high pressure loop: durability tests, and the study of systems under abnormal conditions (LOCA, operation of relief valves, etc.).
FIG. 7. Primary containment layout of Carem 25 (measurements in mm).
Special instrumentation has been developed to define the position of the drive mechanism (i.e. the position of the control rod in the core). The method used is called variable magnetic inductance; the hydraulic piston of the drive is made of magnetic stainless steel, while all the other parts are non-magnetic. Accurate measurement of the inductance of an electrical coil around the cylinder provides the position of the device. The resolution obtained was better than 1%.

Several of the design aspects of the RPV internals require experimental verification to determine their behaviour under normal and abnormal conditions, and to
define the manufacturing, assembling and handling procedures, as well as the auxiliary tools. A sector of the core containing the core support, three fuel elements and upper structures with control rod guides has been modelled. The experiments were carried out with and without water at room temperature, and the results are encouraging. At present, a full scale sector of the control rod drive structure (for one control rod) is being constructed; dynamic analysis will determine the natural frequencies, the mode shapes and the response of the system to various external perturbations.

3.5. RA-8 critical facility and benchmarking

The RA-8 has been designed and constructed as an experimental facility to measure the neutronic parameters of the Carem core. There are two possible ways of operating the facility (reactivity regulation): by varying the critical height of the moderator level or by using control rods; and two alternative extinction systems: rapid insertion of the control rods or dumping of the moderator. The facility has two concentric and connected tanks: the inner tank contains the core structure and nuclear instrumentation, while the outer tank provides shielding and reflection. There are hydraulic mechanisms to drive the absorber rods in and out of the core. The control system is able to define some as regulation rods and some as safety rods, and simultaneously controls the water level using safety logic surveillance (checking the rod position).

Facility construction was completed and startup began in April 1997.

The experimental programme takes into account the fact that the core calculations are made with a diffusion code (CITVAP). A central homogeneous zone is needed to study perturbations such as rods loaded with burnable poisons, absorbing rods and guide tubes. Two levels of enrichment (E = 1.8% and E = 3.4%) and non-fuel rods will be used. Studies will be conducted on the influence of various boron concentrations at different temperatures, the critical height and buckling, several disadvantage factors, the fission ratio ($^{235}$U and $^{238}$U), fluxes and spectra in the non-fuel rods and macrocells, etc.

There is an important validation programme for the neutronics calculation line used at INVAR. It includes nuclear data (ESIN library from WIMS, updated with data for Ag, In, Cd and Gd from ENDF/B-4 and Nb from WIMCAL-88, COREA); the cell code CONDOR 1.3, validated mainly with 91 typical PWR cells with a difference of 400/800 pcm$^1$; and the core code CITVAP, validated for plate type fuel elements of

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$^1$ 1 pcm (per cent milli) = $10^{-5} = 0.001\%$ (reactivity).
20% enrichment, with good results. Further validations of the calculation line are under way.

4. CONCLUSIONS

It has been shown that the economic production of potable water using electricity generated in an integral nuclear reactor requires additional design rules to those applied in normal integral PWR designs.

These rules cover lower efficiency designs and lower power density cores when natural convection systems are used for the production of an electric power greater than 150 MW(e). Forced convection designs have several advantages, e.g. lower capital costs, but for an electric power lower than 100 MW(e) the differences are not enough to compensate for the simplicity of the natural convection design.

If other integral reactor designs are compared with the economic criteria presented here, strong disagreement would be found for some designs that may not have been developed with a view to achieving the lowest generation costs necessary to produce economic potable water.

Carem 25 is a well developed project at the detailed engineering level, with several associated experimental facilities. For desalination purposes, the Carem design meets the above mentioned economic criteria.

REFERENCES


COMBINED SYSTEM FOR DESALINATION

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Abstract

COMBINED SYSTEM FOR DESALINATION.

One of the major activities in the Egyptian Atomic Energy Heat Transfer Laboratory is directed towards studying the possibility of adopting nuclear energy as a heat source in the desalination process, while ensuring fulfilment of the operational safety aspects. In this study, a coupling technique between a nuclear power plant and a desalination unit is being examined, with full consideration given to the safety aspects. This can be achieved by using a heat pipe waste heat recovery boiler to utilize the energy from the nuclear plant and direct it to the desalination unit. The heat pipe, which is an individual tube fabricated with a capillary wick structure, is evacuated, filled with operating fluid and permanently sealed. Thermal energy applied to either end of the pipe vaporizes the fluid at that end. The vapour travels to the pipe’s opposite end, where the thermal energy is removed, condensing the vapour into liquid and giving off the latent heat of condensation. The condensate liquid flows back to the hot end to be evaporated, completing the cycle. The closed loop condensing/evaporating heat pipe cycle is characterized as a double separation boundary between the primary heat source and the secondary fluid, which is an ideal double separation boundary if a combined nuclear desalination system is planned. In the process of testing heat pipe performance, consideration is being given to coupling a gas turbine (as an alternative to a nuclear power plant) to a multi-effect–thermal vapour compression (ME–TVC) unit by a heat pipe waste heat recovery boiler. This plant is being implemented in the Egyptian Atomic Energy Authority Laboratory at Hurghada on the Red Sea coast. In the present work, a study is being made of the effectiveness, performance and economics of such a combination. The heat pipe in the waste heat recovery boiler is considered to be more efficient, with easier fault detection, maintenance and replacement than a conventional heat exchanger. Moreover, it forms an additional barrier between the power plant and the desalination unit. Current analyses are based on an Egyptian manufactured 500 kW gas turbine coupled to a 200 m³/d ME–TVC unit. The detailed theoretical results of the exhaust heat capacity, the steam generated from the waste heat recovery boiler, the water product and the water costs are presented.
1. INTRODUCTION

In recent years, research on the desalination process has taken a special interest in those countries of the world in which desalination plants are the main source of potable water.

In Egypt, in spite of the availability of the Nile River, the trend of using desalination processes to supply the water requirements for tourist sites and industrial and agricultural locations is increasing. According to an International Desalination Association report [1], the total installed capacity of desalination plants in Egypt at the end of 1992 was 87,000 m\(^3\)/d; sea water desalination represents 40.5% of this total. Reverse osmosis is the desalination process most used in Egypt, representing 48.1% of the total capacity.

In the present study, the feasibility of coupling a gas turbine (as an alternative to a nuclear power plant) to a multi-effect–thermal vapour compression (ME–TVC) unit using a heat pipe waste heat recovery boiler is discussed.

2. COUPLING OF THE GAS TURBINE AND THE ME–TVC UNIT

The gas turbine electric power plant will provide the electricity and the energy needed for the desalination unit. The gas turbine was chosen because it is now totally manufactured in Egypt, with simple operation and maintenance, low investment costs, rapid delivery, low staff requirements and no cooling water; it also provides high temperature exhaust gases, which are used to generate the thermal energy needed for the desalination unit.

The thermal efficiency of the open cycle gas turbine is usually low because of the large amount of exhaust heat available (compared with the added heat), but the economics of operation could be improved by using the waste heat produced by the exhaust gases for the desalination process.

A TVC unit is better for a desalination unit operated by a waste heat recovery boiler, since it consumes less steam per unit of product (at a higher pressure and temperature) than that consumed by the multi-effect distillation or multi-stage flash process (at a lower steam pressure and temperature) [2].

The exhaust heat passes through a heat pipe waste heat recovery boiler and produces steam, which is used directly as motive steam in the steam jet ejector of the TVC unit. The heat pipe is a very efficient heat exchanger, with a heat transfer coefficient that is double that of an ordinary heat exchanger [3]. Moreover, its working fluid acts as an additional barrier if coupling of a nuclear power plant to a desalination plant is planned. The waste heat recovery boiler inflicts a small pressure...
drop in the exhaust gas duct of the turbine; this has only a slight influence on the efficiency of the gas turbine generator unit.

3. DESCRIPTION OF THE SYSTEM

The proposed system comprises three subsystems: an ME–TVC unit of the horizontal tube evaporator type, a heat pipe waste heat recovery boiler and a gas turbine generator.

The waste heat emitted from the gas turbine is delivered to the waste heat recovery boiler through a duct, where the heat is absorbed by the heat pipe.

The heat pipe is a heat exchanger consisting of numerous individual heat pipe heat exchangers, each of which is a closed pipe containing a working fluid, as shown in Fig. 1. It is divided into two sections: an evaporator section and a condenser section. The heat absorbed in the evaporator section vaporizes the working fluid in that section. The resulting difference in pressure drives the vapour from the evaporator to the condenser section, where it is condensed, releasing the latent heat to water in a drum. Steam is generated in this drum using the heat from the heat pipe; this steam is led to the desalination plant. A schematic representation of the system is shown in Fig. 2.

4. EXHAUST HEAT ENERGY

Current analyses are based on a 500 kW gas turbine unit coupled to an ME–TVC unit with a maximum water capacity of 200 m$^3$/d. At full load, each turbine
emits 2.85 kg/s of exhaust gases at 430°C. This is cooled in the waste heat recovery boiler; 820 kW would be available to supply the boiler with its heat requirement to produce 1.15 t/h of saturated steam. The steam is then fed to the steam jet compressor and operated as motive steam of a higher pressure and temperature.

The motive steam sucks in the vapour produced in the last effect. It expands in the ejector to a pressure slightly lower than that of this effect. The mixture of vapours is then compressed in a diffuser to a pressure that meets the requirement in the top effect. An amount equivalent to the motive steam returns to the boiler loop, while the
rest proceeds down into the ME system. Figures 3 and 4 give the results of preliminary analyses of the heat energy of the exhaust gases and the product water at partial load, respectively.

Figure 5 shows the relationship between the product water and the gas turbine power for a similar system developed by the Sasakura Engineering Company [4].
FIG. 6. Motive steam generated in the waste heat recovery boiler.

FIG. 7. Energy used from the exhaust gases.

The effects of motive steam pressure on the steam generated and the energy used from the exhaust gases are illustrated in Figs 6 and 7, respectively.

5. ECONOMIC STUDIES

In the present study, two methodologies were presented for evaluation of the water costs in a dual purpose plant in which electricity and water are produced [5].
First, following the power credit method, we selected a predetermined value for the electricity costs which was equivalent to that of a single purpose gas turbine plant. Using this value as the cost of energy delivered to the desalination unit, the cost of the product water could be determined. In this method, the product water is credited with all the economic benefits associated with the plant being coupled to the gas turbine.

Second, since the energy source of the desalination unit is obtained from the heat released from the waste exhaust gases, it does not affect the electricity production of the gas turbine. In turn, the thermal energy costs can be omitted in evaluating the water product costs.

The unit costs of the electricity and water produced are arrived at by summing all the expenses (including capital, operation, maintenance and fuelling) and dividing them by the amount of electricity or water produced. The electricity costs are used as input to calculate the energy component of the water costs. The following points should be taken into consideration:

(1) The calculation procedure is based on the present value concept, which takes into account the time value of money;
(2) An economic life of 20 years is used for both the desalination unit and the gas turbine;
(3) The lifetime load factor is assumed to be 85% for the gas turbine and the ME-TVC;
(4) The real interest rate is taken to be 8%;
(5) Operation and maintenance costs include chemicals, labour, management and materials;
(6) Water plant construction costs include the waste heat recovery boiler.

Tables I and II summarize the preliminary cost estimates for the gas turbine and the desalination unit, respectively.

**TABLE I. GAS TURBINE COSTS**

<table>
<thead>
<tr>
<th>Cost Category</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas turbine power (kW(e))</td>
<td>500</td>
</tr>
<tr>
<td>Total specific unit costs (US $/kW(e))</td>
<td>440</td>
</tr>
<tr>
<td>Total investment costs (US $)</td>
<td>352,000</td>
</tr>
<tr>
<td>Annual levelized capital costs (US $)</td>
<td>31,000</td>
</tr>
<tr>
<td>Specific fuel costs (US $/kW-h)</td>
<td>0.048</td>
</tr>
<tr>
<td>Specific operation and maintenance costs (US $/kW-h)</td>
<td>0.006</td>
</tr>
<tr>
<td>Electricity costs (US $/kW-h)</td>
<td>0.062</td>
</tr>
</tbody>
</table>
TABLE II. DESALINATION UNIT COSTS

<table>
<thead>
<tr>
<th>Water plant capacity (m$^3$/d)</th>
<th>200</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plant specific unit costs (US $/m$^3$.d$^{-1}$)</td>
<td>1700</td>
</tr>
<tr>
<td>Total investment costs (US $)</td>
<td>414 00</td>
</tr>
<tr>
<td>Annual levelized capital costs (US $/m^3$)</td>
<td>0.454</td>
</tr>
<tr>
<td>Energy consumption (kW(e)-h/m$^3$)</td>
<td>8</td>
</tr>
<tr>
<td>Energy consumption (kW(e)-h/m$^3$)</td>
<td>2</td>
</tr>
<tr>
<td>Specific energy costs (US $/m^3$)</td>
<td>0.552</td>
</tr>
<tr>
<td>Specific energy costs (US $/m^3$)</td>
<td>0.138</td>
</tr>
<tr>
<td>Specific operation and maintenance costs (US $/m^3$)</td>
<td>0.205</td>
</tr>
<tr>
<td>Water costs (US $/m^3$)</td>
<td>0.797</td>
</tr>
<tr>
<td>Water costs (US $/m^3$)</td>
<td>1.211</td>
</tr>
</tbody>
</table>

a Energy consumption based on electric energy only.

6. CONCLUSIONS

If a nuclear power plant is coupled to a desalination unit it is essential that the possibility of radioactive material penetrating the desalination unit be eliminated. This is achieved through an additional isolation loop [6]. Coupling of a PWR to a desalination unit using an intermediate loop provides two barriers between the reactor coolant in the nuclear unit and the saline water of the desalination unit. The first barrier is the steam generator fluid of the secondary cycle and the second is the intermediate loop fluid. If the intermediate loop contains a heat pipe as a heat exchanger, then the heat pipe working fluid is considered to be the third barrier between the nuclear plant and the desalination unit.

REFERENCES


FLOATING NUCLEAR POWER–DESALINATION COMPLEX USING A NUCLEAR POWER PLANT OF THE KLT-40 TYPE AND THE REVERSE OSMOSIS PROCESS

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Abstract

FLOATING NUCLEAR POWER–DESALINATION COMPLEX USING A NUCLEAR POWER PLANT OF THE KLT-40 TYPE AND THE REVERSE OSMOSIS PROCESS.

Recently, the Russian Federation prepared proposals on the options for a single purpose floating nuclear power plant to supply external consumers with electricity or potable water, and for a dual purpose station for the co-generation of various amounts of electricity and potable water. A nuclear power plant of the KLT-40 type, which meets international safety requirements, is proposed as the power source for the floating nuclear power plant. Analogous plants have been successfully operated for many years in nuclear powered ships, one of which, the lighter carrier Sevmorput, operates on international lines calling at foreign ports. The main advantages of the nuclear power–desalination complex are as follows: (1) the established fabrication technology, and the confirmed long term reliability and service life of KLT-40 type nuclear power plants and desalination facilities; (2) the high quality of fabrication at the shipbuilding plant, and the possibility of handover of the complex to the customer on a turnkey basis within the shortest possible time; (3) the possibility of siting in various coastal regions of the world; and (4) ease of maintenance by a special service ship at the mooring place, and simple decommissioning by towing to the supplier country. The floating nuclear power–desalination station for producing potable water is a special non-self-propelled ship equipped with a twin unit nuclear power plant of the KLT-40 type intended for sea water desalination in a protected water area, together with service facilities at the plant mooring place. Distillation–desalination plants with film type, horizontal tube evaporators are used in the floating station for thermal desalination. The floating nuclear power station (FNPS) is a special non-self-propelled ship intended for power generation in a protected water area. The station includes two nuclear steam supply systems of the KLT-40 type, a steam turbine plant, a power plant, and servicing and shipboard systems. The floating nuclear dual purpose station for
co-generating electricity and potable water using the reverse osmosis (RO) process includes two floating structures: the FNPS and a ship for producing potable water from sea water using RO. The organizational structure for the development and operation of the floating nuclear power–desalination complex has been studied.

1. FLOATING NUCLEAR POWER–DESALINATION STATION FOR PRODUCING POTABLE WATER

1.1. Main technical and economic characteristics of the station

The floating station (Fig. 1) is a special non-self-propelled ship equipped with a twin unit nuclear power plant of the KLT-40 type and intended for sea water desalination in a protected water area, together with service facilities at the plant mooring place [1]. The main characteristics of the station are given in Table I.

Under normal operating conditions, the plant operates in the base mode, producing a rated quantity of desalinated water for consumers (80 000 m³/d). In this mode, two reactors are in operation, each of which delivers steam to the main turbogenerator. The latter generates electricity and permits heat transfer through intermediate circuits to two units of the distillation–desalination plant producing desalinated water, which is then conditioned to the required quality in the potable water
TABLE I. TECHNICAL AND ECONOMIC CHARACTERISTICS OF THE FLOATING NUCLEAR POWER–DESALINATION STATION

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Length of vessel</td>
<td>160 m</td>
</tr>
<tr>
<td>Width of vessel (maximum)</td>
<td>44 m</td>
</tr>
<tr>
<td>Draught</td>
<td>7 m</td>
</tr>
<tr>
<td>Drinkable water output</td>
<td>80 000 m³/d</td>
</tr>
<tr>
<td>Service life</td>
<td>Up to 40 years</td>
</tr>
<tr>
<td>No. of reactors</td>
<td>2</td>
</tr>
<tr>
<td>No. of desalination facilities</td>
<td>4</td>
</tr>
<tr>
<td>Refuelling interval</td>
<td>2–3 years</td>
</tr>
<tr>
<td>Average load factor</td>
<td>Up to 0.85</td>
</tr>
<tr>
<td>No. of staff</td>
<td>60</td>
</tr>
<tr>
<td>Term of pilot station development</td>
<td>About 5 years</td>
</tr>
<tr>
<td>Cost of pilot station development</td>
<td>About US $300 × 10⁶</td>
</tr>
<tr>
<td>Average operational costs per year</td>
<td>US $50–60 × 10⁶</td>
</tr>
<tr>
<td>Cost of 1 m³ of water</td>
<td>Not more than US $2.5</td>
</tr>
<tr>
<td>Recoupment period</td>
<td>6–8 years</td>
</tr>
</tbody>
</table>

preparation facility. Each reactor operates at a power level of approximately 80 MW(th).

The design provisions completely exclude the influence of the operating nuclear power plant on the desalinated sea water because of the absence of discharges to the environment; the existence of protective barriers that prevent the release of radioactivity excludes the possibility of its propagation beyond station boundaries [2]. Sea water activation in a nuclear steam supply system (NSSS) location is absent because of effective biological shielding.

Correct selection of the structural materials and the desalinated water production technology excludes the release of Cu and Fe ions into the sea and any adverse effects on sea fauna, and makes desalination plant operation environmentally clean. The relatively small amount of heat released during operation does not have a significant influence on the environment in the regions located near to the plant.

The external support facilities include a hydrotechnical complex (protection dam, water intake unit, and overpasses for electricity and water transmission) and
coastal structures (water storage tanks, pumping plant, transformer substation, etc.). The costs for constructing these external facilities depend on the place of deployment, but they do not exceed about US $50 million. Construction time is the same as that of the floating plant.

### 1.2. Nuclear power plant

The nuclear power plant is the main power source in the ship, and includes the NSSS with the related support and safety systems (Fig. 2). The design solutions are based on the experience gained in the design and long term successful operation of nuclear icebreakers with a similar NSSS of the KLT-40 type. The technical characteristics of the KLT-40 nuclear power plant are given in Table II.

The main equipment of the nuclear power plant is serially fabricated, and its reliability has been confirmed by analogous operation for more than 100 000 hours. At the same time, international experience and the trend towards the enhancement of nuclear power plant safety were taken into account. The safety of the NSSS meets all national and international standards for nuclear power plants on ships, which removes any limitations to their being located in the vicinity of settlements.

Plant safety is based on inherent self-protection features and defence in depth barriers. All the radiation sources are surrounded by biological shielding, which guarantees the safety of both the personnel and the population, and eliminates the impact on the environment. The KLT-40 NSSS is included in an IAEA document [3]. In a competition on low powered nuclear power plant designs, carried out by the Russian Nuclear Society in 1995, the KLT-40 NSSS won first place among nuclear power plants of the same unit power.

### 1.3. Distillation–desalination plant

Distillation–desalination plants with film type, horizontal tube evaporators are used in the floating station for thermal desalination; these were designed by a leading Russian institution, SverdNIIkhimmash. Their most distinctive feature is the implementation of head free tube bundles, which were designed and developed in co-operation with the Nuclear Research Centre in Grenoble (France) [4]. Analogous desalination plants have been successfully operated for a long time at industrial complexes in Aktau (Kazakhstan), Novochercassk and Urengoy (Russian Federation), and elsewhere. The manufacturers of equipment for desalination facilities are enterprises of the chemical and power machine building industries: Uralkhimmash (Ekaterinburg), Atommash (Rostov region), etc.

The purpose of the desalination plant is to produce potable water from sea water. It is characterized by high economic efficiency, an effective desalination process, a high quality and stable distillate, a low energy consumption, a low metal
FIG. 2. KLT-40 nuclear power plant (1 = reactor; 2 = reactor coolant pump; 3 = protective shell; 4 = gas cylinder; 5 = steam generator; and 6 = steam–water shielding tank).
TABLE II. TECHNICAL CHARACTERISTICS OF THE KLT-40 NUCLEAR POWER PLANT

<table>
<thead>
<tr>
<th>Plant type</th>
<th>Block type PWR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal power</td>
<td>Up to 160 MW(th)</td>
</tr>
<tr>
<td>Steam generating capacity</td>
<td>Up to 72 kg/s (260 t/h)</td>
</tr>
<tr>
<td>Steam temperature</td>
<td>Up to 300°C</td>
</tr>
<tr>
<td>Steam pressure</td>
<td>Up to 4 MPa</td>
</tr>
<tr>
<td>Power variation range</td>
<td>10–100% nominal</td>
</tr>
</tbody>
</table>

content, a small occupation area, and simple control, maintenance and repair during operation.

Desalinated water is produced from sea water at the floating complex in four desalination plants, each with a capacity of 20 000 m³/d. The plants are equipped with 20 film type, horizontal tube evaporators. For the heat transfer surfaces, the external surface of the tubes has a special longitudinal shape that enhances functional efficiency.

Sea water is desalinated by heat (hot water) supplied through the intermediate circuit from the NSSS (Fig. 3); 35 MW of thermal energy is necessary to generate 20 000 m³/d.

2. FLOATING NUCLEAR POWER STATION (FNPS)

The FNPS is a special non-self-propelled ship (Fig. 4) intended for power generation in a protected water area. The station includes two NSSSs of the KLT-40 type, a steam turbine plant, a power plant, and servicing and shipboard systems. The main characteristics of the FNPS are given in Table III.

Under normal operating conditions, the power station operates in the base mode, providing electricity to consumers via transmission lines within the limits of its operating power range. There are two nuclear power plants, each operating for a respective steam turbine plant, with turbogenerators that provide 6.3 and 10 kV of current, respectively. The high manoeuvrability of the KLT-40 type NSSS allows the load demand to be constantly followed, thus providing economic, effective operation of the power station.

On the basis of 30 years of experience in nuclear icebreakers, construction and operation of a series of nuclear heat and power plants are being carried out. These incorporate floating power units with a KLT-40 type NSSS, intended for deployment in the far north of the Russian Federation and in similar remote regions.
FIG. 3. Flow diagram of the desalination plant (1 = coolant; 2 = steam generator; 3 = pre-heater; 4 = evaporation stage; 5 = de-aerator; 6 = water jet ejector; 7 = sea water; 8 = distillate to the consumer; 9 = distillate cooler; 10 = filter; 11 = sea water; 12 = sea water concentrate tank; 13 = distillate tank; 14 = sea water with increased salt concentration; 15 = chlorination; 16 = anti-scale additive inlet; 17 = sodium sulphite inlet; and 18 = gas jet ejector).
FIG. 4. Longitudinal view of the FNPS (1 = boiler division; 2 = refuelling compartment; 3 = machine division; 4 = helicopter landing site; 5 = nuclear power plant; 6 = refuelling equipment storage; and 7 = auxiliary equipment room).
TABLE III. TECHNICAL AND ECONOMIC CHARACTERISTICS OF THE FLOATING NUCLEAR POWER STATION

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length of vessel</td>
<td>140 m</td>
</tr>
<tr>
<td>Width of vessel</td>
<td>30 m</td>
</tr>
<tr>
<td>Draught</td>
<td>3.5–4.5 m</td>
</tr>
<tr>
<td>Electric power (brutto)</td>
<td>About 70 MW(e)</td>
</tr>
<tr>
<td>Voltage</td>
<td>6.3; 10 kV</td>
</tr>
<tr>
<td>Auxiliary power</td>
<td>About 5 MW(e)</td>
</tr>
<tr>
<td>Total service life</td>
<td>40 years</td>
</tr>
<tr>
<td>No. of nuclear reactors</td>
<td>2</td>
</tr>
<tr>
<td>Thermal power</td>
<td>About 150 MW(th)</td>
</tr>
<tr>
<td>No. of main turbogenerators</td>
<td>2</td>
</tr>
<tr>
<td>Average load factor</td>
<td>Up to 0.85</td>
</tr>
<tr>
<td>Refuelling interval</td>
<td>2–3 years</td>
</tr>
<tr>
<td>No. of staff</td>
<td>55</td>
</tr>
<tr>
<td>Term of pilot station development</td>
<td>About 5 years</td>
</tr>
<tr>
<td>Cost of pilot station reactor</td>
<td>About US $250 \times 10^6</td>
</tr>
<tr>
<td>Average operation costs per year</td>
<td>US $35–40 \times 10^6</td>
</tr>
<tr>
<td>Cost of 1 kW-h of energy</td>
<td>Not more than US $0.08</td>
</tr>
<tr>
<td>Recoupment period</td>
<td>6–8 years</td>
</tr>
</tbody>
</table>

The leading plant of this type, with a 60 MW(e) rated output and a 50 Gcal/h heat output, is likely to be located at places such as Port Peveck in the Chukot national district, Norilsk town (Taimir Peninsula), or in the Murmansk region.

3. FLOATING NUCLEAR DUAL PURPOSE STATION FOR THE CO-GENERATION OF ELECTRICITY AND POTABLE WATER USING THE REVERSE OSMOSIS (RO) PROCESS

3.1. Floating nuclear power–desalination station

The dual purpose desalination station includes two floating structures: the FNPS and a ship for producing potable water from sea water using the RO process.
(Fig. 5). The electric energy generated by the FNPS is partially transmitted to the ship that produces potable water, while the remainder is supplied to coastal consumers.

This ship is a non-self-propelled structure which houses the systems and equipment that provide sea water, carry out pretreatment and desalination, and supply potable water to users. The possible options of an electric power to potable water output relationship are given in Fig. 6.

The unique CANDESAL approach has been utilized to develop the integrated floating co-generation station based on the KLT-40 reactor and Canadian RO water purification technology [5]. Integrating the reactor and the RO process into a single co-generation facility gives a design in which all the benefits of design optimization and system integration, including RO feedwater preheating, can be fully realized. These benefits include lower capital costs and longer RO membrane lifetimes, resulting in reduced membrane replacement, minimum operation and maintenance costs, improved energy efficiency and reduced water production costs. This 'marriage' of technologies from Canada and the Russian Federation leads to improved economics in small scale nuclear desalination systems. Such systems then become more attractive in developing areas, where the requirements for fresh water production are of the order of 100 000 m³/d or less, and where the need for additional electrical generation exists but where the existing electric grids cannot absorb the supply from larger nuclear generating stations.

Figure 5 shows a typical installation of the KLT-40 reactor being operated as a base load generator and providing electricity to the grid, with the condenser cooling water discharge serving as the preheated feedwater supply to the RO process. This schema is then integrated into the simplified schematic flow diagram of the RO desalination system shown in Fig. 7.

The period required for the development of a leading complex is about 5 years, with capital costs of about US $300 million. If the complex generates only electric energy, its technical and economic performance indicators would be the same as those of the FNPS. If the complex operates only in the desalination mode, the cost of 1 m³ of water produced will be about US $1–1.5. If the complex co-produces water and electric energy, the cost of 1 m³ of water may be lower because of the revenue accrued from the sale of electricity.

3.2. Desalination plant using the RO process

The production of potable water by RO is a method that removes the salt from sea water using semi-permeable membranes operating at about 7 MPa. It is proposed that spiral wound membrane elements be used, manufactured by the Dow FilmTec Company, which are capable of reducing the salt content from 39–43 g/L in the sea water to 500 mg/L at the desalination plant outlet.
FIG. 5. Flow diagram of the complex (1 = reactor; 2 = primary circuit circulation pump; 3 = steam generator; 4 = turbogenerator; 5 = sea water; 6 = condenser; 7 = secondary circuit electric pump; 8 = twin layer pressure filter; 9 = booster pump; 10 = gravity filter; 11 = filtrate intake tank; 12 = potable water storage tank; 13 = potable water preparation facility; 14 = electric pump of the potable water preparation facility; 15 = filtrate; 16 = clarified water tank; 17 = high pressure pump; 18 = fresh water pump; 19 = RO module; and 20 = hydroturbine).

FIG. 6. Electric power versus potable water output at the given thermal power (1, 2 and 3 = specific consumption of power per 1 m³ of desalinated water = 5, 7 and 10 kW-h, respectively).
Development of the joint Russian–Canadian project for a desalination facility using FNPS on the basis of new technologies of sea water desalination by RO seems to be expedient. At a specific power consumption of about 5 kW-h/m³, the output of such a facility could be approximately 300 000 m³/d.

At present, co-ordinated scheduling and development activities are being carried out jointly by the Ministry of the Russian Federation for Atomic Energy and CANDESAL Inc. for the conceptual design of a floating desalination station with a nuclear reactor plant of the KLT-40 type and desalination stations on the basis of RO. Each side has undertaken initiatives to solve the respective financial issues.

4. PROPOSALS ON THE ORGANIZATION OF ACTIVITIES AND CO-OPERATION

The organizational structure of the floating nuclear power–desalination complex development and operation includes:

(1) Development of the complex in compliance with customer requirements, and its construction and handover on a turnkey basis;
(2) Investigation into complex siting, and development of external support facilities at the mooring place;
(3) Complex transportation to the mooring place, and its operation and maintenance;
(4) Complex removal from operation (decommissioning) after expiration of its service life.

Activities on the development of a demonstration (leading) floating complex could be started immediately after contract conclusion. The established technology of nuclear plant serial fabrication, the experience gained in installation and operation, the manufacturing capabilities and the existing co-operation of available scientific, design and industrial enterprises are the real guarantees of high quality and of the shortest time possible for complex development. This time is not longer than 4–5 years, starting with contract signing for the leading plant. Serial plants could be supplied, their periodicity depending on customer needs.

The following main options of co-operation in developing a floating nuclear power–desalination complex are possible:

(a) Development of the floating complex on a contractual basis by the Russian Federation, with the potential participation of foreign partners. The work would be financed by credits granted by potential customers (users), with compensation in the form of profits accruing from the sale of products (water, electric energy). In the event of such co-operation, the complex would be the property of the Russian Federation.

(b) Organization of a joint international venture, including potential executors and customers (consumers), with shared financing of the work and the return on invested capital being in proportion to the investment made during the recoupment period. In the event of such co-operation, the floating complex would be the property of the joint enterprise participants, while the Russian Federation would be the designer, supplier and owner of the reactor plant.

The estimated investment for the construction and operation of the floating complex over a 5 year period (in per cent of the total development costs) is evaluated as follows: first year = 5–10%; second year = 20–25%; third year = 35–40%; fourth year = 25–30%; and fifth year = 10–15%.

An organizational scheme for financing the development of external support facilities is to be defined in a separate contract, and will depend on the extent of Russian Federation involvement in the work.

REFERENCES


ANALYSIS OF THE NHR-200 NUCLEAR SEA WATER DESALINATION PLANT AND ITS INTERFACE DESIGN

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Abstract

ANALYSIS OF THE NHR-200 NUCLEAR SEA WATER DESALINATION PLANT AND ITS INTERFACE DESIGN.

Safety is important to nuclear sea water desalination, and concerns the safety of the reactor itself and the prevention of potable water contamination. The NHR-200 has an integrated arrangement with natural circulation. It is an LWR of the vessel type with self-pressurized performance. Safety is achieved by its inherent and passive safety features, including a reactor core that is always covered by coolant under any LOCA conditions, a large negative reactivity feedback, a fairly large departure from nucleate boiling ratio, perfect containment systems, etc. For these reasons, the site of the NHR-200 can be located near to a populated area. The NHR-200 nuclear desalination plant is an integrated plant. Coupling between the NHR-200 and the multi-effect distillation plant is designed to prevent potable water from being contaminated through multi-isolation barriers. The composition of the water production costs and the results of sensitivity analysis show that if the water production costs are to be reduced greatly, investment in the water plant will have to be lower. A high load factor is also an important factor if these costs are to be reduced.

1. INTRODUCTION

Sea water desalination is one way of solving the problem of potable water shortages, which have become increasingly more urgent as the economy has developed and with the increase in population.

From the point of view of safety, technology, economy and environmental protection, it is feasible to use nuclear energy for sea water desalination. An issue of importance to nuclear desalination is the safety of the reactor itself, and the prevention of potable water contamination.

A nuclear heating reactor (NHR) has to be located near to a populated area because of the heat transmission (hot water or low pressure steam) required. Distance
from the reactor is no longer required because the public is protected by the safety features built into the reactor. This has been achieved by adopting more inherent and passive safety features. Therefore, when NHR development began, the designers paid most attention to the safety of the NHR and to the prevention of heating grid contamination.

The key technologies have been proved by the operation of NHR-200 and the experiments carried out in the NHR-5 [1]. These technical measures also meet the requirements of the NHR-200 nuclear sea water desalination plant.

2. NHR-200

2.1. Design features [2, 3]

The NHR-200 was developed on the basis of the experience gained from the design, construction and operation of the NHR-5. It was designed with a number of advanced and innovative features to achieve safety and economic viability.

The NHR-200 is an LWR of the vessel type with an integrated arrangement, natural circulation, self-pressurized performance and a dual vessel structure.

The reactor core is located at the bottom of the reactor pressure vessel (RPV). Six primary heat exchangers (PHEs) are arranged in the annular space between the riser and the vessel wall. Above the core outlet there is a riser (5.1 m high) to enhance natural circulation. Figure 1 shows the reactor structure.

Primary system pressure is maintained by the partial pressures of nitrogen and saturated steam, which correspond to the core outlet temperature. The RPV is surrounded by a tight containment.

Gadolinium oxide (as burnable poison) is used to control the reactivity along the B₄C control rods. The reactor coolant does not contain boric acid during normal operation.

The hydraulic control rod drive system used in the NHR-200 has a fail-safe design feature, i.e. control rods that drop down into the core under gravity in the event of loss of power supply, depressurization, and pipe or pump failure.

A boric acid injection system, as a secondary reactor shutdown system, will operate under gravity if anticipated transient without scram (ATWS) occurs.

The nuclear steam supply system (NSSS) contains triple loops. An intermediate loop has been adopted to separate the primary circuit and the steam circuit. Steam is delivered to the multi-effect distillation (MED) plant or to the turbine.

Two independent residual heat removal systems (RHRSs) have been installed in the NHR-200, each with a capacity of 1.5% rated power. The ultimate heat sink is natural circulation. There is no emergency core cooling system or emergency makeup water system. The main design data for the primary circuit are listed in Table I.
FIG. 1. Structure of the NHR-200 (1 = reactor core; 2 = control rod; 3 = spent fuel storage; 4 = primary heat exchangers; 5 = reactor pressure vessel; 6 = tight containment; and 7 = pipes for secondary loop).
TABLE I. MAIN DESIGN DATA OF THE NHR-200

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal power</td>
<td>200 MW(th)</td>
</tr>
<tr>
<td>Primary system pressure</td>
<td>2.5 MPa</td>
</tr>
<tr>
<td>Core inlet/outlet temperature</td>
<td>154/213°C</td>
</tr>
<tr>
<td>Average linear heat rate</td>
<td>7.67 kW/m</td>
</tr>
<tr>
<td>Volumetric power density</td>
<td>36.2 kW/L</td>
</tr>
<tr>
<td>No. of fuel assemblies</td>
<td>96</td>
</tr>
<tr>
<td>No. of control rods</td>
<td>32</td>
</tr>
<tr>
<td>Active core height</td>
<td>1.9 m</td>
</tr>
<tr>
<td>Active core diameter</td>
<td>1.9 m</td>
</tr>
<tr>
<td>Initial inventory of UO₂</td>
<td>14.87 t</td>
</tr>
<tr>
<td>Enrichment of initial core</td>
<td>1.8/2.4/3%</td>
</tr>
<tr>
<td>Refuelling enrichment</td>
<td>3%</td>
</tr>
<tr>
<td>RPV diameter/height</td>
<td>5/13.6 m</td>
</tr>
<tr>
<td>No. of PHEs</td>
<td>6</td>
</tr>
</tbody>
</table>

2.2. Safety features

2.2.1. Reactor core

One of the fundamental design criteria for the NHR-200 is that the reactor core is always covered by coolant under any LOCA conditions. For this purpose, the following provisions have been incorporated:

1. The NHR-200 is of an integrated design with self-pressurized performance and natural circulation under full power in the primary system. There are no separate pressurizers, primary pumps or large bore pipes extending from the RPV, therefore large LOCA is excluded.

2. All the small bore vessel penetrations are located on the upper parts of the RPV, so that loss of primary coolant is limited and the core is covered by coolant for all LOCA events.

3. A metal tight containment surrounds the RPV, and the core continues to be covered by coolant even if small breaks occur at the bottom of the RPV.
In addition, the large subcooled water inventory (~1 m³/MW(th)) will also lead to less serious LOCA consequences. Because the core is always covered by coolant under any LOCA conditions, an emergency makeup water system such as that found in current PWRs is excluded. The results of LOCA analysis for the NHR-200 are listed in Table II [3].

**TABLE II. RESULTS OF LOCA ANALYSIS FOR THE NHR-200 [3]**

<table>
<thead>
<tr>
<th>Events(^a)</th>
<th>Duration (s)</th>
<th>Ultimate pressure in the RPV (MPa)</th>
<th>Amount of water lost (t)</th>
<th>Amount of water remaining above the core (t)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>~1 000</td>
<td>~1.65</td>
<td>~14</td>
<td>124</td>
</tr>
<tr>
<td>2</td>
<td>~72 000</td>
<td>0.12</td>
<td>25.7</td>
<td>112.3</td>
</tr>
<tr>
<td>3</td>
<td>~11 000</td>
<td>~0.6</td>
<td>~10.1</td>
<td>128</td>
</tr>
<tr>
<td>4</td>
<td>~10 000</td>
<td>~0.9</td>
<td>18.2</td>
<td>~120</td>
</tr>
<tr>
<td>5</td>
<td>~3 000</td>
<td>~2.37</td>
<td>6.8</td>
<td>131.2</td>
</tr>
</tbody>
</table>

\(^a\) Event 1 = D50 pipe break inside the tight containment; event 2 = D50 pipe break outside the tight containment, followed by isolation failure; event 3 = safety valve stuck in an open position; event 4 = small break at the bottom of the RPV; and event 5 = ATWS initiated by loss of off-site power, followed by a safety valve stuck in an open position.

2.2.2. *Natural circulation*

The NHR-200 is designed to be cooled by natural circulation under full power. Rapid loss of flow in the core cannot occur under any conditions. In addition, the NHR-200 has a low power density and a large negative reactivity feedback, as well as a fairly large departure from nucleate boiling ratio (DNBR) under accident conditions, therefore the integrity of the fuel cladding can be maintained at any transient accident. For example, in the event of ATWS initiated by loss of off-site power, the DNBR still maintains a high value of 1.99. For these reasons, and because the core is always covered by coolant, there is no need for an emergency core cooling system.

2.2.3. *Passive safety system*

A passive safety system has been adopted which ensures that the core decay heat is removed to the ultimate heat sink by natural circulation.
The hydraulic control rod drive system meets the fail-safe principle and eliminates the possibility of ejection of the control rods. This has been demonstrated in a special experiment in which the control rods were dropped down into the core under gravity.

The boron acid injection system also has a passive design feature, i.e. boron acid is injected under gravity.

2.2.4. Containment systems

Multi-barriers, including fuel cladding, a reactor coolant pressure boundary, and tight and secondary containments have been built into the NHR-200 to prevent the release of radioactive substances.

The RPV, as the boundary of the primary coolant pressure system, is designed to lower the operating pressure and temperature to values that are below those of a PWR under normal operation, so there are no large or rapid changes in the pressure and temperature during any accidents because of high thermal inertia. In addition, because of very low fast neutron exposure, the wall of the RPV shows negligible embrittlement, which means that the integrity of the coolant pressure boundary is properly maintained, and that the fission products and radioactive materials are confined within the first two barriers.

The tight containment is designed for a pressure of 1.7 MPa and a temperature of 200°C. The secondary containment, with a volumetric leakage of 5% per day, can withstand a pressure 0.13 MPa and a temperature of 70°C. Because of the existence of these two containments, the release of radioactive substances is very low.

2.2.5. Prevention of potable water contamination

The intermediate circuit in the NHR-200 is designed to prevent contamination of the heating grid. This technical measure is also necessary for the application of nuclear sea water desalination.

The pressure in the intermediate circuit is higher than that in the primary circuit. Therefore, if tube failures occur in the PHEs, the leakage direction is towards the primary circuit. In fact, there are three physical isolation barriers between the NHR-200 and the MED plant: the PHEs, the steam generator and the evaporator of the first effect. The probability of simultaneous leakage in all three separate facilities, followed by failure of the isolation action, is very low, therefore assurance is given that the product water is not contaminated.
2.2.6. Site [4, 5]

The NHR-200 has to be located near to the user. The distance factor for protecting the population from overexposure no longer exists because the public is protected by the inherent and passive safety features built into the NHR-200 itself. The core damage frequency for the NHR-200 is much less than $10^{-7}$ per reactor-year, which is negligible. In this way, core melt is no longer considered to be a design basis accident. For the NHR-200, the dose limitation for the maximum design basic accident is 5 mSv without any emergency action. Therefore, under such safety conditions the water plant can be located on the same site as the reactor.

3. NUCLEAR SEA WATER DESALINATION PLANT [6, 7]

The benefits of integrating the NHR-200 and the MED plant include the sharing of common facilities, service systems, site infrastructure, maintenance facilities, joint plant staffing, and a short transportation distance for the potable water, all of which favour a reduction in the water production costs. There are two interface designs: one for water production only, and the other for co-generation of water and electricity.

3.1. Coupling scheme options

To attain the optimum technical, economic and safety objectives, an analysis was performed for the NHR-200 nuclear sea water desalination plant using different coupling schemes. In two interface designs, various coupling schemes were considered as candidates for comparison. Of these, a steam generator/MED plant for water production only, and a steam generator/turbine/MED plant for co-generation of water and electricity were selected; the former was given priority. The main parameters for the two optimum coupling schemes are given in Table III.

3.2. Analysis of water production costs and sensitivity

An estimate of the water production costs and their sensitivity factors was made for the NHR-200 nuclear desalination plant [7, 8]. The composition of the water production costs shows that the annual fixed capital charges and the heat charges for the plant are the main constituents of the water production costs.

Table IV lists the main factors that influence the water production costs, derived from the sensitivity analysis results, which show that in the event of a low interest rate and low investment costs, as well as a high load factor, the water production costs will be considerably lower. A reduction in investment costs for the water plant will
TABLE III. MAIN PARAMETERS FOR THE TWO COUPLING SCHEMES

<table>
<thead>
<tr>
<th>Design parameters</th>
<th>Water production only</th>
<th>Co-generation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactor power (MW(th))</td>
<td>200</td>
<td>200</td>
</tr>
<tr>
<td>Core outlet/inlet temperature (°C)</td>
<td>213/154</td>
<td>213/154</td>
</tr>
<tr>
<td>Outlet/inlet temperature of intermediate circuit (°C)</td>
<td>163/135</td>
<td>163/135</td>
</tr>
<tr>
<td>Outlet steam temperature (°C)</td>
<td>130</td>
<td>145</td>
</tr>
<tr>
<td>Maximum temperature of brine water (°C)</td>
<td>120</td>
<td>102</td>
</tr>
<tr>
<td>Unit capacity of the MED process (m³/d)</td>
<td>48 000</td>
<td>48 000</td>
</tr>
<tr>
<td>No. of units</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>No. of effects</td>
<td>30</td>
<td>23</td>
</tr>
<tr>
<td>Gained output ratio</td>
<td>20.76</td>
<td>17.89</td>
</tr>
<tr>
<td>Electric power (MW(e))</td>
<td>—</td>
<td>~14</td>
</tr>
<tr>
<td>Maximum product water (m³/d)</td>
<td>156 000</td>
<td>127 000</td>
</tr>
</tbody>
</table>

TABLE IV. MAIN FACTORS THAT INFLUENCE THE WATER PRODUCTION COSTS

<table>
<thead>
<tr>
<th>Factors</th>
<th>Changes in the water production costs (%)(^a)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interest rate</td>
<td>0.63</td>
</tr>
<tr>
<td>Load factor of the NHR-200</td>
<td>-0.71</td>
</tr>
<tr>
<td>Load factor of the MED plant</td>
<td>-0.89</td>
</tr>
<tr>
<td>Investment costs of the NHR-200</td>
<td>0.20</td>
</tr>
<tr>
<td>Investment costs of the MED plant</td>
<td>0.46</td>
</tr>
<tr>
<td>Amount of product water</td>
<td>-0.39</td>
</tr>
</tbody>
</table>

\(^a\) The percentage change in the water production costs is calculated for conditions that assume an increase of 1% in the sensitivity factor, the other conditions remaining constant.

enhance the economics of high temperature MED. In this case, the cost of potable water would also be low, but this depends on innovations to the MED process.

Clearly, the water production costs of the NHR-200 are higher than those of the RO process with low electricity costs, or of the low temperature MED process coupled to a large scale nuclear power plant. On the other hand, the difficulties (funding, site selection and infrastructure) faced by a small NHR are not as serious as those of a large nuclear power plant, especially in developing countries.
4. SUMMARY

Safety is one of the most important issues for a nuclear sea water desalination plant. The NHR-200 was designed as a new generation nuclear reactor with inherent and passive safety features, which have been demonstrated by NHR-5 operation. These isolation measures are sufficient to prevent potable water contamination. The joint site for the NHR-200 and the MED plant can be located near to the consumer, which will result in a reduction in the water production costs because of the sharing of some facilities, and also a reduction in the water transportation distance.

Even though shortages of potable water prevail worldwide, the demand for such water in local areas depends on the size of the population. The scale of the NHR-200 nuclear desalination plant is suitable for regions where the demand for potable water ranges between 10 000 and 100 000 m³/d.

The water production costs are slightly higher than those of the RO and MED processes coupled to a large nuclear power plant. For the NHR-200 nuclear desalination plant, the approach taken towards reducing water production costs is mainly to reduce the investment costs of the water plant.

REFERENCES

NUCLEAR DESALINATION FOR THE PETROCHEMICAL COMPLEX OF THE NATUNA PROJECT

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Abstract

NUCLEAR DESALINATION FOR THE PETROCHEMICAL COMPLEX OF THE NATUNA PROJECT.

At present, Natuna is the largest gas field in the world, with the highest CO₂ content. Of the total reserves (210 × 10¹² standard ft³ (SCF)), more than 70% are CO₂. The Pertamina–National Oil and Gas Company, in co-operation with the Ministry of Research and Technology, will develop the Natuna project for 8 years, with plans to start in 1997. The facilities of the first train, with a production capacity of 0.4 × 10⁹ SCF/d of saleable gas (methane), are planned to be completed by the year 2004. Since Natuna has a very high CO₂ content, special treatment is required to protect the environment from the released CO₂. The proposed processes are CO₂ re-injection to the aquifer, and CO₂ conversion to useful products such as methanol, methane and syngas. Using the current re-injection process would more than double the investment and operation costs without producing any significant additional by-products. It would also have an impact on the production costs of liquefied natural gas (LNG), which is the main export commodity of Indonesia for continuing development in all sectors. However, adopting a more reasonable, integrated CO₂ conversion technology would provide some advantages, e.g. the higher investment costs would be compensated by additional by-products such as methanol, syngas or methane, which would provide some LNG cost sharing as the main product of Natuna. On the basis of environmental considerations, a high
temperature gas cooled reactor (HTGR) was proposed as the heat source for the Natuna project for CO₂ conversion. To convert CO₂ to useful products, a large amount of high quality water is required for the chemical processes, boilers and other purposes. One LNG production train (maximum of six trains) would produce $0.4 \times 10^9$ SCF/d of saleable gas and $1.4 \times 10^9$ SCF/d of CO₂ (in the case of the Exxon process). This CO₂ gas would then be converted to automobile fuel (methane, methanol), which requires a large amount of water. Natural gas from an off-shore gas field is piped to the petrochemical complex on Natuna Island (about 228 km). Natuna is a small island that, apart from sea water, does not have much available water. The desalination process is considered to be the only solution to the water demand problems of the petrochemical complex. A nuclear desalination system was designed to provide high quality water for this complex. Of the commercial scale desalination processes, multi-stage flash, multi-effect distillation and reverse osmosis and hybrids are considered to be good candidates for the coupling scheme for producing high quality water. The availability of waste heat from the HTGR and an exothermic chemical reaction was also evaluated. It seems that an additional small to medium sized nuclear power plant may be required to produce water for the petrochemical complex of the Natuna project.

1. INTRODUCTION

The Natuna gas field is located in the Natuna Sea, approximately 228 km to the northeast of Natuna Island, in water that is 145 m deep. The total reserves of this field are estimated to be $210 \times 10^{12}$ standard ft³ (SCF) ($6000 \times 10^9$ m³), including CO₂, which comprises more than 70% of the total gas [1]. A liquefied natural gas (LNG) project is planned for Natuna that consists of off-shore gas production and on-shore gas liquefaction on Natuna Island. At present, Natuna is the largest gas field in the world, both in terms of the total gas in place and the recoverable hydrocarbons. Development on Natuna Island will be similar to that previously carried out at the Arun and Bontang LNG plants. In addition to the LNG plant and its associated marine harbour, facilities will be provided for warehouses and the logistics of on-shore and off-shore operations. A new airport and other infrastructures, including a potable water production plant, will be constructed to provide ready access and support to both the plant and the completely self-contained community of off-shore and on-shore workers and their families [1].

Since the Natuna gas field contains a large amount of CO₂, special treatment is required to protect the environment. Exxon, as the main contractor of the Natuna project, has proposed to the Pertamina–National Oil and Gas Company that the re-injection process be used to handle the CO₂, at an additional cost of about

---

1 $1 \text{ ft}^3 = 2.832 \times 10^{-2} \text{ m}^3$. 
50–60% of the total capital investment [2, 3]. To increase the profits of the Natuna project, the National Atomic Energy Agency–Puspitek has also proposed alternative processes for converting CO₂ to synthetic fuel (methanol, methane, syngas, etc.). The proposal is currently under discussion at Pertamina and the Ministry of Research and Technology [2, 3]. On the basis of present estimates, the first LNG deliveries could commence from the Natuna Island marine terminal about 8 years after the start of the project. The Exxon scenario of one LNG train (maximum of six trains) would produce $0.4 \times 10^9$ SCF/d of methane and $1.4 \times 10^9$ SCF/d of CO₂. Conversion of this amount of CO₂ to automobile fuel (methane, methanol) requires a large amount of water.

Since Natuna is a very small island, approximately 65 km long and 45 km wide, there is not enough conventional surface water available to supply the petrochemical complex. Therefore, it is considered that only sea water could be the raw water source for this complex, including the harbour, airport, and office and housing areas.

Since a high temperature gas cooled reactor (HTGR) is proposed for the CO₂ conversion process, the waste heat and the chemical processes will first be considered as the heat sources for sea water desalination. This would reduce the production costs of water and have an impact on the final products of methanol, methane or syngas.

The purpose of this paper is to report on the current status of the Natuna project and the proposed design of the nuclear desalination system for supplying high quality water to the petrochemical complex, including the harbour, airport, office and housing areas, and other related facilities.

2. PROPOSED CHEMICAL PROCESSES

2.1. Exxon proposal

Exxon, a gas company in the United States of America, and the Pertamina–National Oil and Gas Company have been co-operating in the development of the Natuna gas field since 1980 [2, 3]. On the basis of the Exxon proposal, the re-injection process would be adopted to handle 70% of the CO₂ in the total gas reserves. This process would increase the capital investment and operation costs, and would also result in LNG production costs that are two to three times higher than those of other gas fields (Arun and Bontang). The Exxon proposal involves at least three processes (separation, compression and injection), and requires 18 platforms for drilling, compressing and treating, as well as a piping system that is about 910 km long, from drilling and treating platforms off-shore to the LNG plant on Natuna Island, and then back to the injection platform off-shore [1–3]. Impurities (mainly
sulphur and mercury) in the Natuna gas from the drilling platforms are removed, followed by a cryogenic process to separate the CO$_2$ from the saleable gas (mainly methane); this liquid CO$_2$ is then piped to aquifer storage [1-3]. The maximum methane gas production is not more than the original amount (25%), as shown in Table I [3].

2.2. Puspitek proposal

To reduce the production costs of LNG from the Natuna gas field and to increase the use of Natuna products, Puspitek [2] has proposed alternative, promising processes, as shown in Tables I—III [3].

2.2.1. CO$_2$ conversion process

The CO$_2$ conversion process mainly consists of separation of the sulphur and mercury off-shore and conversion of CO$_2$ to methane or methanol on Natuna Island. This process needs hydrogen, which would be supplied by an electrolysis plant powered by a non-CO$_2$ emitting power plant. This hydrogen would be produced from the high quality water of a desalination plant, as shown in Fig. 1 [3]. Since almost all the facilities for this process would be located on Natuna Island, the number of

<p>| TABLE I. MAXIMUM PRODUCTION RATIO OF THE PROCESSES PROPOSED FOR THE NATUNA PROJECT [3] |</p>
<table>
<thead>
<tr>
<th>Proposals</th>
<th>Processes involved</th>
<th>Maximum production ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO$_2$ re-injection process (Exxon)</td>
<td>Separation, Compression, CO$_2$ re-injection</td>
<td>CH$_4$ (25%)</td>
</tr>
<tr>
<td>CO$_2$ conversion process (Puspitek)</td>
<td>Separation, Hydrogenation</td>
<td>CH$_4$ (25%), CH$_4$/CH$_3$OH (66%), or others (66%)</td>
</tr>
<tr>
<td>CH$_4$ enrichment process (Puspitek)</td>
<td>Reforming, Hydrogenation (methanation)</td>
<td>Syngas (50%)$^a$, CH$_4$ (41%), or others (50%)</td>
</tr>
<tr>
<td>CH$_3$OH mass production process (Puspitek)</td>
<td>Reforming, Hydrogenation (methanolation)</td>
<td>CH$_3$OH (91%)$^b$</td>
</tr>
</tbody>
</table>

$^a$ Syngas (CO + H$_2$): gas turbine fuel; chemical feedstock.

$^b$ Methanol: automobile fuel; chemical feedstock.
### TABLE II. THERMODYNAMIC DATA OF THE CONVERSION PROCESSES [3]

<table>
<thead>
<tr>
<th>Processes</th>
<th>Enthalpy of total reaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methanation</td>
<td></td>
</tr>
<tr>
<td>CO₂ + 4H₂ → CH₄ + 2H₂O</td>
<td>ΔH°₂₉₈ = -165 kJ/mol</td>
</tr>
<tr>
<td>4H₂O→ 4H₂ + 2O₂ (electric)</td>
<td>ΔH°₂₉₈ = 4(286) kJ/mol</td>
</tr>
<tr>
<td>CO₂ + 2H₂O→ CH₄ + 2O₂</td>
<td>ΔH°₂₉₈ = 979 kJ/mol</td>
</tr>
<tr>
<td>Methanolation</td>
<td></td>
</tr>
<tr>
<td>CO₂ + 3H₂ → CH₃OH + H₂O</td>
<td>ΔH°₂₉₈ = -49 kJ/mol</td>
</tr>
<tr>
<td>3H₂O → 3H₂ + 1.5O₂ (electric)</td>
<td>ΔH°₂₉₈ = 3(286) kJ/mol</td>
</tr>
<tr>
<td>Reforming</td>
<td></td>
</tr>
<tr>
<td>CO₂ + 2H₂O → CH₃OH + 1.5O₂</td>
<td>ΔH°₂₉₈ = 803 kJ/mol</td>
</tr>
<tr>
<td>CO₂ + CH₄ → 2CO + 2H₂</td>
<td>ΔH°₂₉₈ = 247 kJ/mol</td>
</tr>
<tr>
<td>2CO + 4H₂ → 2CH₃OH</td>
<td>ΔH°₂₉₈ = 2(−128) kJ/mol</td>
</tr>
<tr>
<td>2H₂O → 2H₂ + O₂ (electric)</td>
<td>ΔH°₂₉₈ = 2(286) kJ/mol</td>
</tr>
<tr>
<td>CO₂ + CH₄ + 2H₂O→ 2CH₃OH + O₂</td>
<td>ΔH°₂₉₈ = 563 kJ/mol</td>
</tr>
</tbody>
</table>

*a In the event of a syngas product being used for methanol chemical feedstock, some hydrogen has to be added to form syngas with the remaining CO₂.

### TABLE III. BENEFITS OF USING THE PROCESSES PROPOSED BY PUSPITEK COMPARED WITH THOSE PROPOSED BY EXXON [3]

<table>
<thead>
<tr>
<th>Methane production target (10⁹ SCF/d)</th>
<th>Natuna gas demand (10⁹ SCF/d)</th>
<th>Energy demand (GW(e))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Exxon</td>
<td>Puspitkek</td>
</tr>
<tr>
<td>0.4</td>
<td>1.8</td>
<td>0.47</td>
</tr>
<tr>
<td>0.8</td>
<td>3.6</td>
<td>0.94</td>
</tr>
<tr>
<td>1.2</td>
<td>5.4</td>
<td>0.99</td>
</tr>
<tr>
<td>2.4</td>
<td>10.8</td>
<td>2.82</td>
</tr>
</tbody>
</table>

*a Limited to a fossil fired plant located off-shore.

*b Nuclear power plant (HTGR) for CO₂ conversion and desalination on Natuna Island.
off-shore platforms and piping systems could be reduced. The maximum conversion production ratio (methane, methanol) could be up to 91%, of which 66% would originate from the proposed CO₂ conversion process [2, 3]. All the production schemes could be adjusted to market demand.

2.2.2. Methane enrichment process

A methane enrichment process has been proposed [3] with a view to raising interest in the Natuna project and to anticipating the future market demand for LNG; it consists of reforming and hydrogenation processes. Natuna gas is cleansed of sulphur and mercury, then fed to the HTGR reformer at 700–800°C; using a well known catalyst, syngas (CO + H₂) is formed. Syngas is an intermediate product and could be used as feedstock for petrochemical industries (hydrogen, methane, methanol, aldehyde, ketone, etc.). The remaining CO₂ is fed to the methane converter together with hydrogen, which is produced by the electrolysis plant. Using the catalysts, methane is formed in this converter. The maximum methane production ratio is 41% (as opposed to 25% in the Exxon process). These production schemes could also be adjusted to the market demand for methane. In this case, the water used for producing hydrogen in the electrolysis plant would be provided by a sea water desalination plant.
2.2.3. Methanol mass production process

The methanol mass production process has been specially proposed for the Natuna project [3] and is based on a future methanol demand scenario for automobile fuel; it also consists of reforming and hydrogenation processes. Natuna gas is cleansed of sulphur and mercury and then introduced to the reformer at 700–800°C; syngas (CO + \( H_2 \)) is formed. This syngas and the remaining \( CO_2 \) is fed to the converter together with \( H_2 \), which is supplied by the electrolysis plant. In this converter, methanol is formed in two ways: from a syngas reaction, and from \( CO_2 \) and \( H_2 \) reactions. The maximum methanol production ratio is 91\%, as shown in Table I. This production scheme would also be adjusted to the market demand for methanol. Again, the water used for producing hydrogen would be provided by a sea water desalination plant.

2.3. Heat source

Since the proposed Puspitek processes need a high temperature, especially for the hydrogen production and reforming processes, an HTGR is considered to be the appropriate heat source. It is well known that the coolant operating range of an HTGR is 700–950°C, which is three times higher than that of an LWR. This high temperature heat could be used to produce electricity and to supply industrial processes, e.g. for chemical plants in the medium to high temperature range of 250–950°C. It is also possible to use the heat from the HTGR in the low temperature range of 80–140°C or the waste heat for a sea water desalination plant.

3. ANALYSIS OF WATER REQUIREMENTS

3.1. Chemical processes

The water used in the chemical processes must be of a high quality, i.e. every effort must be made to avoid any impurities entering the production line. The amount of water required is shown in Table IV. As can be seen in the table, a large amount of water is used for producing hydrogen.

3.2. Other facilities

The facilities related to the Natuna project include the harbour, airport, and office and housing areas, all of which need water, although it does not need to be of such a high quality as that used for the chemical processes. The water demand was
calculated according to the number of people present and the activities in the harbour, airport, and office and housing areas, as shown in Table IV.

4. DESIGN OF THE NUCLEAR DESALINATION SYSTEM

4.1. Energy source

Generally, the energy for sea water desalination is supplied by a conventional fossil fired plant or a nuclear power plant [4–8]. For certain reasons, the nuclear option is considered favourably as an energy source for sea water desalination. One reason is that all the rejected heat in a nuclear power plant goes to the condenser, from where it is removed, while in a fossil fired plant at least 20% of the rejected heat is exhausted directly into the atmosphere. Over past decades, many authors have reported on the status of nuclear desalination technology [6, 9]. The technical feasibility, compliance with safety requirements and reliability have been proved by many years of successful operation of nuclear co-generation plants that supply electric power and energy for district heating or for industrial use [6]. In future, large scale commercial deployment of nuclear desalination will mainly depend on its economic competitiveness with the available alternative options and on adequate confidence in its application. There appear to be sufficient incentives for nuclear desalination plants to penetrate the potable water market, just as nuclear power plants have penetrated the electricity market worldwide. It is not realistic to believe that nuclear desalination will replace currently operating fossil fuelled desalination plants, even in the foreseeable

<table>
<thead>
<tr>
<th>Production target of CH₄ equivalent(^a) (10⁹ SCF/d)</th>
<th>Water demand (m³/d)</th>
<th>Total demand</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Puspitek processes</td>
<td>Common facilities</td>
</tr>
<tr>
<td>0.4</td>
<td>15 000</td>
<td>6500</td>
</tr>
<tr>
<td>0.8</td>
<td>30 000</td>
<td>6500</td>
</tr>
<tr>
<td>1.2</td>
<td>45 000</td>
<td>7000</td>
</tr>
<tr>
<td>2.4</td>
<td>90 000</td>
<td>7500</td>
</tr>
</tbody>
</table>

\(^a\) Based on the proposed Puspitek processes.
FIG. 2. Application of the HTGR [10].
future, but it could be commercially deployed in situations where new facilities are being considered, e.g. in the Natuna project. A few nuclear reactors (PWRs in the 600 and 50 MW(e) ranges, PHWRs in the 450–600 MW(e) range, and heat only reactors (HTGRs) up to about 200 MW(th)) were preferred [10]. The possibility of using nuclear power plants as the energy source for desalination facilities has been reported by many authors (Figs 2 and 3) [7, 10, 11]. Most of the chemical processes proposed above use an HTGR as the heat source, producing waste heat during operation. Some of these chemical processes also produce heat from their chemical reactions (exothermic reaction). These heat sources could be used in the pretreatment process for a desalination system to increase efficiency.

4.2. Desalination processes

Of the desalination processes, reverse osmosis (RO) and multi-effect distillation (MED) appear to be the most promising in the medium to long term because of their relatively low energy consumption and investment costs, as well as their high reliability. Earlier, multi-stage flash (MSF) was also considered a candidate. However, the MED process has a lower energy consumption and appears to be less sensitive to corrosion and scaling than the MSF process [8, 11]; also, the partial load operability of MED is more flexible. Therefore, MSF was excluded because it shows no inherent advantages over MED [6, 7]. Canada has suggested that the performance of RO could be improved by preheating the feedwater up to 40°C. For the Natuna project, two
different qualities of water are required: high quality water for the chemical processes, and drinking water for the harbour, airport, and office and housing areas.

4.3. Coupling

The desalination technologies suitable for coupling to nuclear power have been reported [6]. To produce water of a different quality, a nuclear power plant with hybrid desalination is considered to be the best design approach for the Natuna project. An example of a nuclear power plant with hybrid MED and RO desalination is presented in Fig. 4. The intermediate loop produces steam in a two stage flash tank; the steam produced in each stage is mixed and fed into the MED plant; preheated sea water from the MED plant condenser is fed to the RO plant; electricity is taken directly from the power plant. This hybrid system would be suitable for the processes proposed by Puspitek, where large quantities of high quality water are required. For the processes proposed by Exxon, hybrid desalination with a fossil fired plant as the energy source is being considered for the off-shore option to supply makeup boiler feedwater as well as drinking water for around 400 workers on the platforms. For the on-shore facilities of the Exxon proposal, a fossil fired plant with stand alone RO system would be adequate.
4.4. Size

An industrial scale RO plant (56 800 m³/d) was built in Jeddah, Saudi Arabia, in 1989 [8]. At present, the capacity of a MED or MSF plant is 48 000 m³/d. It has been reported [6, 11] that a 200 MW(th) heating reactor is capable of producing 110 000–144 000 m³/d, and a 20–50 MW(e) PWR 20 000–80 000 m³/d and 3–44 MW(e) of electricity. For the first production train of saleable gas at Natuna, a 24 000 m³/d desalination plant (MED and RO) would be sufficient to supply water to the petrochemical complex; for the full production line of saleable gas, a 100 000 m³/d hybrid MED and RO plant would be required.

5. CONCLUSIONS

(1) Introducing Puspitek processes to the Natuna project will show some benefits; these will indirectly have an impact on the LNG production costs of the Natuna gas field;
(2) One unit of a small to medium sized nuclear power plant could be considered to be the main energy source for the nuclear desalination system;
(3) Waste heat from the nuclear plant and the chemical processes could be used in the pretreatment process of the nuclear sea water desalination system to increase efficiency;
(4) Coupling of a nuclear power plant to hybrid MED and RO desalination is considered to be the best option for supplying water to the petrochemical complex of the Natuna project.

REFERENCES


COMPARATIVE DESIGN OF TWO 60 000 m$^3$/d DESALINATION PLANTS USING THE MULTI-STAGE FLASH AND REVERSE OSMOSIS PROCESSES

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Abstract

COMPARATIVE DESIGN OF TWO 60 000 m$^3$/d DESALINATION PLANTS USING THE MULTI-STAGE FLASH AND REVERSE OSMOSIS PROCESSES.

A comparison is made of the designs of two 60 000 m$^3$/d desalination plants that use the multi-stage flash (MSF) and reverse osmosis (RO) processes, respectively. The objective is to assess the fundamental differences between the MSF and RO technologies based on multi-parametric analysis and cross-comparison of the normalized technical characteristics of the two installations. Such assessment and analysis focused on the most important comparison criteria in order to help decision making engineers and planners with the implementation of desalination projects and with the choice of the desalination process most appropriate to specific site conditions. Normalization of the plant capacity at a range of 60 000 m$^3$/d for the two processes, as well as site condition normalization (the Mostaganem site, located 100 km to the east of Oran, is the reference site for both desalination plants), allowed easier cross-comparison of the study output data and other operational parameters. The aspects covered by the comparative study included plant sizing in terms of the number of units to be installed, the specific electricity and gas consumption, the efficiency, the effectiveness, the availability and the load factor for each process. The MED process was not taken into consideration because, as yet, Algeria has no plans to introduce any large scale MED projects. The assessment included the cross-comparison of major criteria such as operation and maintenance, the influence of sea water quality on the desalination processes, the quality of the product water and the appropriate post-treatment, the need for and use of chemical products, the choice of corrosion resistant materials, the lifetime of structures and equipment and the appropriate pretreatment. Also discussed are water intake and drainage, energy efficiency and optimum coupling, the area for the installations, operation, maintenance and administration staff, the environmental impact and the construction time.

1. BASIC DESIGN PARAMETERS (TABLES I, II AND FIGS 1, 2)

The basic design parameters of the multi-stage flash (MSF) and reverse osmosis (RO) plants are as follows:
FIG. 1. General flowsheet of the 60 000 m³/d MSF desalination plant (for explanation of measurement points I–XI, see Table I).
**MSF:** Design capacity ............................................ 59 800 m³/d  
Brine temperature in the circuits .................... 109°C  
Outlet brine temperature (maximum) ............ 33°C  
Desalinated water temperature  
(maximum) .................................................. 31°C  
Production ratio ........................................... 8  
Flow rate of sea water intake ...................... 493 000 m³/d  
Flow rate of sea water rejection ................. 433 000 m³/d  

**RO:** Production capacity ............................. 60 500 m³/d  
Module pressure ......................................... 59–66 kg/cm²  
Feedwater temperature ............................... 14–26°C  
Flow rate of sea water intake ................. 186 000 m³/d  
Module feed flow rate ................................. 173 000 m³/d  
Rejection flow rate ................................. 125 500 m³/d  
Feedwater pH ............................................. 6–6.5

---

**TABLE I. MAIN DESIGN PARAMETERS AND MASS AND HEAT BALANCE OF THE 60 000 m³/d MSF DESALINATION PLANT IN ALGERIA**

<table>
<thead>
<tr>
<th>Measurement point in Fig. 1</th>
<th>Element or section</th>
<th>Fluid</th>
<th>Parameters for a 30 000 m³/d unit</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td><strong>TDS</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(mg/L)</td>
</tr>
<tr>
<td>I</td>
<td>Water supply</td>
<td>Sea water</td>
<td>37 500</td>
</tr>
<tr>
<td>II</td>
<td>Heat recovery</td>
<td>Sea water outlet</td>
<td>37 500</td>
</tr>
<tr>
<td>III</td>
<td>Water make-up</td>
<td>Water make-up</td>
<td>37 500</td>
</tr>
<tr>
<td>IV</td>
<td>Circulation pump</td>
<td>Brine outlet</td>
<td>67 800</td>
</tr>
<tr>
<td>V</td>
<td>Heater</td>
<td>Brine outlet</td>
<td>67 800</td>
</tr>
<tr>
<td>VI</td>
<td>Discharge</td>
<td>Brine</td>
<td>77 000</td>
</tr>
<tr>
<td>VII</td>
<td>Desalinated water</td>
<td>Desalinated water</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(maximum)</td>
<td></td>
</tr>
<tr>
<td>VIII</td>
<td>Heating steam</td>
<td>Heating steam</td>
<td>—</td>
</tr>
<tr>
<td>IX</td>
<td>Ejector</td>
<td>Driving steam</td>
<td>—</td>
</tr>
<tr>
<td>X</td>
<td>Condensate</td>
<td>Condensate</td>
<td>—</td>
</tr>
<tr>
<td>XI</td>
<td>Air condensor</td>
<td>Cooling sea water</td>
<td>37 500</td>
</tr>
</tbody>
</table>
FIG. 2. General flowsheet of the 60 000 m$^3$/d RO desalination plant (for explanation of measurement points 1–15, see Table II).
TABLE II. MAIN DESIGN PARAMETERS AND MASS AND HEAT BALANCE OF THE 60 000 m³/d RO DESALINATION PLANT IN ALGERIA

<table>
<thead>
<tr>
<th>Measurement point in Fig. 2</th>
<th>Fluid and installation</th>
<th>TDS (mg/L)</th>
<th>Temperature (°C)</th>
<th>Capacity (m³/d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Sea water</td>
<td>39 000</td>
<td>14–20</td>
<td>185 000</td>
</tr>
<tr>
<td>2</td>
<td>Sea water intake</td>
<td>—</td>
<td>—</td>
<td>185 000</td>
</tr>
<tr>
<td>3</td>
<td>Pretreatment installation No. 1</td>
<td>—</td>
<td>—</td>
<td>92 500</td>
</tr>
<tr>
<td>4</td>
<td>Pretreatment installation No. 2</td>
<td>—</td>
<td>—</td>
<td>92 500</td>
</tr>
<tr>
<td>5</td>
<td>Pretreatment installation storage tank</td>
<td>—</td>
<td>—</td>
<td>171 500</td>
</tr>
<tr>
<td>6</td>
<td>Rinsing water</td>
<td>—</td>
<td>—</td>
<td>7 600</td>
</tr>
<tr>
<td>7</td>
<td>Counter current and de-plugging of waste water</td>
<td>—</td>
<td>—</td>
<td>5 900</td>
</tr>
<tr>
<td>8</td>
<td>RO unit No. 1</td>
<td>—</td>
<td>—</td>
<td>15 000</td>
</tr>
<tr>
<td>9</td>
<td>RO unit No. 2</td>
<td>—</td>
<td>—</td>
<td>15 000</td>
</tr>
<tr>
<td>10</td>
<td>RO unit No. 3</td>
<td>—</td>
<td>—</td>
<td>15 000</td>
</tr>
<tr>
<td>11</td>
<td>RO unit No. 4</td>
<td>—</td>
<td>—</td>
<td>15 000</td>
</tr>
<tr>
<td>12</td>
<td>Concentrate</td>
<td>—</td>
<td>—</td>
<td>111 500</td>
</tr>
<tr>
<td>13</td>
<td>Concentrated mud</td>
<td>—</td>
<td>—</td>
<td>(6 t/d)</td>
</tr>
<tr>
<td>14</td>
<td>Concentrated effluents</td>
<td>57 400</td>
<td>—</td>
<td>124 994</td>
</tr>
<tr>
<td>15</td>
<td>Product water</td>
<td>&lt; 1000</td>
<td>—</td>
<td>60 000</td>
</tr>
</tbody>
</table>

2. CAPACITY OF THE PLANTS

The capacity of each plant is as follows:

**MSF:** This plant can have a high desalinated water capacity. A desalination plant of a given capacity can have a reduced number of units. Scale formation is less than that in the RO process. The plant capacity is 30 000 m³/d, and there are two desalination units.

**RO:** The maximum capacity is comparatively low. For a project of a given desalination capacity, more units are required for RO than for MSF. The plant capacity is 15 000 m³/d, and four units are required.
3. ENERGY CONSUMPTION: ELECTRICITY

The electric energy consumption is as follows:

**MSF**: Electric energy is mainly needed for driving the pumps. The study has, however, retained the concept of turbines to drive some pumps, e.g. for brine circulation, and of feed sea water pumps. In this way, the electric energy consumption is reduced to 0.47 kW-h/m³ of desalinated water. The total installed power is 3 MV-A, and the electric supply, 60 kV, 50 Hz (triphasic).

**RO**: All the pumps, including the high pressure pumps, are very efficient and driven electrically. However, the high pressure pumps are fitted out with an energy recovery turbine. The electric energy consumption is high (5.9 kW-h/m³ of desalinated water). The total installed power is 19 MV-A, and the electric supply, 60 kV, 50 Hz (triphasic).

4. ENERGY CONSUMPTION: GAS

The gas energy consumption is as follows:

**MSF**: Natural gas was chosen as the fuel for the steam generators because of its availability in Algeria. On the basis of 9300 kcal/Nm³, the gas consumption is estimated to be 24 000 Nm³/h, i.e. 9.4 Nm³/m³ of desalinated water.

**RO**: Natural gas is not required in RO units. Taking the international value as the reference price of gas shows that RO is more competitive than MSF.

5. EFFICIENCY, EFFECTIVENESS, AVAILABILITY AND LOAD FACTOR

The above factors are as follows:

**MSF**: The efficiency can be assessed through the water production ratio (the quotient of the desalinated water quantity (m³) over the heating steam quantity (t)); the higher the water production ratio, the better the efficiency. The water production ratio is 8, and the annual availability, 320 days. Annually, a period of about 25—35 days is required to carry out preventive maintenance. Organization of such surveys on one unit after the other allows maintenance to be carried out during half-load operation. The load factor of each unit can vary between 25 and 100%, proceeding in successive stages.
RO: The quotient of the desalinated water quantity over the inlet sea water quantity, or the recovery ratio in per cent, constitutes the main efficiency indicator. For the designed installation, this ratio is 35%. Availability is close to 325 days per year. Annually, a period of about 28–35 days is required for preventive maintenance. Successive shutdown of each unit permits maintenance of the plant to be carried out at three-quarters of its production capacity. In terms of the water requirements, the load factor can be modified by changing the number of modules in operation or, more generally, by varying the number of units in operation in the installation. For instance, the load factor of each unit can vary between 25 and 100%, proceeding in load stages of 25% each.

6. OPERATING CONDITIONS

The operating conditions are as follows:

MSF: The manual startup and shutdown phases require more operator ability and know-how than RO, although under a stabilized, normal operating regime, operation is much easier, since it is automated. The operator tasks consist mainly of monitoring the measuring equipment and the operating parameters. The annual survey is used to control corrosion of the circuits, the repairs linked to this corrosion, and scaling of the piping, exchangers and evaporators.

RO: Startup and shutdown are easier than for MSF. A rather high degree of automation can be obtained because of the design of the installation. Automatic remote control can be easily implemented under a constant load regime. In normal service, this process requires better control of the measuring equipment. RO also requires enhanced management of the chemical products, e.g. the coagulants and acids used for pretreatment. The annual survey is devoted mainly to membrane cleaning and replacement.

7. INFLUENCE OF THE SEA WATER QUALITY

The influence of the sea water quality is as follows:

MSF: In general, the sea water quality exerts little influence on operation. The heat efficiency is higher when the sea water temperature is low. No elements are likely to affect the desalinated water quality other than some volatile polluting substances, e.g. phenol or ammonia, which may pass along the product water circuits.
RO: Under some temperature limits imposed by the behaviour of the membranes, the production of RO is greater when the sea water temperature is higher. It is desirable that RO has sea water that is as pure as possible. If the quality of the water that supplies the desalination circuits is high, pretreatment is easier and the behaviour and performance of the membranes are good.

8. QUALITY OF THE PRODUCT WATER AND THE APPROPRIATE POST-TREATMENT

The quality and Algerian standards of the product water are as follows:

MSF:

Quality of the product water

| Total dissolved solids (TDS): 50 mg/L (maximum) | 500 mg/L |
| pH: 7 | 6.5–8.5 |
| Ion chlorine: 30 mg/L (maximum) | 250 mg/L |
| Ion sulphate: 5 mg/L (maximum) | 200 mg/L |
| Ion calcium: 28 mg/L (maximum) | 75 mg/L |
| Ion magnesium: 2 mg/L (maximum) | 50 mg/L |
| Calcium CO₃: 60 mg/L (maximum) | 100 mg/L |
| Temperature: 32°C (maximum) | < 25°C |

Sterilization–chlorination and an improvement in the water hardness are essential for post-treatment. The design study foresees that the desalinated water will be mixed with the water of the existing network.

RO:

Quality of the product water

| TDS: 500 mg/L (maximum) | 500 mg/L |
| pH: 5 | 6.5–8.5 |
| Ion chlorine: 250 mg/L | 250 mg/L |
| Ion sulphate: 28 mg/L | 200 mg/L |
| Ion calcium: 23 mg/L | 75 mg/L |
| Ion magnesium: 17 mg/L | 50 mg/L |
| Calcium CO₃: 56 mg/L | 100 mg/L |
| Temperature: 16–26°C | < 25°C |
Sterilization–chlorination and an improvement in the pH of the water are essential; mixing the desalinated water with the existing network water will cover this need.

9. THE NEED FOR AND USE OF CHEMICAL PRODUCTS

These are as follows:

**MSF:** A scaling inhibitor (31 kg/h), an anti-moss agent (0.5 kg/h) and solid limestone (140 kg/h) are the only chemical products required.

**RO:** Significant amounts of chemical products are required. These include the pretreatment coagulant, ferric chloride (90 kg/h); an anionic macromolecular coagulant for the effluents (12 kg/d); a cationic macromolecular coagulant for the mud (5 kg/d); 98% sulphuric acid for pH adjustment (450 kg/h); slaked lime powder for adjustment of the desalinated water quality (70 kg/h); citric acid (70 000 kg/a); and ammonia (20 000 kg/a) for cleaning of and pH adjustment in the modules. These quantities (about 650 kg/h of all of the chemical products) are for a design capacity of 60 000 m³/d.

10. CHOICE OF CORROSION RESISTANT MATERIALS

The choice of corrosion resistant materials is as follows:

**MSF:** This process is subject to more corrosion problems than the RO process. The higher the temperature of the medium, the more severe the corrosion. Materials that are highly resistant to corrosion are used particularly for those elements that are in contact with sea water. The evaporator is made of carbon steel coated with austenitic steel 316L for the high temperature stage and with epoxy for the low temperature stage. The tubular beam of the brine heater is made of cupro–nickel and that of the recovery section, of aluminium–brass; titanium is also used in some parts of the heat exchangers. The pipes are made of steel coated with rubber or mortar (the sea water and low temperature brine pipes), or of austenitic steel 304 (the soft water and condensate pipes). Protection from corrosion is ensured by maintaining a high pH value for the circulating brine (which reduces scaling without having to use acid), by maintaining, with the help of a de-aerator, the dissolved oxygen content in the sea water at a level of less than 20 μg/L, and by providing some circuit parts with cathodic production.
RO: As this process operates at a low temperature, corrosion problems are less apparent. However, some corrosion resistant materials are required: the pipes are coated internally with polyethylene and epoxy; the plastic pipes are strengthened with fibreglass; and the carbon steel is coated with epoxy, austenitic steel 316 and cast iron. In contrast to MSF, no specific protection against corrosion is necessary.

11. LIFETIME OF STRUCTURES AND EQUIPMENT

A reasonable lifetime for both processes, if appropriate maintenance and operation are carried out, is 30 years for the unit structures, frames, supports and various pipes; 15 years is possible for the production equipment.

12. APPROPRIATE PRETREATMENT

Pretreatment for the two processes is as follows:

MSF: To reduce corrosion, de-aeration of the make-up sea water is carried out by a vacuum de-aerator. Scaling of the heat exchange tubes (which could result in a decrease in the exchange coefficient) decreases if an inhibitor is used.

RO: Flake formation, which is necessary for efficient decanting of the sea water that supplies the unit, is obtained by using a coagulant. Sea water pretreated in this way is then filtered through a gravity filter. The pH of the sea water feed is adjusted to a suitable level by adding acid. Mud formation in the osmosis modules is avoided by using a sterilizing agent. To complete the sea water pretreatment, residual chlorine, dissolved oxygen and the other noxious substances have to be eliminated.

13. WATER INTAKE AND DRAINAGE

Water intake and drainage are as follows:

MSF: A significant amount of water is required for cooling: eight times more sea water is pumped than desalinated water produced. This naturally has an effect on the size of the sea water pumping station (499 000 m\(^3\)/d has to be pumped through the water intake pipe from a depth of at least 10 m). Water discharge, corresponding to a flow rate of 439 000 m\(^3\)/d (18 292 m\(^3\)/h), occurs through an open channel.
**RO:** In contrast to MSF, the amount of sea water pumped is relatively small (only three times the amount of soft water produced (185 000 m$^3$/d)), which leads to a reasonably sized pumping station. The effluent flow rate is also much lower (125 000 m$^3$/d), even if an open channel system is used.

14. ENERGY EFFICIENCY AND OPTIMUM COUPLING

Energy efficiency and optimum coupling are as follows:

**MSF:** The best heat efficiency is obtained when coupling an MSF desalination plant to a power station fitted with steam turbines or, even better, with gas turbines. To supply the brine heater with heat energy, it is possible to recover the low enthalpy heat steam at the low pressure stage in the steam turbine, or the high enthalpy heat exhaust gas (600°C) at the gas turbine outlet. The latter is the most interesting as far as energy efficiency is concerned. In general, coupling of the electric energy needs to those of the desalinated water results in an increase in the energy efficiency and a significant decrease in the desalinated water costs. This reduction makes desalination more competitive than other mobilization processes.

**RO:** The energy recovery turbines enhance efficiency. Use of low enthalpy energy (when it exists) results in a slight increase in the temperature of the sea water feed, which compensates for the reduced water production, caused by the lower sea water temperature.

15. AREA FOR THE INSTALLATIONS

The 60 000 m$^3$/d MSF installation requires a total area of 37 200 m$^2$, including all pathways, green spaces and parking, which is 50% more than that required for an RO installation (25 000 m$^2$).

16. OPERATION, MAINTENANCE AND ADMINISTRATION STAFF

The workforce is as follows:

**MSF:** Operation requires a staff of 50 persons, comprising 30 for operation, 10 for maintenance and 10 for administration. The operating staff is made up of two analysts and four teams, each of which has seven operators (one foreman and six
operators). This workforce does not include drivers, specialized workers and periodic maintenance staff.

**RO:** Operation requires a staff of 38 persons, comprising 20 for operation, nine for maintenance and nine for administration. The operating staff is made up of four teams, each of which has four operators (one foreman and three operators), as well as two operators and two analysts. Specialized workers, drivers and periodic maintenance staff are not included.

17. ENVIRONMENTAL IMPACT

The environmental impact is as follows:

**MSF:** Warm effluents (with a temperature which is 9°C higher than that of the raw sea water and a concentration which is equal to 42 000 mg/L of TDS) are discharged in great quantities. Treatment of these effluents is, however, unnecessary. Exhaust gases that arise from natural gas combustion in the steam generator are also discharged into the atmosphere. Sound problems emanate mainly from the high pressure steam exhaust in the ejector and valves.

**RO:** The effluents to be discharged consist essentially of the concentrated residual waters arising from the modules (with a temperature which is 1°C higher than that of the raw sea water and a concentration which is equal to 57 400 mg/L of TDS), as well as water and mud arising from filter washing. The latter, produced at the rate of 6 t/d, should be processed before being discharged by mud coagulation–decanting–thickening–dehydration. Since there is no exhaust gas, electric energy takes the place of heat energy. Sound problems are associated with the high pressure pumps, the energy recovery turbines and the high pressure water valves.

18. CONSTRUCTION TIMES

The construction times for the two processes are almost identical, with some advantage for RO (24 months) over MSF (26 months).

19. CONCLUSIONS

Even if MSF desalination technology remains acceptable for large sea water desalination plants and, at the moment, provides most of the total installed
desalination capacity worldwide, RO technology is making rapid progress, including for sea water desalination. Over the past 10 years, development of high performance membranes with a high rejection ratio has resulted in the RO process being used for sea water desalination. The demand for RO is increasing, even for large sea water desalination installations.

**BIBLIOGRAPHY**


LOW TEMPERATURE VACUUM EVAPORATION PROCESS FOR SEA WATER DESALINATION USING WASTE HEAT FROM PHWRs

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Abstract
LOW TEMPERATURE VACUUM EVAPORATION PROCESS FOR SEA WATER DESALINATION USING WASTE HEAT FROM PHWRs.

Most of the nuclear reactors in India are of the PHWR type and use natural uranium oxide (UO₂) as fuel. Heavy water (D₂O) is used as the coolant and moderator. About 40 and 100 MW(th) waste heat are available in the moderator system of 220 and 500 MW(e) PHWRs, respectively. A significant part of this waste heat can be utilized for sea water desalination, producing fresh water in the coastal nuclear power stations. Coastal regions generally face water scarcity problems and normally do not have any source of good quality water. The available raw waters have a higher salt content, leading to a high production cost for makeup demineralized (DM) water. A scheme has been suggested that produces up to 1000 t/d of pure water by sea water desalination using the waste heat of the D₂O moderator in a 500 MW(e) coastal PHWR to meet the makeup DM water requirements of the power station. The low temperature vacuum evaporation (LTE) desalting system, using the waste heat of the D₂O moderator for producing low cost pure water from sea water, is discussed. The technical specifications and performance of the 30 t/d LTE desalination plant set up and operated at the Bhabha Atomic Research Centre (BARC) are presented. Also discussed is the performance of a water jet ejector for creating and maintaining the vacuum in the system and for pumping out the concentrated brine from the evaporator system. Details are given of a proposed 15 t/d LTE desalination pilot plant coupled to a nuclear research reactor (CIRUS) at BARC, utilizing part of the waste heat of the reactor coolant for conducting an immediate practical demonstration.

1. INTRODUCTION

Desalting requires energy for the conversion of saline water into pure water. The minimum energy requirement to separate 1 m³ of pure water from sea water for the reversible isothermal process is about 0.7 kW·h.

\[ E_{\text{min}} = RT \ln \frac{p}{p_0} \]
where $E_{min}$ is the minimum energy requirement; $p$ is the vapour pressure of the sea water; $p_0$ is the vapour pressure of the pure water; $R$ is the universal gas constant; and $T$ is the absolute temperature.

In practice, the energy requirement varies from 6 to 20 kW·h/m³ of desalted water, depending on the type of desalination process. The energy cost contributes a significant fraction (35–55%) of the desalted water cost. Efforts are directed towards utilization of the waste heat for thermal desalination to reduce the energy cost substantially and to produce low cost pure water from sea water.

2. PHWRs

The nuclear reactors in India are of the PHWR type and use natural uranium oxide ($\text{UO}_2$) as the fuel. Heavy water ($\text{D}_2\text{O}$) is used as the coolant and moderator. The moderator is maintained at 65°C and 7.5 bar in a 220 MW(e) PHWR. It is cooled from 65 to 44°C by process water, which in turn is cooled by sea water in coastal power stations. About 40 MW(th) is available as the waste heat in the moderator system of a 220 MW(e) PHWR. For a 500 MW(e) PHWR, the $\text{D}_2\text{O}$ moderator is cooled from 80 to 55°C by process water, which in turn is cooled from 55 to 35°C by sea water that enters at 32°C and exits at 42°C. About 100 MW(th) is available as the waste heat. The process parameters of the moderator system of 220 and 500 MW(e) PHWRs are given in Table I. Of late, it is being recognized that one way of utilizing the heat of the moderator is through sea water desalination.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core power (MW(th))</td>
<td>790</td>
</tr>
<tr>
<td>Maximum net electric output (MW(e))</td>
<td>220</td>
</tr>
<tr>
<td>Moderator</td>
<td>$\text{D}_2\text{O}$</td>
</tr>
<tr>
<td>Type</td>
<td>$\text{D}_2\text{O}$</td>
</tr>
<tr>
<td>Pressure (bar)</td>
<td>7.5</td>
</tr>
<tr>
<td>Inlet temperature (°C)</td>
<td>44</td>
</tr>
<tr>
<td>Outlet temperature (°C)</td>
<td>65</td>
</tr>
</tbody>
</table>
3. LOW TEMPERATURE VACUUM EVAPORATION (LTE) DESALINATION

A 30 t/d LTE desalination plant (Fig. 1) using waste heat at 65°C for producing pure water from sea water has been tested at the Bhabha Atomic Research Centre (BARC) [1]. It operates at 41°C and 710 mm of Hg vacuum. The design parameters are given in Table II. It is a self-contained unit suitable for installation on a stationary structure or a floating platform [2]. Water jet ejectors are used to create a vacuum and to pump out concentrated sea water from the evaporator. Scale formation is practically eliminated because of the low boiling temperature and brine density. This unit is eco friendly, since it does not require chemical pretreatment of the feed sea water, and is reliable and maintenance free. Apart from the electric energy required for the pump, no other power or fuel is necessary, except for waste heat at around 65°C. However, the overall heat transfer coefficients for the heater and condenser sections are low because of low temperature operation.

FIG. 1. Process flow diagram of a 30 t/d LTE desalination plant.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Product water output (m³/h)</td>
<td>1.25</td>
</tr>
<tr>
<td>Sea water salinity (ppm)</td>
<td>35 000</td>
</tr>
<tr>
<td>Product water quality (ppm)</td>
<td>20</td>
</tr>
<tr>
<td>Total sea water requirements for cooling (m³/h)</td>
<td>144</td>
</tr>
<tr>
<td>Feed sea water requirements (part of total requirements) (m³/h)</td>
<td>4.5</td>
</tr>
<tr>
<td>Hot water temperature (°C)</td>
<td>65</td>
</tr>
<tr>
<td>Sea water boiling temperature (°C)</td>
<td>41</td>
</tr>
<tr>
<td>Operating pressure (abs) (bar)</td>
<td>0.08</td>
</tr>
<tr>
<td>Waste heat requirements (MW(th))</td>
<td>1</td>
</tr>
<tr>
<td>Electric power consumption (kW(e))</td>
<td></td>
</tr>
<tr>
<td>If sea water is available at 6 bar</td>
<td>2.25</td>
</tr>
<tr>
<td>If sea water is available at 1 bar</td>
<td>15</td>
</tr>
<tr>
<td>Heat transfer coefficient (kW⋅m⁻²⋅K⁻¹)</td>
<td></td>
</tr>
<tr>
<td>Heater section</td>
<td>0.8</td>
</tr>
<tr>
<td>Condenser section</td>
<td>1.0</td>
</tr>
</tbody>
</table>

4. WASTE HEAT UTILIZATION OF A PHWR FOR SEA WATER DESALINATION

The modified system for the waste heat utilization of the moderator of a 500 MW(e) PHWR for sea water desalination is shown in Fig. 2. The details have been determined using 55°C process water to avoid any changes in the moderator system. The scheme is being considered for a 500 MW(e) PHWR. The desalination plant produces around 1000 t/d of pure water from sea water, which is about 25% more than the total makeup demineralized (DM) water requirements in a 500 MW(e) PHWR. It is economical to use this water as makeup DM water, with minor polishing, in the coastal power stations because of the following factors:

(1) The LTE desalination plant utilizes the waste heat as the energy source for desalting, hence the energy cost is nil;
(2) It replaces the cation and anion exchangers and eliminates the necessity for regeneration chemicals; the raw water used as feed for the DM plant is released to the local population for domestic use;
1. Moderator heat exchanger
2. Process water heat exchanger
3. Desalination unit
4. Product water pump

Note: When the desalination unit is shut down, the sea water required for the process water heat exchanger is 2430 kg/s at 32°C

FIG. 2. Modified system for the waste heat utilization of the moderator of a 500 MW(e) PHWR for sea water desalination.

(3) It is eco friendly and does not require chemical pretreatment of the feed sea water;
(4) It uses sea water as the motive fluid for the water jet ejectors meant for creating a vacuum and for pumping out the concentrated sea water; sea water is available at 6 bar in a PHWR power plant; electric power is required only for the product water pump.

5. DEMONSTRATION PLANT AT A RESEARCH REACTOR

To conduct an immediate practical demonstration it was decided to set up a 15 t/d LTE desalination plant coupled to a nuclear research reactor (CIRUS). The desalination plant is readily available; to study performance, it was tested and operated around the clock for a number of hours at different hot water temperatures. Product output as a function of hot water temperature is given in Fig. 3. A schematic diagram of this desalination plant coupled to CIRUS is shown in Fig. 4. An intermediate heat exchanger is incorporated between the primary coolant water (PCW) and
FIG. 3. Product output as a function of hot water temperature.

FIG. 4. Schematic diagram of the 15 t/d LTE desalination plant coupled to CIRUS.
the desalination plant to ensure that no radioactive material reaches the desalted water. The intermediate circuit consists of a booster pump, the intermediate heat exchanger, the evaporator unit of the desalination plant, and the associated piping and isolation valves. The intermediate circuit water is maintained at a pressure that is slightly higher than the PCW pressure in the intermediate heat exchanger, so that spread of activity to the inactive intermediate circuit is prevented in the event of leakage in the heat exchanger tubes. It ensures an extremely low probability of radioactive contamination and high protection of the product water. A provision to monitor the radioactivity in the desalination plant also exists. A purification circuit, consisting of a filter and an ion exchange unit, is incorporated to maintain the chemistry of the intermediate circuit. The product water from the desalination plant is transferred to a 30 m³ overhead tank and sent to an underground dump tank through a mixed ion exchange bed. At present, the CIRUS PCW makeup requirement is approximately 10–13 L/min, which is nearly the same as the production rate of the desalted water from the desalination plant.

6. CONCLUSIONS

Excellent prospects for the utilization of waste heat from the PHWR and nuclear research reactor for sea water desalination are foreseen. It is possible to utilize a significant part of the nuclear waste heat and to produce the entire makeup DM water from sea water using LTE desalination in an economical and environmentally friendly manner. The raw water used as feed for the DM plant is released to the local population for domestic use.

ACKNOWLEDGEMENTS

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REFERENCES

MODELLING AND SIMULATION OF THE THERMAL VAPOUR COMPRESSION DESALINATION PROCESS

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Abstract

MODELLING AND SIMULATION OF THE THERMAL VAPOUR COMPRESSION DESALINATION PROCESS.

A description is given of a steady state mathematical model developed to analyse the single effect thermal vapour compression (TVC) desalination process. The model considered the effects of all thermodynamic losses on the unit thermal performance ratio, the specific heat transfer area and the specific flow rate of the cooling water. The losses contemplated are the boiling point elevation, the non-equilibrium allowance and the temperature depression corresponding to the pressure drop in the demister and during the vapour condensation process. The model also takes into consideration the variation in the physical properties of the sea water with temperature and salt concentration, the effect of fouling factors and the presence of non-condensable gases on the heat transfer coefficients in the evaporator and the condenser. The relationships between the parameters that control the product water cost (e.g. the thermal performance ratio, the specific heat transfer area and the mass flow rate of the cooling water) and important parameters such as the motive steam pressure, the vapour compression ratio and the boiling temperature have been established and presented in detail.

1. INTRODUCTION

Many areas, especially in the Middle-East, suffer from the gap that exists between the increasing demands for fresh water and the limited natural water resources available. The Arabian Gulf countries cover the largest area in the world without a single river. These countries have struggled over the past four decades to build a considerable number of desalination plants to secure their fresh water needs. Nevertheless, many other nations still suffer from water shortages and cannot afford the high capital and running costs required for desalination units.

Among the various sea water desalination processes of practical interest, thermal vapour compression (TVC) is particularly attractive because of its high performance ratio (PR) with a lower number of effects, good flexibility to load variation, simple geometry and the absence of moving parts. The latter feature makes the
process robust, and considerably minimizes the maintenance skills required and spare part stocking. The process can be driven by superheated or saturated steam at low or intermediate pressures without the formation of hot spots that augment scale formation. A distinct advantage offered by the process is that tube leaks, if they occur, do not cause contamination of the product distillates. This is because the fresh water side is necessarily at a higher pressure than the salt water side. All these facts make the process a potential candidate for future application in large scale installations, and better than any other desalination system when coupled to nuclear power stations.

There are a limited number of publications that handle the TVC desalination system. Most have concentrated on describing application of the process in relatively low capacity plants and on comparing its features with other desalination processes. Examples of recent publications are Temstet et al. [1], Temstet and Laborie [2] and Michels [3]. Michels [3] described three low capacity units of multiple effect TVC that have been built in the remote western areas of Abu Dhabi, United Arab Emirates. The plants superseded the more classical multi-stage flash (MSF) process in the range of unit production of up to $10 \times 10^3$ t/d. Temstet and Laborie [2] outlined the main characteristics of three units of high performance (PR = 17), each producing 2500 m$^3$/d. The evaporator has 12 effect, low temperature units that were designed and constructed for the Kompania di Awa I Eleckrisidat di Korsou N.V. The 12 effect desalination units with Trapani thermocompression have been described by Temstet et al. [1]. The plant comprises four units, each producing 9000 m$^3$/d of distillate water. The ejectocompressors are fed with 45 bar steam raised by dedicated boilers. The design gained output ratio of the units is 16.7. On the other hand, El-Dessouky and Assassa [4] carried out a simple analysis of the multi-effect evaporation (MEE)–TVC desalination process, assuming a constant heat transfer area in all the effects and constant physical properties of the water. They also showed, for the first time, the advantages of the MEE–TVC process compared with other thermal processes.

The main purpose of this paper is to describe a steady state mathematical model developed to analyse the single effect TVC sea water desalination process. The relationships between the parameters that control the product water cost (e.g. the thermal PR (steam economy), the specific heat transfer surface area and the mass flow rate of cooling water) and other design and operating variables such as the motive steam pressure, the boiling temperature and the vapour compression ratio have been established. The model considered the variation in the physical properties of the water with temperature and salt concentration, the boiling point elevation, and the pressure drop in the demister and during the condensation process inside the tubes. The model also takes into consideration the effects of the presence of non-condensable gases and the release of vapour in the venting system. It is important to emphasize that most of the industrial TVC plants are based on the MEE–TVC system. The paper also describes
the basic processes that take place in actual industrial units; the model developed can be extended easily for any number of effects.

2. DESCRIPTION OF PROCESS

The single effect TVC desalination unit (simplified) is illustrated in Fig. 1. The main components of the unit are the evaporator, the steam jet ejector and the feed heater or condenser. Accessories such as the circulating pumps, the venting system, and the measuring and control instrumentation are not shown in the figure. The evaporator consists of an evaporator/condenser–heat exchanger, a vapour space, a water distribution system and a mist eliminator. The steam jet ejector is composed of a steam nozzle, a suction chamber, a mixing nozzle and a diffuser. The feed heater or

![FIG. 1. Single effect TVC desalination unit.](image-url)
the heat sink unit is usually a counter current surface condenser in which the non-condensable gases leave at a temperature approaching that of the feedwater. This permits cooling of the non-condensable gases to the minimum possible temperature, thereby minimizing the amount of vapour that may be removed with the gases and decreasing the volume of the pumped gases. In addition, it is possible to operate the counter current condenser so that the exit water is within a condensation temperature of 3–5 K of the saturated vapour. This will improve the thermal performance of the unit and minimize the mass flow rate of cooling water.

A known mass of sea water \((M_c + M_f)\) at temperature \(T_s\) and salt concentration \(X_f\) is introduced into the tube side of the condenser, where its temperature increases to \(T_f\). The cooling water \(M_c\) is dumped back into the sea. The function of circulating the cooling water in the condenser is to remove the excess heat added to the system at a relatively high pressure and temperature in the form of the motive steam needed to drive the steam jet ejector. It is important to emphasize that the evaporator does not consume much of the supplied heat, it simply degrades it. Heating of the feed sea water \(M_f\) in the condenser from \(T_s\) to \(T_f\) is essential if the thermal performance of the process is to be increased. The heat needed to warm the sea water inside the condenser is supplied by condensing a controlled portion of the vapour formed by boiling in the evaporator \(M_h\). The vapour condensation temperature, and consequently the pressure in the vapour space for both the evaporator and the condenser, are controlled by the cooling water flow rate \(M_c\), the feedwater temperature \(T_f\), the available heat transfer area in the condenser \(A_c\), and the overall heat transfer coefficient between the condensing vapour and the circulating sea water \(U_c\). This means that the condenser has three functions: (1) to remove the extra heat from the system; (2) to improve the process thermal efficiency; and (3) to adjust the boiling temperature inside the evaporator.

The feed sea water \(M_f\) is chemically treated and de-aerated before being pumped to the evaporator. Chemical treatment is needed to reduce foaming and the tendency to form scale. Operation of the evaporator may be seriously impaired by scale and/or foam formation. Within the evaporator, the feedwater at \(T_f\) is sprayed at the top, from where it falls (in the form of a thin film) on to the succeeding rows of tubes arranged horizontally. The feedwater temperature is raised from \(T_f\) to the boiling temperature \(T_1\). The magnitude of \(T_1\) is dictated by the nature of the chemicals used to control scale formation and the state of the heating steam. This temperature is mastered through settling the pressure in the vapour space of the evaporator. The vapour formed by boiling at a rate of \(D\) is free of salts. The temperature of the generated vapour \(T_v\) is less than the boiling temperature \(T_1\) by the boiling point elevation (BPE). The vapour generated therein flows through a knitted wire mist separator, known as a wire mesh demister, to remove the entrained brine droplets. The vapour should be completely freed from these brine droplets to prevent contamination of both the product water and the heat transfer surfaces on which it condenses. Also,
the presence of entrained water droplets will erode the nozzles and diffusers in the steam jet ejector. The saturation temperature of the vapour leaving the demister is lower than $T_v$ because of the temperature depression resulting from frictional pressure loss in the demister. Vapour flows from the demister to the condenser, where it splits into two portions: the first, $M_{hh}$, condenses outside the condenser tubes, while the rest is entrained by the steam jet ejector. Although the two streams are drawn separately in the flow diagram, in the actual process they flow from the evaporator to the condenser along the same pipeline. The non-condensable gases accumulated in the vapour space of the condenser must be vented to avoid downgrading of the heat transfer capacity of the condenser. The blanket of non-condensables masks some of the heat transfer area from the condensing operation. If the condenser operates at a pressure that is less than the atmosphere, a pumping device, such as an ejector, is needed to pump the vent gases out of the system.

Figure 2 provides a schematic diagram of the steam jet thermocompressor or steam booster with its corresponding state points and the variations in both the velocity and the pressure for the motive and entrained vapour through the ejector; it also presents the process on an entropy-entropy ($S$-$S$) diagram. The ejector is used to increase the pressure of the entrained vapour $M_e$ from pressure $P_7$ to a relatively higher pressure $P_6$. This process takes place by converting the pressure energy of the motive steam $M_s$ to generate a vacuum and to compress the entrained vapour to the required pressure. As the motive steam (at a flow rate of $M_s$) expands in the nozzle from points 1 to 3, its static pressure energy is converted to kinetic energy. The nozzle is of a converging/diverging shape in order to expand the steam to velocities that are greater than the speed of sound (supersonic). The suction chamber is used to keep the nozzle properly positioned with respect to the diffuser, and to direct the entrained vapour. The entrained vapour $M_e$ enters the suction chamber at pressure $P_3$, where it mixes with the motive steam at point 4; the mixing process is violent and rapid. The two streams mix as they pass through the converging section of the Venturi diffuser (from points 4 to 5). The mixture enters the throat section of the diffuser, completely mixed, at the sonic velocity of the mixture. The combined mixed stream is self-compressed through the diverging section of the Venturi diffuser, where the cross-sectional area increases and the velocity decreases, converting the kinetic energy of the mixture to static pressure energy. The mixture leaves the ejector at pressure $P_6$, which is intermediate to the motive ($P_1$) and suction ($P_7$) pressures.

The steam jet ejector must be designed and operated under critical conditions to ensure normal, stable operating conditions. A stable condition is defined as the absence of violent fluctuations in the suction pressure. If the ejector is designed to operate within a fully stable range, the entrained vapour will have a constant mass flow rate for different discharge pressures when the upstream conditions remain constant. The ejector is critical when the compression ratio is greater than or equal to the critical pressure ratio of the suction vapour; for water vapour, this ratio is 1.81, which
FIG. 2. Processes in the steam jet ejector.
means that the suction pressure must be less than 0.55 times that of the discharge pressure to obtain critical or stable conditions in the steam jet ejector.

3. SYSTEM ANALYSIS

The main data usually required from analysis of the TVC desalination system are the amount of motive steam required per unit mass of fresh water or the thermal performance ratio, PR, the necessary specific heat transfer surface area $A_s$ and the amount of cooling water flowing to the condenser $M_c$. Analysis of the TVC system is based on developing a steady state mass and heat balances coupled with the heat transfer rate equations for both the evaporator and the condenser, and then co-joining them with the ratio between the mass of feed and the mass of product water.

The dry saturated steam flowing from the steam jet ejector and admitted into the evaporator $(M_s + M_e)$ is used to raise the temperature of the feed sea water $M_f$ from the inlet temperature $T_f$ to the boiling temperature $T_1$, and to supply the latent heat required to evaporate the specified mass of vapour $D$:

$$\frac{(M_s + M_e)}{\lambda_2} = M_f C_p (T_1 - T_f) + D \lambda_1 = Q_e \tag{1}$$

where $Q_e$ is the thermal load of the evaporator, $C_p$ is the specific heat at constant pressure of the evaporative brine and $\lambda$ is the latent heat of evaporation. Specific heat depends on the water temperature and the salinity, while latent heat relies on the boiling temperature only. The following relationship is used to calculate $C_p$ and $\lambda$ [5]:

$$C_p = [A + BT + CT^2 + DT^3] \times 10^{-3} \tag{2}$$

and

$$\lambda = 2589.583 + 0.9156 T - 4.8343 \times 10^{-2} T^2 \tag{3}$$

where $T$ is the saturation temperature (°C) and $A$, $B$, $C$ and $D$ are variables and functions of the water salinity, $S$ (g/kg), as follows:

$$A = 4206.8 - 6.6197 S + 1.2288 \times 10^{-2} S^2$$

$$B = -1.1262 + 5.4178 \times 10^{-2} S - 2.2719 \times 10^{-4} S^2$$

$$C = 1.2026 \times 10^{-2} - 5.3566 \times 10^{-4} S + 1.8906 \times 10^{-6} S^2$$

$$D = 6.8777 \times 10^{-7} + 1.517 \times 10^{-6} S - 4.4268 \times 10^{-9} S^2$$
The generated vapour will be at a saturation temperature \( T_v \), corresponding to the pressure in the evaporator vapour space. This temperature is less than the boiling temperature \( T_b \) by BPE. Thus:

\[
T_b = T_v + BPE \tag{4}
\]

The BPE, at a given pressure, is the increase in the boiling temperature due to the salts dissolved in the water. The BPE of sea water cannot be evaluated from any known law. It is usually calculated from the following empirical formula for the ranges of 20 000 \( \leq X \leq 160 000 \) ppm, 20 \( \leq T \leq 180^\circ C \):

\[
BPE = X (B + CX) \times 10^{-3} \tag{5}
\]

where \( B = (6.71 + 6.34 \times 10^{-2} T + 9.74 \times 10^{-5} T^2) \times 10^{-3} \), and \( C = (22.238 + 9.59 \times 10^{-3} T + 9.42 \times 10^{-5} T^2) \times 10^{-8} \). The dimensions of the required heat transfer surface area in the evaporator \( A_e \) are obtained from the amount of the heat to be transferred, \( Q_e \), the overall heat transfer coefficient, \( U_e \), and the difference between the condensation temperature of the steam, \( T_2 \), and the boiling temperature of the sea water, \( T_b \), that is:

\[
A_e = \frac{Q_e}{U_e (T_2 - T_b)} \tag{6}
\]

The heating surface area of the evaporators \( A_e \) is usually, but not always, taken as the area that is in contact with the boiling liquid, whether on the inside or on the outside of the tubes. The most critical step is settlement of the overall heat transfer coefficient, \( U_e \). The overall heat transfer coefficient, based on the outside surface area, \( U_{eo} \), is related to the individual thermal resistances by the following expression:

\[
\frac{1}{U_{eo}} = \frac{1}{h} \frac{r_o}{r_i} + \frac{r_o}{r_i} R_f + \frac{r_o \ln(r_o/r_i)}{k_w} + R_f + \frac{1}{h_o} \tag{7}
\]

where \( h \) is the heat transfer coefficient, \( R_f \) is the fouling resistance, \( k_w \) is the thermal conductivity of the tube material and \( r \) is the radius. Subscripts \( i \) and \( o \) refer to the inner and outer tube surfaces, respectively.

Han and Fletcher [6] developed the following experimental correlation to calculate the boiling heat transfer coefficient, \( h_o \), for thin water film flowing over the outside of the smooth horizontal tubes:

\[
h_o \left( \frac{\mu^2}{\rho^2 g k^3} \right)^{1/3} = 0.0004 Re^{0.2} Pr^{0.65} (q^*)^{0.4} \tag{8}
\]
The ranges in the variables for this relationship are: 770 \( \leq \) Re \( \leq \) 7000, 1.3 \( \leq \) Pr \( \leq \) 3.6, 30 \( \leq \) q" \( \leq \) 80 kW/m\(^2\) and 49 \( \leq \) T\(_i\) \( \leq \) 127°C. The maximum deviation in this equation is \( \pm \) 10%. In the above equation, Re and Pr are Reynolds and Prandtl numbers, respectively, q" is the heat flux, \( \mu \) is the viscosity, \( \rho \) is the density and \( k \) is the thermal conductivity of the fluid.

There are a wealth of correlations in the literature that can be used to calculate the heat transfer coefficient of condensation inside the horizontal tube for a particular flow pattern. However, correlations that can be used for all flow patterns are limited. Perhaps the most verified predictive general technique available for all the flow regimes in the horizontal tubes is the following correlation of Shah [7]:

\[
h_i/h_f = 1 + 3.8/Z^{0.95}
\]  
(9)

The parameter \( Z \) is defined as:

\[
Z = \left( \frac{1}{X} - 1 \right)^{0.8} \text{Pr}^{0.4}
\]  
(10)

where \( X \) is the vapour mass fraction ratio. The local superficial heat transfer coefficient \( h_f \) is calculated as:

\[
h_f = h_e (1 - X)^{0.8}
\]  
(11)

where \( h_e \) is the heat transfer coefficient, assuming all mass to be flowing as liquid, and is calculated by the well known Dittus–Bolter equation:

\[
h_e = 0.023(\text{Re})^{0.8} (\text{Pr})^{0.4} \left( \frac{k}{d_i} \right)
\]  
(12)

The ranges of data over Eq. (9) were verified by Shah: 2.8 \( \leq \) d\(_i\) \( \leq \) 40, 21 \( \leq \) T\(_v\) \( \leq \) 355, 0 \( \leq \) X \( \leq \) 100, 0.158 \( \leq \) q \( \leq \) 16 000 kW/m\(^2\), 11 \( \leq \) G \( \leq \) 4000 kg·m\(^{-2}\)·s\(^{-1}\), 0.7 \( \leq \) P \( \leq \) 1 bar, 0.0019 \( \leq \) Pr \( \leq \) 0.82, 350 \( \leq \) Re \( \leq \) 100 000. The average heat transfer coefficient is obtained by linear interpolation between the values of the local heat transfer coefficient \( h_i \) at \( X = 0.01 \) and 0.99.

The condensation heat transfer coefficient will not be significantly impaired by the presence of non-condensable gases during the condensation process if the evaporators are correctly vented. Continuous withdrawal of gases prevents their accumulation and minimizes their effect on the heat transfer coefficient, usually less than a 5% decrease in \( h_i \) at 10% gases in the vents [8]. A simple means of allowing for the effects of non-condensables on the heat transfer coefficient has been proposed by Standiford [8], who treats them as a fouling factor, with a
magnitude \( m_2 = K \cdot W_1 \) equal to 0.000065 times the volume per cent of the gases. In water desalination plants, the volumetric concentration of non-condensable gases is about 4% [9].

The condensation temperature of the vapour outside the tube bundle of the condenser \( T_c \) is less than the boiling temperature in the evaporator \( T_j \) by BPE, and the saturation temperature depressions associate with the pressure loss during the vapour flow in the demister (\( \Delta T_d \)) and the vapour condensation inside the horizontal tubes (\( \Delta T_c \)). Thus:

\[
T_c = T_j - (BPE + \Delta T_d + \Delta T_c) \quad (13)
\]

In general, the pressure drop during the vapour flow through a wire mesh pad, which is widely used as the mist eliminator in the water desalination industry, is relatively small because of the high void fraction of these pads. Losses in mist separator are about 10 cm of water for 0.15 m of thick knitted mesh. El-Dessouky et al. [10] developed the following correlation to predict the wet pressure drop (\( \Delta P \) in Pa) associated with the vapour flow in a wire mesh mist eliminator. The ranges in variables used in the experiments were \( 1 \leq V \leq 9 \text{ m/s} \), \( 310 \leq \rho_p \leq 470 \text{ kg/m}^3 \) and \( 100 \leq L_p \leq 200 \text{ mm} \); the diameter of the wire used was 0.28 mm. All the measurement results lie in a range when (in practice) the wire mesh mist eliminator predominates, especially in water desalination plants:

\[
\Delta P = 9.583 \times 10^4 \left( \rho_p \right)^{1.597} \left( V \right)^{0.7107} \left( L_p \right)^{1.388} \quad (14)
\]

The pressure drop during the vapour condensation inside the evaporator tubes is the sum of the frictional (\( \Delta P_f \)), gravitational (\( \Delta P_g \)) and accelerational (\( \Delta P_a \)) components, that is:

\[
\Delta P_c = \Delta P_f - (\Delta P_g + \Delta P_a) \quad (15)
\]

The two terms on the right hand side of Eq. (15) have opposite signs. The first gives a drop in pressure due to wall friction, while the second gives a rise in pressure because of the pressure recovery from flow deceleration and gravitational force. For condensation inside the horizontal tubes, the gravitational component of the pressure drop \( \Delta P_g \) is equal to zero. However, it is usual to design the evaporator in desalination plants with a small angle of inclination such that the condensate tends to run out from the end of the tubes at the opposite end to the steam inlet. This makes the flow much more stable than if the tubes were horizontal; it also improves the efficiency of the venting system [11]. This component of pressure drop is estimated from the expression:
\[ \Delta P_g = (\rho_v \nu \alpha + (1 - \alpha) \rho_t) gZ \sin \theta \]  
\hspace{1cm} (16)

where \( \alpha \) is the vapour phase void fraction, \( Z \) is the pipe length and \( \theta \) is the inclination angle.

There are many correlations for the void fraction \( \alpha \). The one most frequently suggested in the literature for condensation in the tube is by Zivi [12]:

\[ \alpha = \frac{1}{\left[ 1 + \frac{1 - X}{X} \left( \frac{\rho_v}{\rho_t} \right)^{0.5} \right]} \]  
\hspace{1cm} (17)

The accelerational pressure drop is calculated from the formula:

\[ \Delta P_a = \frac{m^2}{\rho_t} \left\{ \frac{X_1^2}{\alpha_1 \rho_{v_1}} + \frac{(1 - X_1)^2}{(1 - \alpha_1) \rho_t} - \frac{X_2^3}{\alpha_2 \rho_{v_2}} - \frac{(1 - X_2)^2}{(1 - \alpha_2) \rho_t} \right\} \]  
\hspace{1cm} (18)

Subscripts 1 and 2 refer to the inlet and outlet conditions, respectively. The pressure loss due to friction \( \frac{dP_f}{dZ} \) is generally expressed as a function of the corresponding single phase pressure loss \( \frac{dP_f}{dZ} \), making use of a multiplying coefficient \( \phi_F^2 \). This is defined as the number that must be multiplied by the corresponding loss of flow with the same mass flow rate, considered in a saturated single phase condition, in order to obtain a two phase pressure drop. Thus:

\[ \phi_F^2 = \frac{\left( \frac{dP_f}{dZ} \right)}{\left( \frac{dP_f}{dZ} \right)_t} \]  
\hspace{1cm} (19)

Friedel [13] developed the following correlation for calculating \( \phi_F^2 \):

\[ \phi_F^2 = E + \frac{3.24 FH}{Fr^{0.045} \hat{W}_{28}^{0.035}} \]  
\hspace{1cm} (20)

where

\[ E = (1 - X)^2 + X^2 \left[ \frac{\rho_f f_{\rho}^2}{\rho_v f_t} \right] \]  
\hspace{1cm} (21)

\[ F = X^{0.78} (1 - X)^{0.24} \]  
\hspace{1cm} (22)
\[ H = \left( \frac{\rho_f}{\rho_v} \right)^{0.91} \left( \frac{\mu_v}{\mu_f} \right)^{0.19} \left[ 1 - \frac{\mu_v}{\mu_f} \right]^{0.7} \]  
(23)

\[ \text{Fr} = \frac{m^2}{g d \rho_{TP}^2} \]  
(24)

\[ \text{We} = \frac{m^2 d}{\sigma \rho_{TP}^2} \]  
(25)

where \( m \) is the mass flux, \( \mu \) is the dynamic viscosity and \( \sigma \) is the surface tension. The density of the two phase mixture \( \rho_{TP} \) is defined as:

\[ \rho_{TP} = \left[ \frac{X}{\rho_v} + \frac{(1-X)}{\rho_f} \right]^{-1} \]  
(26)

Hewitt [14] recommended use of the Friedel equation when the value of \( (\mu_f/\mu_v) \) is less than 1000. In the TVC desalination process, this ratio ranges from 65.12 at \( T_1 = 315 \text{ K} \) to 19.856 at \( T_1 = 385 \text{ K} \). The frictional pressure drop is usually calculated in a step-wise manner. The tube is divided into a number of short lengths, \( \Delta Z \), over which the conditions change only moderately.

Assuming that the condensation process takes place only inside the tubes, we have:

\[ \Delta P_g = (\rho_f - \rho_v) g Z \sin \phi \]  
(27)

and

\[ \Delta P_a = m^2 \left[ \frac{\rho_f - \rho_v}{\rho_f \rho_v} \right] \]  
(28)

On the other hand, the pressure drop due to the vapour flow over the condenser tubes, during the vapour condensation process in the condenser, can be calculated, at best, only roughly because of the changes in velocity and flow pattern during the condensation process [15]. This overall pressure drop is the algebraic sum of pressure losses due to two phase friction loss and momentum change. The static head and baffle losses are insignificant in the condensers. The momentum change or flow deceleration during condensation results in pressure recovery [16]. The magnitude of this pressure recovery is high in vacuum operation. The pressure regain can approach or exceed the friction loss [17]. Since the condenser operates at vacuum,
it seems reasonable to assume that the pressure recovery due to the slow down in flow can compensate for the friction pressure drop component; therefore, the net pressure fall, and consequently the saturation temperature depression in the condensation process, can be neglected.

Heat transfer between the condensing vapour and the feedwater in the condenser can be written in terms of an overall heat transfer coefficient \( U_c \), the condenser heat transfer area \( A_c \) and the logarithmic mean temperature difference (LMTD), thus:

\[
Q_c = M_f C_p (T_f - T_s) = \eta M_h \lambda c = U_c A_c (\text{LMTD})_c
\]

The (LMTD)\(_c\) is defined as:

\[
(\text{LMTD})_c = \frac{T_f - T_c}{\ln \left( \frac{T_c}{T_f} \right)}
\]

Combining Eqs (29) and (30) produces:

\[
\frac{T_c - T_f}{T_c - T_s} = \exp \left( \frac{U_c A_c}{(M_f + M_c) C_p} \right) = \exp (\text{NTU}_c)
\]

where \( \text{NTU}_c \) is the number of transfer units. The above equation can be solved for the outlet temperature of feedwater to give:

\[
T_f = T_c - (T_c - T_s) \exp (-\text{NTU}_c)
\]

The term \((T_c - T_f)\) is the condenser terminal temperature difference (TTD), and its value has a strong impact on the condenser heat transfer surface area.

Equation (7) can be used to relate the overall heat transfer coefficient \( U_c \) to the individual coefficients. The inside tube heat transfer coefficient \( h_i \) is calculated from the following empirical formula developed by Wangnick [18] especially for desalination plants:

\[
h_i = \left[ 3293.5 + T_f (84.24 - 0.1714 T_f) - X_f (8.471 + 0.1161 X_f + 0.2716 T_f) \right] \\
\left\{ (d_i / 0.17272)^0.2 \left( 0.656 V \right) ^0.8 \left( \frac{d_i}{d_o} \right) \right\}
\]

(33)
where $X_f$ is the salt concentration in ppm, $T_f$ is the film temperature and $d_i$ and $d_o$ are the inside and outside tube diameters, respectively. Additionally, Hennig et al. [19] obtained this equation to calculate the heat transfer coefficient during vapour condensation outside the tubes:

$$h_0 = 0.725 \frac{(k_f \rho_f (\rho_f - \rho_v) g \lambda_v)}{(d_o \mu \Delta T)^{0.25}} C_1 C_2 \quad (34)$$

The correction factors $C_1$ and $C_2$ consider the influence of the dripping down of condensate and the presence of non-condensable gases, respectively, when they constitute less than 4% by weight, on the condensation heat transfer coefficient. The coefficients $C_1$ and $C_2$ are given by the following equations [20]:

$$C_1 = 1.23795 + 0.353808N_f - 0.0017035N_f^2 \quad (35)$$

$$C_2 = 1 - 34.313X_{nc} + 1226.8X_{nc}^2 - 14923X_{nc}^3 \quad (36)$$

where $X_{nc}$ is the percentage weight of the non-condensable gases and $N_f$ is the number of tube rows in the vertical direction inside the condenser. The value of $N_f$ depends on the total number of tubes $N_t$, the tube arrangements, the pitches $P_t$, the number of tube passes and the nozzle diameter. It is customary practice to arrange the tubes in the condensers in a square pitch pattern to provide adequate mechanical cleaning for the outer surface of the tubes. In this arrangement, four tubes occupy an area of $4P_t^2$ and the number of tubes in the vertical direction is two. Thus, the total number of tubes that can be installed in a shell of diameter $D_s$ and with a pitch of $P_t$ can be approximated by the equation [21]:

$$N_t = \frac{\pi D_s^2}{4P_t} \quad (37)$$

The number of tubes in the vertical direction $N_f$ is related to the shell diameter and pitch by the relation:

$$N_f = \frac{D_s}{\sqrt{2}P_t} = 0.564 \sqrt{N_t} \quad (38)$$

For tubes arranged in an equilateral triangular pitch, the following equation can be used:

$$N_f = 0.481(N_f)^{0.505} \quad (39)$$

The total number of tubes in the feed heater is calculated from the relationship:
\[ N_t = \frac{(M_f + M_c)(T_f - T_s)}{U_c \pi d_o L (LMTD)_c} = \frac{4(M_f + M_c)}{\pi d_o^2 \rho_f V} \]  

where \( L \) is the tube length and \( V \) is the feedwater velocity. The value of \( V \) is limited at the top end by erosion damage to the tube materials and excessive pumping costs, and at the bottom end by higher fouling rates and the need to maintain high side heat transfer coefficients. It ranges, in thermal desalination units, between 1.3 and 2.2 m/s.

The most important and critical step in modelling the TVC desalination system is evaluation of the performance of the steam jet ejector. The main data required from analysing the steam jet ejector are determination of the mass of motive steam required per unit mass of entrained vapour (\( R_a \)), given the pressure of the motive steam (\( P_j \)), the discharge pressure (\( P_6 \)) and the suction pressure (\( P_7 \)). There are a limited number of methods available in the literature to analyse the steam jet ejectors. However, these methods require tedious and lengthy calculation procedures. In addition, most are based on using many correction factors, which depend heavily on the detailed design of the ejector. The technique developed in this paper has been established according to the data and method presented by Power [22], who found that none of the available methods was superior to his simple technique. The method is most accurate for motive steam pressures above 5.1 bar and low compression ratios associated with (\( R_a \)) values of less than 4. The curves used in the calculations represent smoothed data from several sources, and agree with the manufacturer's data within about 10% over the best fit range. We have developed the following relationships to evaluate the steam jet ejector performance:

\[ R_a = 0.296 \left( \frac{P_6}{P_7} \right)^{1.19} \left( \frac{P_j}{P_7} \right)^{0.015} \left( \frac{PCF}{TCF} \right) \]  

where \( R_a \) is the entrainment ratio, defined as the mass of motive steam per unit mass of entrained vapour, \( P_j, P_6 \) and \( P_7 \) are the pressures of the motive steam, discharge mixture and entrained vapour, respectively, \( PCF \) is the motive steam pressure correction factor and \( TCF \) is the entrained vapour temperature correction factor. Two equations are developed to calculate \( PCF \) and \( TCF \):

\[ PCF = 3 \times 10^{-7} (P_j)^2 - 0.0009 (P_j) + 1.6101 \]  

\[ TCF = 2 \times 10^{-8} (T_s)^2 - 0.0006 (T_s) + 1.0047 \]

with \( P_j \) in kPa and \( T_s \) in °C. The previous equations are only valid for an ejector operating with steam as the motive fluid and with water vapour as the entrained gas. These equations are valid in the following ranges: \( R_a \leq 4, 500 \geq T_s > 10, 3500 \geq P_j \geq 100 \) and...
These spectra cover the most widely used ranges in TVC desalination systems.

It is interesting to know that thermodynamic losses, such as BPE and temperature depression corresponding to pressure drops in the demister, increase the energy demand for the jet ejector. This is because the vapour must be compressed, not simply through the drop in working temperature \( (T_2 - T_1) \), but also through the drop in working temperature plus the thermodynamic losses \( (P_2 - [T_1 - (BPE + \Delta T_d)]) \).

The overall mass and salt balances, assuming that the produced water is free of salts, yield:

\[
M_f = M_d + M_b
\]

\[
\frac{M_d}{M_b} = \frac{X_b - X_f}{X_b}
\]

On the other hand, the plant thermal performance (PR), the specific heat transfer area \( (A_s) \) and the specific cooling water flow rate \( (S_{MC}) \) are defined as follows:

\[
PR = \frac{M_h + M_e}{M_s}
\]

\[
A_s = \frac{A_e + A_c}{M_h + M_e}
\]

and

\[
S_{MC} = \frac{M_c}{M_h + M_e}
\]

4. RESULTS

To demonstrate application of the mathematical model developed in the preceding sections, we have developed parametric relationships between the different design and operating variables. The parameters that control the cost of water produced in the single effect TVC desalination unit are the plant thermal performance (PR) or the steam economy, the specific heat transfer area \( (A_s) \) and the specific flow rate of the cooling water \( (S_{MC}) \). These variables were calculated as a function of the most important operating parameters, e.g. the boiling temperature \( (T_1) \), the vapour compression ratio \( (C_v) \) and the motive steam pressure \( (P_1) \). The assumptions used in generating the figures are: sea water temperature, \( T_s = 25^\circ C \); feedwater temperature, \( T_f = T_1 - 5^\circ C \); sea water salinity, \( X_s = 42 \ 000 \ ppm \); salinity of the rejected brine,
$X_b = 70\,000\text{ ppm}$; the sum of the fouling factors, $(R_f + R_{fo}) = 0.00035\text{ m}^2\text{K-W}^{-1}$; the thickness of the demister pad, $L_p = 100\text{ mm}$; the outside diameter of all the heat transfer tubes ($d_o$) = 19.75 mm, with a thickness of 6 mm and made of 70/30 Cu/Ni alloy; the sea water velocity inside the condenser tube, $V = 1.8\text{ m/s}$; and the thermal efficiency of the condenser, $\eta = 90\%$.

Figure 3 shows that the overall heat transfer coefficients in both the evaporator ($V_e$) and the condenser ($V_c$) are augmented by the boiling temperature. It also shows that the overall heat transfer coefficient in the evaporator ($V_e$) is always higher than that of the condenser ($V_c$) for a given boiling temperature. Figures 4–6 show that unit thermal performance (PR) diminishes with the increase in boiling temperature ($T_1$) and the vapour compression ratio ($C_r$). However, the thermal performance ratio rises with the pressure of the motive steam ($P_j$). The specific heat transfer surface area ($A_s$) decreases with the increase in the boiling temperature and the vapour compression ratio, and with the decrease in the motive steam pressure, as shown in Figs. 7–9. Figures 10–12 depict the dependence of the specific cooling water flow rate ($SM_c$) on the boiling temperature, vapour compression ratio and the motive steam pressure, respectively. The specific flow rate of the cooling water lessens with the increase in the boiling temperature and the vapour compression ratio. On the other hand, the specific flow rate of the cooling water decreases as motive steam pressure increases.
FIG. 4. Effect of the boiling temperature on the plant thermal performance ratio.

FIG. 5. Effect of the vapour compression ratio on the plant thermal performance ratio.
FIG. 6. Effect of the motive steam pressure on the plant thermal performance ratio.

FIG. 7. Effect of the boiling temperature on the specific heat transfer surface area.
FIG. 8. Effect of the vapour compression ratio on the specific heat transfer surface area.

FIG. 9. Effect of the motive steam pressure on the specific heat transfer surface area.
FIG. 10. Effect of the boiling temperature on the specific cooling water flow rate.

FIG. 11. Effect of the vapour compression ratio on the specific cooling water flow rate.
It is important to note that the effects of the boiling temperature and the compression ratio on the performance ratio, the specific heat transfer area and the specific flow rate of the cooling water are more pronounced than the effects of the motive steam pressure on the same variables.

5. CONCLUSIONS

The present study introduces an efficient theoretical model to analyse a single effect TVC desalination unit. Detailed results are presented to show the dependence of the factors that control the fresh water cost, which are the thermal performance ratio, the specific heat transfer area and the specific cooling water flow rate, on most design and operating variables. These variables are the brine boiling temperature, the vapour compression ratio and the motive steam pressure. The data obtained show that the unit thermal performance ratio diminishes with the increase in the boiling temperature and the vapour compression ratio, and with the decrease in the motive steam pressure. The specific heat transfer surface area decreases with the increase in the boiling temperature and the compression ratio, and with the decrease in the motive steam pressure. The specific flow rate of the cooling water lessens with the increase in the boiling temperature and the vapour compression ratio. On the other hand, the
specific flow rate of the cooling water decreases as the motive steam pressure rises. Moreover, the data show that the heat transfer coefficients in the evaporator and the condenser are augmented by the boiling temperature.

REFERENCES


OPERATION AND PERFORMANCE OF REVERSE OSMOSIS MODULES IN LARGE SEA WATER DESALINATION PLANTS

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Abstract

OPERATION AND PERFORMANCE OF REVERSE OSMOSIS MODULES IN LARGE SEA WATER DESALINATION PLANTS.

Reverse osmosis (RO) processes, with advantages such as low energy and space requirements, have been adopted in the water purification system of the power generation industry. High quality boiler feedwater is increasingly in demand for power plants. Toyobo double element RO modules have been used in the sea water desalination plants installed in two nuclear power plants and in operation for more than 5 years. This RO module consists of a cellulose triacetate hollow fibre membrane, therefore it has several merits such as high salt rejection, chlorine tolerance and resistance to organic fouling. The operating data obtained from these sea water desalination plants demonstrate that RO performance (e.g. productivity and salt rejection) has been stable and met plant specifications for a long period of time. The RO performance monitoring system has been utilized effectively to minimize the annual replacement ratio of RO elements. Double element RO modules are also widely used in large sea water desalination plants in the Middle East because of the advantages they offer, such as high salt rejection and ease of operation and maintenance.

1. INTRODUCTION

Use of sea water desalination technology increased rapidly in the Middle East and the United States of America in the 1970s. The total capacity of the sea water and brackish water desalination plants installed or contracted by 1995 was 20 million m$^3$/d. The RO process proportion increased to 7.3 million m$^3$/d (36%) [1]. Because this process does not involve energy intensive phase changes, it can reduce energy requirements.

Development of RO membranes and modules for sea water desalination, with merits such as long term durability under high pressure, high salt rejection (more than 99.6%) and resistance to biological fouling, has resulted in the successful use of the
The RO process in large sea water desalination plants over the past decade. Toyobo hollow fibre RO modules have been adopted in large sea water desalination plants (with a total capacity of 276,000 m$^3$/d), including the Medina–Yanbu plant (128,000 m$^3$/d) under construction in Saudi Arabia.

2. THE HOLLOW FIBRE RO MODULE

Four membrane configurations are commercially available: spiral wound, hollow fibre, tubular, and plate and frame. The spiral wound and hollow fibre configurations are widely used for sea water desalination. Of these, the hollow fibre configuration allows a larger membrane surface area per module. The membrane material of the Toyobo hollow fibre RO module is cellulose triacetate (CTA), which is superior to other commercially available membranes in that it shows tolerance to chlorine and resistance to organic fouling because of its hydrophilic properties. The CTA membrane shows a relatively higher salt rejection than commercial cellulose acetate and polyamide membranes.

Toyobo developed double element modules that can reduce hardware costs effectively, and placed them on the market in 1979. The fluid flow patterns of the RO modules were optimized and the series array type was adopted [2]. Two RO elements are installed in a series array in one pressure vessel, as shown in Fig. 1. The RO feedwater flows into the feedwater distribution core of the first element (feed side element) and the water flow expands radially towards the outside of the element. The concentrated brine water of the feed side element flows continuously into the second element (brine side element) from the outside to the inside. Since the Toyobo hollow fibres RO module has relatively large spaces between the hollow fibres because of their cross arrangement, the pressure loss of the brine side element is low.

3. APPLICATION OF RO IN NUCLEAR POWER PLANTS

Two nuclear power plants in Japan (Ohi and Ikata) use the double element module HM9255FI in their boiler feedwater purification processes that operate in
TABLE I. PLANT SPECIFICATIONS

<table>
<thead>
<tr>
<th></th>
<th>Ohi plant</th>
<th>Ikata plant</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>First stage</td>
<td>Second stage</td>
</tr>
<tr>
<td>Capacity</td>
<td>4000 m$^3$/d (at 31°C)</td>
<td>3400 m$^3$/d (at 31°C)</td>
</tr>
<tr>
<td></td>
<td>3250 m$^3$/d (at 10°C)</td>
<td>2600 m$^3$/d (at 10°C)</td>
</tr>
<tr>
<td>Feed pressure</td>
<td>Maximum</td>
<td>Maximum</td>
</tr>
<tr>
<td></td>
<td>65 kg/cm$^2$ (g)</td>
<td>45 kg/cm$^2$ (g)</td>
</tr>
<tr>
<td></td>
<td>(6.4 MPa)</td>
<td>(4.4 MPa)</td>
</tr>
<tr>
<td>Recovery ratio</td>
<td>43% (at 31°C)</td>
<td>85% (at 31°C)</td>
</tr>
<tr>
<td></td>
<td>35% (at 10°C)</td>
<td>80% (at 10°C)</td>
</tr>
<tr>
<td>Feedwater total dissolved solids (TDS)</td>
<td>35 000 mg/L</td>
<td>400 mg/L</td>
</tr>
<tr>
<td>Permeate TDS</td>
<td>400 mg/L</td>
<td>15 mg/L</td>
</tr>
<tr>
<td>Module model</td>
<td>HM9255FI</td>
<td>HM9255FI</td>
</tr>
<tr>
<td>No. of modules</td>
<td>130</td>
<td>60</td>
</tr>
</tbody>
</table>

FIG. 2. Flow sheet of the Ohi plant.
combination with RO and an ion exchanger [3]. The capacities of the sea water desalination plants are 4000 and 2400 m$^3$/d, respectively. Details of the plant specifications are given in Table I.

The flow sheet of the Ohi plant is shown in Fig. 2. Pretreatment of the feedwater is the key process by which the RO membrane maintains a specific performance for a long period of time. The chlorine generated prevents membrane fouling by forming a slime layer. Since the membrane material of the RO module is CTA, which shows resistance to the chlorine disinfectant, it is not necessary to dechlorinate the RO feedwater, therefore the chlorine in the RO feedwater continuously inactivates microorganisms in the RO module. This makes it possible to operate the RO modules in a stable manner, without biological fouling occurring. In-line coagulation, followed by the dual media filter and polishing filter, is used to remove the suspended solids and colloidal materials that also cause membrane fouling. The silt density index (SDI) value of the RO feedwater is controlled so that it does not exceed 4. As shown in Fig. 2, a double pass RO system is adopted to reduce the loading of an ion exchanger in the Ohi plant. Permeate from first stage RO is fed into second stage RO after CO$_2$ stripping to produce pure water of a sufficiently high quality. A single pass RO system, with the same basic flow as that of the Ohi plant, has been adopted in the Ikata plant.

The RO performance monitoring system utilized in these plants controls the quality of the circulating water very strictly. In this system, the water quality of the individual RO elements is measured and analysed automatically. It also makes it possible to determine the RO element to be replaced, and therefore the replacement ratio.

4. OPERATION AND PERFORMANCE OF RO MODULES

The changes in feedwater temperature and pressure of the first stage RO modules in the Ohi plant are shown in Figs 3 and 4, respectively. The feedwater temperature varies from about 10 to 30°C, depending on the season. Because of the changes in feedwater temperature, the feedwater pressure varies, with a limited range of 48 kg/cm$^2$ (4.7 MPa) to 55 kg/cm$^2$ (5.4 MPa), which is somewhat lower than the permissible maximum pressure of 65 kg/cm$^2$ (6.4 MPa). Under these conditions of operation, the permeate flow rates have met plant specifications. Figure 5 shows that the permeate conductivity of each train increased gradually. Considering the low replacement ratio of the RO elements during this operating period, it can be concluded that permeate conductivity changes as predicted, and is controllable.

The annual replacement ratio in the Ohi plant decreased from 25 (plant specification) to 11%, as shown in Table II. This improvement resulted from effective use of the RO performance monitoring system.
The changes in temperature and pressure of the RO feedwater in the Ikata plant are shown in Figs 6 and 7, respectively. The feedwater pressure is reduced from 68 kg/cm² (6.7 MPa) to 53 kg/cm² (5.2 MPa) with the increase in feedwater temperature to control the permeate flux rates. The water quality parameters of RO feedwater, such as the SDI and pH values, are checked routinely. The pH value of RO feedwater is adjusted to 6.5.

As shown in Table II, 40% of the RO elements were replaced during an operating period of about 46 months. The annual replacement ratio is around 10%,
**FIG. 5.** Changes in the permeate conductivity in the Ohi plant.

**TABLE II.** ANNUAL REPLACEMENT RATIO OF THE RO ELEMENTS (%)

<table>
<thead>
<tr>
<th>Years</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ohi plant</td>
<td>0</td>
<td>25</td>
<td>15</td>
<td>15</td>
<td>11</td>
</tr>
<tr>
<td>Ikata plant</td>
<td>0</td>
<td>20</td>
<td>20</td>
<td>0</td>
<td>—</td>
</tr>
</tbody>
</table>

**FIG. 6.** Changes in the feedwater temperature in the Ikata plant.
FIG. 7. Changes in the feedwater pressure in the Ikata plant.

FIG. 8. Changes in the permeate conductivity in the Ikata plant.

TABLE III. PERMEATE QUALITY OF THE JEDDAH PHASE I AND II PLANTS (APRIL 1995) [4]

<table>
<thead>
<tr>
<th></th>
<th>Phase I</th>
<th>Phase II</th>
<th>Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Permeate conductivity ($\mu$S/cm)</td>
<td>538</td>
<td>281</td>
<td></td>
</tr>
<tr>
<td>Permeate chloride (mg/L)</td>
<td>157</td>
<td>82</td>
<td>625</td>
</tr>
<tr>
<td>Startup date</td>
<td>April 1989</td>
<td>March 1994</td>
<td></td>
</tr>
<tr>
<td>Elapsed time (years)</td>
<td>6</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Average annual replacement ratio (%)</td>
<td>16.7</td>
<td>0</td>
<td>10 (phase II)</td>
</tr>
<tr>
<td>Country</td>
<td>Plant</td>
<td>Capacity (m$^3$/d)</td>
<td>Operation year</td>
</tr>
<tr>
<td>-------------------------</td>
<td>----------------</td>
<td>-------------------</td>
<td>----------------</td>
</tr>
<tr>
<td>Saudi Arabia</td>
<td>Medina–Yanbu 2</td>
<td>128 000</td>
<td>1997</td>
</tr>
<tr>
<td>Saudi Arabia</td>
<td>Al Jobail</td>
<td>90 909</td>
<td>1996</td>
</tr>
<tr>
<td>Saudi Arabia</td>
<td>Jeddah</td>
<td>56 800</td>
<td>1988</td>
</tr>
<tr>
<td>Saudi Arabia</td>
<td>Jeddah I</td>
<td>56 800</td>
<td>1994</td>
</tr>
<tr>
<td>Bahrain</td>
<td>Al Dur</td>
<td>45 000</td>
<td>1989</td>
</tr>
<tr>
<td>Spain</td>
<td>Las Palmas 3</td>
<td>36 000</td>
<td>1990</td>
</tr>
<tr>
<td>Malta</td>
<td>Pembroke</td>
<td>27 600</td>
<td>1994</td>
</tr>
<tr>
<td>United States of America</td>
<td>Santa Barbara</td>
<td>26 100</td>
<td>1992</td>
</tr>
<tr>
<td>United States of America</td>
<td>Lompoc</td>
<td>23 360</td>
<td>1993</td>
</tr>
<tr>
<td>Malta</td>
<td>Ghar Lapsi</td>
<td>20 000</td>
<td>1983</td>
</tr>
</tbody>
</table>
which is lower than the specified replacement ratio of 20%. The change in permeate conductivity in the Ikata plant is shown in Fig. 8, confirming that it has met plant specifications for a long period of time.

5. SEA WATER DESALINATION PLANTS IN SAUDI ARABIA

The Toyobo double element RO module HM10255FI has also been adopted in large sea water desalination plants in the Middle East such as the Jeddah phase I and II plants (total capacity of 113 600 m$^3$/d), which have been in operation since April 1989 and March 1994, respectively. Table III describes the plants [4]. RO performances have been stable in both plants, and the water quality has met plant specifications, as shown in Table III. These actual results have won wide recognition, and double element RO modules have been adopted in the world's largest plant, Medina–Yanbu, which will start up in 1997. Table IV shows the capacities and membrane manufacturers of the top ten sea water desalination plants in the world.

6. CONCLUSIONS

The operating data obtained from large sea water desalination plants demonstrate that the Toyobo hollow fibre RO modules, which have many advantages, including high salt rejection and ease of operation and maintenance, have shown excellent RO performance for a long period of time.

Double element RO modules have been widely used in the world and brought significant improvements to the sea water RO desalination processes.

REFERENCES


DESALINATION OF SEA WATER IN THE UKRAINE

Justification and history

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Abstract

DESALINATION OF SEA WATER IN THE UKRAINE: JUSTIFICATION AND HISTORY.

About 46% of the total electric energy in the Ukraine is generated by nuclear power plants. At the same time, development of many regions, particularly those in the southern part of the country, is restricted by the lack of fresh water. To solve this problem, various scientific institutes have been carrying out research on sea water desalination, and the multi-effect distillation process has shown many advantages. The prospects for nuclear desalination in the Ukraine are good.

In 1996, nuclear power plants produced about 46% of the total electric energy of the Ukraine. At present, there are 14 nuclear power plants in operation: (1) 11 plants of the WWER-1000 type at Zaporozhye (six units), South Ukraine (three units), Khmelnitsky (one unit) and Rovno (one unit); (2) two plants of the WWER-440 type at Rovno; and (3) one plant of the RBMK-1000 type at Chernobyl. Unit 1 of the Chernobyl nuclear power plant was shut down in November 1996; the question of decommissioning the entire plant is still under consideration.

After the country became independent in 1991, the Ukrainian Parliament adopted a moratorium on the construction of new nuclear power plants, and the building of WWER-1000 units at Zaporozhye, Rovno and Khmelnitsky was stopped, as well as a new nuclear power plant in the Crimea.

In 1995, the moratorium was cancelled and unit 6 at Zaporozhye was commissioned. This moratorium has caused a considerable delay in the development of the nuclear energy industry in the Ukraine because two WWER-1000 units (one at Rovno and the other at Khmelnitsky, whose construction was halted by the moratorium) are urgently needed as substitutes for the Chernobyl nuclear power plant in the event of it being decommissioned.

The national economic development programmes that have been elaborated since independence did not foresee use of nuclear energy to solve economic problems...
such as the production of fresh water. Various ways of supplying the population, industry and agriculture with fresh water have been implemented over the past 20–30 years:

(1) Creation of natural water reservoirs (artificial seas);
(2) Construction of channels and reservoirs using water from the largest rivers;
(3) Use of purified sewage waters;
(4) Construction of high capacity industrial desalination plants in cities located at the sea, as well as low capacity units for individual users.

Five large reservoirs were constructed on the Dnieper River and a channel now supplies the Crimea Peninsula with this water. However, development of these water supplies has been practically exhausted.

In the former USSR, a sea water desalination plant coupled to a nuclear reactor was constructed in Shevchenko City (now Aktau, Kazakhstan); details are given in another paper in these Proceedings [1].

Various institutes in the Ukraine have been dealing with the problem of sea water desalination: the Kharkov Institute ‘Energoproekt’, the Kiev Institute ‘Energoproekt’ and the Institute of Colloidal and Water Chemistry of the Ukrainian Academy of Science.

Design and engineering as well as technical and economic analyses have shown that sea water desalination is economically viable at large distillation facilities which use the heat produced by nuclear power plants. Distillation–desalination facilities have a number of advantages, e.g. simplicity of design; high productivity; simplicity and high reliability in operation; good quality fresh water; and relatively low water production costs. Coupled with these are the possibility of using the low temperature heat of nuclear power plants and the multi-effect distillation process, including brine reprocessing. The latter process, in which the power plant produces fresh water at the same time as electric and thermal energy, has been shown to be economically viable. However, when designing a desalination plant it is necessary to take into account the fact that during the production of fresh water a considerable amount of high concentration brine is produced.

One of the main problems with distillation facilities is scale formation on the heat transfer surfaces. Many attempts have been made to solve this problem, most of which deal with improving the evaporators, e.g. water heating without boiling; high vacuum evaporation; calculated brine evaporation; use of moving heat surfaces; vibration of the heat transfer surface; maintenance of the brine movement speed; use of special materials for the heat transfer surfaces; use of grained additives and other anti-scale actions; softening of the sea water; and use of thermal methods to clean the moving heat surfaces. Much of this research has been carried out by Ukrainian specialists.
The southern regions of the Ukraine, which are located close to the Black and Azov Seas and the Crimea Peninsula, are rich in natural resources, and have a moderate climate and fertile soils, therefore they are very favourable for the development of industry, agriculture, tourism and recreation. However, such development is restricted by the lack of fresh water.

It has been shown that to produce 1 t of wheat requires 1000 t of fresh water; a nuclear power plant with a capacity of 1200 MW(th) can produce about 1 million tonnes of fresh water per day.

The prospects for sea water desalination using nuclear energy are good in the Ukraine because:

(a) Experience has been accumulated in the nuclear power industry;
(b) Considerable scientific and design bases exist for sea water desalination;
(c) The moratorium on nuclear power plant construction has been cancelled;
(d) Development is necessary in a number of regions where there is a lack of fresh water.

It is hoped that the research, design and development discussed and reviewed at this Symposium will be widely distributed in the Ukraine, so stimulating interest in the development of nuclear desalination.

**REFERENCE**

EXPERIENCE IN DESALINATION USING NUCLEAR, FOSSIL AND OTHER ENERGY SOURCES

(Session 4)

Chairpersons

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China

N.H. Mahmoud
Egypt
EXPERIENCE GAINED IN THE OPERATION AND MAINTENANCE OF THE NUCLEAR DESALINATION PLANT IN AKTAU, KAZAKHSTAN

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Abstract

EXPERIENCE GAINED IN THE OPERATION AND MAINTENANCE OF THE NUCLEAR DESALINATION PLANT IN AKTAU, KAZAKHSTAN.

The main design features of the 250 MW(e), 120,000 m³/d nuclear desalination plant in Aktau, Kazakhstan, are outlined. The experience gained over 20 years of operation and maintenance is discussed, with data presented on the materials used and on corrosion and scale formation. Determination of the water costs, and the impact on the environment and water quality, has confirmed the efficiency and reliability of nuclear desalination.

1. INTRODUCTION

As humanity develops, water supply problems are aggravated by the increasing consumption of water by industrial enterprises and agriculture, resulting in pollution of the surface water and a decrease in the groundwater stocks. Among other solutions, the one with the most perspective is sea water desalination. All known desalination processes need thermal and/or electric power. Because organic fuel is a valuable chemical raw material, much interest has been shown in the use of nuclear energy for producing potable water. A study of existing experience will enable the acceptance of optimum solutions for the design and construction of new desalination plants integrated with nuclear reactors.

2. DESCRIPTION

2.1. Layout

The Mangyshlak Atomic Energy Complex is located on the Mangyshlak Peninsula, which is on the east coast of the Caspian Sea. It is an arid zone, with low
rainfall and a limited stock of groundwater that has a salinity of 3.5–5.8 g/L. To supply water to industrial enterprises and to the population of the growing City of Aktau (formerly Shevchenko), thermal distillation of sea water using heat generated by an FBR was chosen. The complex was constructed on a platform located 12 km from the city, next to industrial enterprises, and a potable water preparation station was built nearer to the town (Fig. 1).

The objectives for constructing the complex at this site were:

1. To minimize heat losses during the transmission of steam to the industrial enterprises;
2. To minimize the water transport costs.

Prevention of population exposure to radioactivity beyond the specified limits for accidents also had to be taken into consideration.

2.2. Construction history

Because water was necessary for the City of Aktau and its developing industries, a desalination unit, with an output of 5000 m³/d, two fossil fired boilers
FIG. 2. General arrangement of the nuclear desalination plant.

and a backpressure turbine were constructed in 1963. In the next phase, a thermal power station and a reactor were built, and distillation units of five effects, with a productivity of 12,000 m$^3$/d each, were attached to three 50 MW turbines with a backpressure of 0.6 MPa; steam was supplied from the nuclear reactor. In the third phase, distillation units of ten effects, with forced circulation and a productivity of 14,500 m$^3$/d, were constructed between 1971 and 1990.

At present, the Mangyshlak Atomic Energy Complex consists of:

1. A gas–oil fuelled thermal power station;
2. A potable water preparation station;
3. A nuclear desalination plant (Fig. 2), which includes a liquid metal FBR; a 100 MW condensation turbine, and three 50 MW backpressure turbines; ten multi-effect distillation (MED) desalination units, with a productivity of 8000–14,500 m$^3$/d each; and a feedwater pretreatment plant for the steam generators.

2.3. Nuclear desalination plant (NDP)

The NDP was constructed several kilometres from the sea. It comprises an intake channel for sea water (about 2 km long) and a brine outfall channel, which
TABLE I. TECHNICAL PARAMETERS OF THE NUCLEAR DESALINATION PLANT

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total thermal power</td>
<td>1000 MW(th)</td>
</tr>
<tr>
<td>Electric power</td>
<td>250 MW(e)</td>
</tr>
<tr>
<td>Total desalination capacity</td>
<td>120,000 m³/d</td>
</tr>
<tr>
<td>Fraction of water transported from the complex</td>
<td>0.89</td>
</tr>
<tr>
<td>Average time availability</td>
<td>0.85</td>
</tr>
</tbody>
</table>

flows into a shallow artificial lake (Kara-Kol) that also has an outlet to the sea (Fig. 1). The intake channel is used to purify the sea water of silt, and the shallow lake performs the function of brine aeration and suspended particle cleanup. A nuclear reactor and a thermal power station were also located on the complex with a view to minimizing the heat losses during transmission of the steam from the nuclear reactor to the turbogenerators, which are installed in the turbine hall of the thermal power station. Because the desalination units are situated rather far from the backpressure turbines, significant losses of heat occur. The technical parameters of the NDP are given in Table I.

2.4. Reactor and desalination plant

The BN-350 is a loop type FBR cooled with liquid sodium. It has six primary loops located in individual air tight rooms and six secondary loops located in two rooms at opposite ends of the reactor vessel [1]. Each loop has a pump and an intermediate Na–Na heat exchanger. The thermal section of the reactor consists of six steam generators with natural circulation. The reactor core is surrounded by a blanket of depleted uranium. Iron ore concentrate, graphite, steel and concrete are used for bioprotection. The negative power and temperature reactivity coefficient provides self-regulation of the reactor. Heat release in the core is stable and redundant reactivity is low. Operation of the reactor is simple. The low pressure of the sodium and the absence of any noticeable corrosion ensure leak tightness of the sodium piping and components. The intermediate sodium circuit acts as a reliable barrier between the radioactive sodium of the primary loop and the water and steam of the thermal section.

The desalination plant includes three distillation–desalination units of five effects, with a boiling zone located above the heat exchange surface, and seven units of ten effects. The evaporated solution circulates naturally in the evaporators of the units of five effects. Each unit of ten effects represents a vertical tube evaporator with an axial circulating pump; the operating period, between acid cleanings, is 6–8 months. The technical data of the distillation–desalination plant are given in Table II.
### TABLE II. TECHNICAL DATA OF THE DISTILLATION-DESALINATION PLANT (ONE UNIT)

#### Technical characteristics

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of effects</td>
<td>10</td>
</tr>
<tr>
<td>Heat exchange area</td>
<td></td>
</tr>
<tr>
<td>Evaporator</td>
<td>1760 m²</td>
</tr>
<tr>
<td>Regenerative preheater</td>
<td>550 m²</td>
</tr>
<tr>
<td>Length of tubes</td>
<td>5 m</td>
</tr>
<tr>
<td>Outer/inner diameter</td>
<td>38/33.5 mm</td>
</tr>
<tr>
<td>Recycled brine in the evaporator</td>
<td>18 000 t/h</td>
</tr>
</tbody>
</table>

#### Distillate

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Daily production</td>
<td>145 000 t/d</td>
</tr>
<tr>
<td>Temperature</td>
<td>30°C</td>
</tr>
<tr>
<td>Maximum salinity (total dissolved solids)</td>
<td>200 mg/L</td>
</tr>
<tr>
<td>Performance ratio</td>
<td>8.4 kg/kg</td>
</tr>
</tbody>
</table>

#### Sea water

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total flow</td>
<td>1500–4500 t/h</td>
</tr>
<tr>
<td>Required pressure (absolute)</td>
<td>0.3 MPa</td>
</tr>
<tr>
<td>Concentration ratio</td>
<td>3.3</td>
</tr>
<tr>
<td>Maximum brine temperature</td>
<td>105°C</td>
</tr>
</tbody>
</table>

#### Steam to evaporator

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure (absolute)</td>
<td>0.4 MPa</td>
</tr>
<tr>
<td>Flow</td>
<td>67.8 t/h</td>
</tr>
<tr>
<td>Specific consumption of heat</td>
<td>295 kJ/kg</td>
</tr>
<tr>
<td></td>
<td>(81.4 kW-h/t)</td>
</tr>
<tr>
<td>Condensate salinity</td>
<td>&lt; 2 mg/L</td>
</tr>
</tbody>
</table>

#### Steam to vacuum ejector

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure (absolute)</td>
<td>1.2 MPa</td>
</tr>
<tr>
<td>Flow (approximate)</td>
<td>1.3 t/h</td>
</tr>
</tbody>
</table>

#### Electricity

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Consumption per tonne of distillate</td>
<td>3.9 kW-h/t</td>
</tr>
</tbody>
</table>

### 2.5. Technological data

The plant is based on a nuclear reactor, and one condensation and three back-pressure turbines (Fig. 3). Exhaust steam (0.6 MPa) is used as the heat source in the
heating chambers of the first stage evaporators of the MED desalination plant. Pressure reducing and cooling devices are installed to provide steam to the desalination units during periods of low electric power demand, or in the event of turbine failure. Another set of devices provides steam to the NDP from the fossil fired boilers of the thermal power station when the reactor is shut down or when there is a shortage of steam. To supply daily peaks of water, tanks are provided for the distillate and feedwater of the steam generators and boilers.

The turbogenerators are separate from the reactor building, in the turbine hall of the thermal power station, for ease of maintenance by the staff of the power station. The steam circuit of the reactor is open because part of the steam is used by consumers. The feedwater for the steam generators is prepared from the distillate. The condensate from the desalination plant is cleaned in the feedwater pretreatment plant before being fed back to the steam generators. The distillate is of high quality and only requires some final processing. Compared with conventional technologies, the costs of feedwater pretreatment are several times lower. Regeneration of the ion exchange filters is done twice a year. One disadvantage of the simplified feedwater pretreatment system is that it is not designed to operate with a source water salinity of more than 10–15 mg/L, therefore it is necessary to keep a permanent reserve stock of distillate for times when there is a deterioration in the quality of the source water.
In the event of system failure and disconnection from the regional electric grid, there is an independent source of electric power and water that allows startup of the complex.

2.6. Quality of the product water

The characteristics of the sea water and product water are given in Tables III and IV, respectively. The quality of the product water meets World Health Organization (WHO) requirements, and does not depend on the heat source used, i.e. nuclear or conventional. The amount of radioactive substances in the product water depends on their content in the source water that is added to the distillate to obtain water of drinking quality. Analysis of tritium in the NDP streams has shown that it is at a background level, close to that of sea and groundwaters. In preparing the potable water, measures to reduce the tritium concentration in the distillate can nevertheless be taken. This is done by separating the distillate streams and by using the steam condensate of the reactor stream cycle only for technological needs.

3. OPERATION AND MAINTENANCE

3.1. Reliability of operation

The reactor has been in operation since 1973, with an operating time of more than 100 000 hours. During this period, there were no sodium leaks in the primary and secondary loops, and abnormal operation of the sodium pumps and cavitation in the driving wheels of the pumps were insignificant. In the first period of reactor operation, depressurization of the heat exchange tubes of the steam generators took place repeatedly as a result of poorly manufactured tubes. The steam generators and the feedwater pretreatment system were reconstructed, and the water now has the following parameters:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conductivity</td>
<td>&lt; 40 µS/cm</td>
</tr>
<tr>
<td>pH</td>
<td>9.1 ± 0.2</td>
</tr>
<tr>
<td>Iron</td>
<td>&lt; 10 µg/L</td>
</tr>
<tr>
<td>Copper</td>
<td>&lt; 5 µg/L</td>
</tr>
<tr>
<td>Total hardness</td>
<td>&lt; 33.2 µg/L</td>
</tr>
</tbody>
</table>

In the event of one loop of the thermal section being disconnected, another is maintained in reserve, resulting in more stable operation of this section. Because of the availability of a reserve loop, damage to the exchange tubes does not result in a decrease in the operating power of the reactor. Since the NDP has been in operation,
### TABLE III. SEA WATER CHARACTERISTICS

<table>
<thead>
<tr>
<th>Substance</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calcium</td>
<td>338.6 ± 8.2 mg/L</td>
</tr>
<tr>
<td>Magnesium</td>
<td>772.6 ± 7.8 mg/L</td>
</tr>
<tr>
<td>Sodium</td>
<td>3337.8 ± 29.4 mg/L</td>
</tr>
<tr>
<td>Potassium</td>
<td>84.0 ± 0.7 mg/L</td>
</tr>
<tr>
<td>Chloride</td>
<td>5571.2 ± 59.0 mg/L</td>
</tr>
<tr>
<td>Sulphate</td>
<td>3192.3 ± 23.4 mg/L</td>
</tr>
<tr>
<td>Bicarbonate</td>
<td>213.1 ± 7.1 mg/L</td>
</tr>
<tr>
<td>Total dissolved solids</td>
<td>13 489 ± 99 mg/L</td>
</tr>
</tbody>
</table>
| Seasonal variation in temperature | 2–24°C

### TABLE IV. PRODUCT WATER CHARACTERISTICS

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Distillate G</th>
<th>Distillate A</th>
<th>Potable water</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total dissolved solids (mg/L)</td>
<td>&lt;1000</td>
<td>198.6</td>
<td>389.4</td>
</tr>
<tr>
<td>Temperature (°C)</td>
<td>NG</td>
<td>45</td>
<td>28</td>
</tr>
<tr>
<td>Colour (total colour units) b</td>
<td>15</td>
<td>-</td>
<td>2</td>
</tr>
<tr>
<td>Turbidity (formazin turbidity units) c</td>
<td>5</td>
<td>-</td>
<td>1.7</td>
</tr>
<tr>
<td>Conductivity (mS/cm)</td>
<td>NG</td>
<td>4.05</td>
<td>326.7</td>
</tr>
<tr>
<td>pH</td>
<td>6.5–8.5</td>
<td>8.46</td>
<td>8.07</td>
</tr>
<tr>
<td>Total hardness (CaCO₃) (mg/L)</td>
<td>500</td>
<td>0.78</td>
<td>126.0</td>
</tr>
<tr>
<td>Chloride (mg/L)</td>
<td>250</td>
<td>0.48</td>
<td>138.8</td>
</tr>
<tr>
<td>Sulphate (mg/L)</td>
<td>400</td>
<td>0.31</td>
<td>91.7</td>
</tr>
<tr>
<td>Calcium (mg/L)</td>
<td>NG</td>
<td>0.08</td>
<td>25.2</td>
</tr>
<tr>
<td>Magnesium (mg/L)</td>
<td>NG</td>
<td>0.09</td>
<td>10.0</td>
</tr>
<tr>
<td>Sodium (mg/L)</td>
<td>200</td>
<td>0.18</td>
<td>105.4</td>
</tr>
<tr>
<td>Alumínium (mg/L)</td>
<td>0.3</td>
<td>-</td>
<td>0.1</td>
</tr>
<tr>
<td>Copper (mg/L)</td>
<td>1.0</td>
<td>0.013</td>
<td>0.05</td>
</tr>
<tr>
<td>Iron (mg/L)</td>
<td>0.3</td>
<td>0.033</td>
<td>0.27</td>
</tr>
<tr>
<td>Zinc (mg/L)</td>
<td>5.0</td>
<td>-</td>
<td>0.028</td>
</tr>
<tr>
<td>Fluoride (mg/L)</td>
<td>1.5</td>
<td>-</td>
<td>0.1</td>
</tr>
<tr>
<td>Nitrate (normal) (mg/L)</td>
<td>10.0</td>
<td>-</td>
<td>0.44</td>
</tr>
<tr>
<td>Alpha activity (Bq/L)</td>
<td>0.1</td>
<td>-</td>
<td>0.012</td>
</tr>
<tr>
<td>Beta activity (Bq/L)</td>
<td>1.0</td>
<td>-</td>
<td>0.09</td>
</tr>
</tbody>
</table>

a NG = WHO guideline value set.

b The samples were filtered using No. 1 filter paper, and the absorption intensity of the filtrates was measured spectrophotometrically at 450 nm (TCU). Blanks were measured with de-ionized water of less than 0.2 μS/cm of conductivity.

c Turbidity was measured spectrophotometrically at 450 nm using formazin standards (FTU).
there have been no serious problems with the equipment that produces the electric power and distillate.

Failures in the desalination equipment include corrosion of the pipes, shell parts and heat exchange tubes of the evaporators and preheaters, and erosion and corrosion of the circulating pump blades. However, these have not influenced the reliability of operation of the whole complex; even the shutdown of one of ten units did not lead to a significant decline in water productivity.

3.2. Control

The complex is operated from several control panels located in the nuclear reactor, the thermal power station, the desalination plant and the potable water preparation station. All are connected to the central dispatching console and to each other. A central board regulates consumers’ demands and distributes the load between the reactor, the thermal power station and the desalination plant. Data collection systems are computerized, therefore problems can be solved in time, the reliability of information evaluated and parameter trends observed.

Consumption of water, heat and electric power during the day and in the course of the year is not uniform. As most of the water is required in summer, repairs and acid cleaning of the desalination units are carried out at other times of the year. If the water needed to cover the daily peak loads is insufficient, the reserve tanks can be used. However, such a procedure is not possible for electric power and heat. Therefore, the responsibility assigned to the operating staff of the nuclear reactor and the thermal power station is great, because incorrect operation such as a switch in transient regimes could trigger operation of the emergency protection systems, with a consequent decrease in frequency of the power grid, disconnection of the consumers, or system failure.

The desalination units have large high thermal inertia, therefore sharp variations in the input parameters of the plant do not cause emergency situations. Unit productivity ranges between 70 and 110% of the nominal level. If necessary, some units can be taken out of operation and placed in the hot or cold reserve mode; startup takes between 8 and 24 hours.

Load following is conventional: the reactor operates in the base mode and the power of the thermal station varies. Steam production is regulated by maintaining a pressure of 0.6 MPa in the collector, electric power is controlled by the frequency of the power grid, and the water production depends on the level in the potable water and distillate tanks.

Twice a year, the nuclear reactor is shut down (for about 20 days) for refuelling and scheduled maintenance. During these periods, heat for the desalination plant is supplied by the thermal power station. Such switchings have been carried out regularly for more than 20 years, and no problems have arisen.
3.3. Emergency response systems and operator actions

The emergency protection systems of the NDP are similar to those proved at other reactors and desalination plants. Activation of local protection systems does not have much influence on operation. However, a different situation exists if the high speed reactor shutdown system is activated. In this case, only one steam generator remains in the operating mode for reactor cooling. Steam production decreases from 700 to 0 t/h within a few minutes, therefore to keep the system working it is necessary to increase the load of the fossil fired boilers. It is impossible to offset such a deficit in a short time, therefore some heat and electric power consumers have to be temporarily disconnected.

For decision making that adequately covers any situation that may arise and for harmonization of the work of the operating staff, appropriate instructions have been developed and regular training sessions carried out. Decisions are taken by senior operators on the basis of important basic parameters displayed on the computer monitoring system. Redundant information can be used to assess the reliability of the operating parameters. The main parameters that have an influence on safety analysis are subjected to two or three independent measuring systems.

3.4. Materials and corrosion

The operating behaviour of reactor equipment, made of special steel alloys, has been generally satisfactory. Cu–Ni and stainless steel tubes were used for the tube bundles of the steam generators. Repeated cases of steam generator tube damage have occurred because of their poor durability under high temperature conditions.

The shell parts of the heat exchange equipment of the desalination plant were made of stainless clad steel, consisting of carbon steel and a thin, corrosion resistant layer of stainless steel 12 X 18H10T (0.12% carbon, 18% chromium, 10% nickel and up to 1% titanium), and the internals of the evaporators of austenitic stainless steel. Carbon steel was also applied to the equipment used under low temperature conditions. The heat exchange tubes of the evaporators and the regenerative preheaters were made of aluminium brass, stabilized by arsenic, and the tubes of the main condenser, of Cu–Ni alloy. The average corrosion rate of brass was 0.02–0.04 mm/a, and that of carbon steel, 0.1 mm/a. During 20 years of operation, numerous cases of pitting corrosion have been observed on the stainless steel. The pipelines carrying the evaporated solution between evaporators were replaced after 15–20 years of operation. At high temperature, the brass heat exchange tubes also frequently failed. After 15 years of operation, the number of defective heat exchange tubes in the first evaporators ranged between 15 and 30%. In several heating chambers, complete substitution of the heat exchange surface was carried out. Most corrosion–erosion
was observed on the driving wheels of the pumps for the chalk seeding pulp and blades of the circulating pumps of the evaporators. These are replaced every 2 years.

3.5. Scale control

Because of the high quality of the feedwater, scaling has not been observed in the heat exchange tubes of the reactor's steam generators or in the fossil fired boilers.

The methods used for scale control in the desalination plant are based on: (1) application of CaCO$_3$ seeding crystals in the evaporators; and (2) bicarbonate ion stabilization of the feedwater for the desalination units in the regenerative preheaters by adding carbon dioxide from the blow away devices of the second evaporators.

Plant equipment is cleaned twice a year using hydrochloric acid.

4. EVALUATION OF THE PRODUCTION COSTS

The costs of water, electric power and heat depend on the cost of fuel. As the price of gas and reactor fuel rose between 1994 and 1996, production costs rose accordingly. Analysis of the average data has shown that these costs increased by 10–15% when the reactor was shut down for refuelling or repair (Table V).

<table>
<thead>
<tr>
<th></th>
<th>Normal operation</th>
<th>Reactor shutdown</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distillate (US $/t)</td>
<td>0.956</td>
<td>1.08</td>
</tr>
<tr>
<td>Electric power (US $/kW-h)</td>
<td>0.016</td>
<td>0.018</td>
</tr>
<tr>
<td>Thermal energy (US $/GJ)</td>
<td>1.09</td>
<td>1.22</td>
</tr>
<tr>
<td>Potable water (US $/t)</td>
<td>1.15</td>
<td>1.27</td>
</tr>
</tbody>
</table>

5. RADIOLOGICAL IMPACT ON THE ENVIRONMENT

An important advantage of the BN-350 reactor is the minimum radiological impact it has on the environment. Average emissions of radioactive gases are 10–15 Ci/d (the permissible level is 500 Ci/d), including argon, xenon and krypton.$^1$

$^1$ Ci = $3.70 \times 10^{10}$ Bq.
The gases have a short half-life and are not harmful to the population. Operational experience and analysis of the design basis and beyond design basis accidents of the reactor have shown that the radiological consequences of all normal and abnormal operating conditions do not have any effect on the quality of the product water.

The chemical contents of the brine and cooling water discharged to the sea are also within the permissible limits. For many years, the artificial shallow lake, in which aeration and cleaning of the disposal water are carried out, has served as a wintering place for birds and for fishing.

6. CONCLUSIONS

The scheme applied at the NDP in Aktau has shown high reliability and flexibility of control owing to the combined use of a nuclear reactor and fossil fuel fired boilers.

The radiological characteristics of the product water do not differ from those of the water obtained from conventional desalination plants, and meet WHO standards.

Over 20 years of experience in the successful operation of the NDP in Aktau has confirmed the high reliability and efficiency of nuclear desalination.

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OPERATING EXPERIENCE GAINED WITH NUCLEAR DESALINATION PLANTS
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Abstract

OPERATING EXPERIENCE GAINED WITH NUCLEAR DESALINATION PLANTS BY
JAPANESE ELECTRIC POWER COMPANIES.

As of March 1997, 51 nuclear power plants are being operated by ten electric power
companies in Japan. All are located at the sea because they need sea water as the ultimate heat
sink. Some are equipped with sea water desalination plants to secure the fresh water required
for boiler feedwater and for on-site household water. The first nuclear power plant (gas cooled
reactor) came into operation in 1966. The first nuclear sea water desalination plant in Japan,
using the multi-stage flash (MSF) distillation process with a capacity of 1300 m$^3$/d, started
operation in 1974 at the Ohi nuclear power station (PWR, 1175 MW(e)), Kansai Electric Power
Co., Inc. Today, nine nuclear sea water desalination plants have been installed by the Tokyo,
Shikoku and Kyushu Electric Power Companies, in addition to Kansai, eight of which are
currently in operation. The capacity of the desalination facilities ranges between 1000 and
2600 m$^3$/d. The average salinity of the intake sea water is 35 000 mg/L, and the average
temperature is 17°C. Three types of desalination process, reverse osmosis (RO), multi-effect
distillation (MED) and MSF, have been chosen. Initially, the MSF process (unit capacity of
1300 m$^3$/d was selected, but the MED and/or RO processes were later chosen because of their higher efficiency (unit capacity ranging between 1000 and 1300 m$^3$/d) and because of the direct application of electricity (for RO). Among the eight operating nuclear desalination plants, two MSF (1300–2000 m$^3$/d), three MED (1000–2600 m$^3$/d) and three RO (1000–2600 m$^3$/d) processes are in use. To date, no serious anomalies have been experienced at these operating nuclear sea water desalination plants, and no leakage of radioactive substances into the product water has taken place.

1. DESALINATION PLANTS

Several nuclear power stations, e.g. Ohi (Kansai), Ikata (Shikoku) and Genkai (Kyushu), have sea water desalination plants that use the heat and/or electricity from these plants to produce boiler feedwater and/or potable water for other purposes. The capacity of these desalination plants ranges between 1000 and 2600 m$^3$/d. Initially, the general tendency in Japan was to select the multi-stage flash (MSF) desalination process, but multi-effect distillation (MED) and/or reverse osmosis (RO) were later installed. RO is becoming the mainstream of desalination because the process has a low energy consumption. The desalination plants in nuclear power stations consist of two or three units with a capacity of 1000–1300 m$^3$/d. In some nuclear power stations, the desalted water is being used as household water.

Table I shows the current status of the nuclear desalination plants in some electric power companies in Japan [1]. The MSF process installed at the Kashiwazaki nuclear power station is not operating at present because the local government currently supplies potable water to the station. Table II gives the specifications of nuclear desalination plants with the MED and MSF systems, and Table III gives those with the RO systems.

2. OHI NUCLEAR POWER STATION [2]

The Ohi nuclear power station (units I to IV) is located at the head of a peninsula. Hence, the fresh water intake from rivers and streams is not sufficient. The fresh water demand for each reactor is 1200 m$^3$/d during normal operation. At startup, more water is needed, e.g. for cleaning, and fresh water consumption increases to 1900 m$^3$/d. When all four units are in operation, 4800 m$^3$/d of fresh water are required; when two units are started up, 6200 m$^3$/d of fresh water are needed. To supply fresh water to units I and II, one MSF train and two MED trains are operated. To supply fresh water to units III and IV, which were added later, two RO trains are provided; each train can produce 1300 m$^3$/d of fresh water. Construction of the RO plants was started in June 1988, and regular operation began in February 1990. Only the RO plants are discussed here.
<table>
<thead>
<tr>
<th>Name</th>
<th>Location</th>
<th>Type</th>
<th>Unit capacity (MW(e))</th>
<th>Grid connection</th>
<th>Process</th>
<th>Capacity (m³/d)</th>
<th>Year of startup</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ohi-I, II</td>
<td>Fukui</td>
<td>PWR</td>
<td>1175</td>
<td>1979/1979</td>
<td>MSF</td>
<td>1300</td>
<td>1974</td>
<td>1300 m³/d × two units</td>
</tr>
<tr>
<td>Ohi-III, IV</td>
<td>Fukui</td>
<td>PWR</td>
<td>1180</td>
<td>1991/1993</td>
<td>RO</td>
<td>2600</td>
<td>1990</td>
<td>1300 m³/d × two units</td>
</tr>
<tr>
<td>Takahama</td>
<td>Fukui</td>
<td>PWR</td>
<td>870</td>
<td>1985</td>
<td>MED</td>
<td>2000</td>
<td>1983</td>
<td>1000 m³/d × two units</td>
</tr>
<tr>
<td>Ikata-I, II</td>
<td>Ehime</td>
<td>PWR</td>
<td>566</td>
<td>1975/1975</td>
<td>MSF</td>
<td>2000</td>
<td>1975</td>
<td>1000 m³/d × two units</td>
</tr>
<tr>
<td>Ikata-III</td>
<td>Ehime</td>
<td>PWR</td>
<td>566</td>
<td>1992</td>
<td>RO</td>
<td>2000</td>
<td>1992</td>
<td>1000 m³/d × two units</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>MED</td>
<td>1000</td>
<td>1992</td>
<td></td>
</tr>
<tr>
<td>Kashiwazaki</td>
<td>Niigata</td>
<td>BWR</td>
<td>1100</td>
<td>1985</td>
<td>MSF</td>
<td>1000</td>
<td>1985</td>
<td>Not in operation</td>
</tr>
</tbody>
</table>
### TABLE II. SPECIFICATIONS OF THE SEA WATER MED AND MSF DESALINATION SYSTEMS

<table>
<thead>
<tr>
<th>Specifications</th>
<th>Ohi-I, II</th>
<th>Ohi-I, II</th>
<th>Takahama</th>
<th>Ikata-I, II</th>
<th>Genkai-III, IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Process</td>
<td>MED</td>
<td>MSF</td>
<td>MED</td>
<td>MSF</td>
<td>MED</td>
</tr>
<tr>
<td>No. of stages/effects</td>
<td>8</td>
<td>18</td>
<td>8</td>
<td>27</td>
<td>8</td>
</tr>
<tr>
<td>Total capacity (m³/d)</td>
<td>2600</td>
<td>1300</td>
<td>2000</td>
<td>2000</td>
<td>1000</td>
</tr>
<tr>
<td>Train capacity (m³/d)</td>
<td>1300 × 2</td>
<td>1300 × 1</td>
<td>1000 × 2</td>
<td>1000 × 2</td>
<td>1000 × 1</td>
</tr>
<tr>
<td>Gained output ratio</td>
<td>6</td>
<td>6</td>
<td>6</td>
<td>8</td>
<td>6</td>
</tr>
<tr>
<td>Inlet sea water</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Brine temperature (°C)</td>
<td>118</td>
<td>104</td>
<td>94</td>
<td>116</td>
<td>94</td>
</tr>
<tr>
<td>TDS (mg/L)</td>
<td>35 000</td>
<td>35 000</td>
<td>35 000</td>
<td>35 000</td>
<td>35 000</td>
</tr>
<tr>
<td>Potable water</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TDS (mg/L)</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>5</td>
<td>5</td>
</tr>
</tbody>
</table>

### TABLE III. SPECIFICATIONS OF THE SEA WATER RO DESALINATION SYSTEMS

<table>
<thead>
<tr>
<th>Specifications</th>
<th>Ohi-III, IV</th>
<th>Ikata-III</th>
<th>Genkai-III, IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Membrane type</td>
<td>Cellulose acetate</td>
<td>Cellulose acetate</td>
<td>Cross-linked polyether</td>
</tr>
<tr>
<td></td>
<td>Hollow fibre</td>
<td>Hollow fibre</td>
<td>Spiral wound</td>
</tr>
<tr>
<td>Total capacity (m³/d)</td>
<td>2600 (at 10°C)</td>
<td>2000</td>
<td>1000</td>
</tr>
<tr>
<td>Train capacity (m³/d)</td>
<td>1300 × 2</td>
<td>1000 × 2</td>
<td>1000 × 1</td>
</tr>
<tr>
<td>No. of modules</td>
<td>95 × two lines</td>
<td>36 × two lines</td>
<td>54 × one line</td>
</tr>
<tr>
<td></td>
<td>(first stage = 65; second stage = 30)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inlet pressure (MPa)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>First stage</td>
<td>6.5</td>
<td>6.8</td>
<td>6.5</td>
</tr>
<tr>
<td>Second stage</td>
<td></td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>Recovery ratio (%)</td>
<td>28 (at 10°C)</td>
<td>40 (at 17°C)</td>
<td>25–40</td>
</tr>
<tr>
<td></td>
<td>37 (at 31°C)</td>
<td>33.3 (at 10°C)</td>
<td></td>
</tr>
<tr>
<td>Inlet sea water</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TDS (ppm)</td>
<td>35 000</td>
<td>35 000</td>
<td>35 000</td>
</tr>
<tr>
<td>Potable water</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TDS (mg/L)</td>
<td>15</td>
<td>350</td>
<td>150</td>
</tr>
<tr>
<td>Conductivity (µS/cm)</td>
<td>30 (at 30°C)</td>
<td>700</td>
<td>300 (at 25°C)</td>
</tr>
</tbody>
</table>
2.1. RO plants

Each RO plant consists of sea water intake facilities, pretreatment facilities, first stage RO, second stage RO and discharge treatment facilities. The desalted water capacity of each train is 1300 m³/d at a sea water temperature of 10°C, and 1700 m³/d at 31°C. The facility is fully automated. The RO plants can be started and stopped by a control in the control room for the secondary auxiliary system at the station. All the important process parameters can be monitored.

The desalted water thus produced is stored in two tanks, each with a capacity of 8500 m³. Some of the fresh water (about 200 m³/d) is processed by a drinking water facility and used as potable water at the station. The make-up water is fed to the station via the demineralized water facilities.

2.2. Water intake facilities

Sea water is pumped by three pumps (one on stand-by), each with a capacity of 200 m³/h. Part of the sea water is sent to an electrolyser. Part of the chlorine generated by electrolysis is injected into the sea water intake line to control the residual chlorine (0.1–0.3 mg/L) at the inlet of the first stage RO membrane and, in turn, to prevent biological fouling of the facilities.

2.3. Pretreatment facilities

The pretreatment facilities consist of two lines with a dual media filter and a polishing filter for each train. The silt density index (SDI) of the sea water treated in the pretreatment facilities is maintained at less than 4.

2.4. First stage RO plant

The treated and filtered sea water is adjusted to a pH of 6.6 before it is introduced to the first stage RO membrane via safety filters. The pH, SDI and residual chlorine are continuously measured at a point upstream of the first stage RO membrane. If any differ from the predetermined range, operation of the plant is automatically stopped.

As the regulations related to nuclear power plants in Japan do not permit use of plastic casings for a pressure vessel, the membrane elements are enclosed in a fibreglass reinforced plastic container covered by a carbon steel pressure vessel. Variations in sea water temperature are expected to range from 6 to 31°C. A system has been adopted that automatically changes the recovery rate when there is a change in the sea water temperature. According to the design specifications, at a sea water temperature of 10°C the recovery rate is 35% and the fresh water
production 1625 m$^3$/d. At 31°C, the recovery rate is 43% and the production 2000 m$^3$/d. The total dissolved solids (TDS) in the first stage RO plant are about 400 mg/L.

2.5. Second stage RO plant

In this plant, the TDS of the product water is reduced to about 10 mg/L. According to the design specifications, at 10°C the fresh water production capacity is 1300 m$^3$/d, and at 31°C, 1700 m$^3$/d. The product water stored in a tank is passed through an activated carbon filter to remove the residual chlorine, sodium hydroxide is added to adjust the product water to a pH of 6–7, and then the water is sent to the fresh water tanks. The addition of sodium hydroxide increases the TDS by 2–3 mg/L.

2.6. Discharge facilities

All the waste water from the RO plants is constantly monitored to check the pH, chemical oxygen demand, turbidity and presence of residual chlorine. The facilities are arranged in such a manner that waste water cannot be discharged if it does not meet the allowable waste standards.

2.7. Maintenance of membranes

When the RO plants are to be shut down for 3 days or less, they are flushed with product water to reduce the salt concentration on the membrane surfaces. When the plant is to be shut down for more than 3 days, a storage solution (500 mg/L of sodium bisulphite) is kept in the RO membranes. When outage takes 1 week or more, the concentration of sodium bisulphite is 2500 mg/L.

2.8. Operational records

The conductivity of the product water at the second stage was 5 μS/cm in the test operation; after the addition of sodium hydroxide it was 10 μS/cm. These values are much lower than the design parameter of 30 μS/cm, hence the quality of the desalted water was satisfactory. Water production was 1730 m$^3$/d when the sea water temperature was 26.8°C, therefore it is believed that production must have exceeded 1700 m$^3$/d at 31°C. The operational records for 3 years (1992–1994) are given in Table IV, including those of the MSF plant.

In addition to the Ohi nuclear power station, the Kansai Electric Power Co., Inc. has installed two units of MED in the Takahama nuclear power station to secure the supply of make-up water for the nuclear reactors.
TABLE IV. OPERATIONAL RECORDS OF THE SEA WATER RO AND MSF
DESALINATION PLANTS

<table>
<thead>
<tr>
<th>Fiscal year</th>
<th>Operational period (months)</th>
<th>Water produced (m³/a)</th>
<th>Load factor (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactor: Ohi-I, II (MSF)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1992</td>
<td>12</td>
<td>644 000</td>
<td>70</td>
</tr>
<tr>
<td>1993</td>
<td>12</td>
<td>601 000</td>
<td>68</td>
</tr>
<tr>
<td>1994</td>
<td>12</td>
<td>572 000</td>
<td>65</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Fiscal year</th>
<th>Operational period (months)</th>
<th>Water produced (m³/a)</th>
<th>Load factor (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactor: Ohi-III, IV (RO)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1992</td>
<td>12</td>
<td>725 000</td>
<td>71</td>
</tr>
<tr>
<td>1993</td>
<td>12</td>
<td>629 000</td>
<td>60</td>
</tr>
<tr>
<td>1994</td>
<td>12</td>
<td>524 000</td>
<td>51</td>
</tr>
</tbody>
</table>

3. IKATA NUCLEAR POWER STATION [3]

The Ikata nuclear power station (Ikata-I, II and III) has two types of desalination plant: one uses the MSF process (Ikata-I and II) and the other the RO process (Ikata-III).

3.1. RO in Ikata-III

RO was selected for the following reasons: (1) corrosion is low and operation and maintenance are easy because the sea water is used at a normal temperature; and (2) recent developments made in the technology of, for example, the membrane, with good prospects for the future.

3.1.1. Flow diagram

Ikata-I, II and III need fresh water (about 1000–2000 m³/d) as make-up and potable water for each unit during operation, so the capacity of the desalination system has to be large enough to be able to supply the required amount of water.

The quality of the water desalted with MSF in Ikata-I and II is equivalent to that of normal city water treated with a two bed, three column demineralizer. The quality of the water desalted with RO in Ikata-III is almost the same as that of Ikata-I and II after it has passed through the above mentioned demineralizer. All the desalted water is controlled at the fresh water storage tank located between Ikata-I, II and Ikata-III.

The desalted water stored in the fresh water storage tank is used as make-up water for the plant after passing through a mixed bed type polisher. Some of it is
transported to the filtered water tank, where it is used for household water after being mixed with filtered river water.

3.1.2. System description

The Ikata-III desalination plant consists of sea water intake pumps, pretreatment facilities for the sea water and RO membranes. The sea water is drawn up by intake pumps (with a capacity of 700 m$^3$/h) and some of it (20%, 140 m$^3$/h) is transported to the pretreatment facilities. The rest (80%) is led to the discharge pit to dilute the brine from the RO plant. This system is designed to obtain treated sea water with an SDI of less than 4.

After the pretreated sea water has passed through the safety filter (to protect the RO membranes), it is transported to the RO modules (at a high pressure and constant flow rate (125 m$^3$/h)), where it is separated into desalted water and brine. The RO modules have 36 RO vessels arranged in parallel. The desalted water is transported to the purification system through another tank, and then the brine is drained to the discharge pit through the brine tank.

3.1.3. Capacity

If the recovery rate of the system is too high, some water may remain on the surface of the membrane and certain compounds, e.g. calcium sulphate, may be deposited, resulting in reduced membrane performance. Consequently, the maximum recovery rate is designed to be 45% in this RO system, while it is 40% in normal operations. It is planned that 20% of the RO membranes be replaced each year to maintain a recovery rate of 40%.

3.1.4. Control system

The flow rate of sea water at the inlet of the RO modules is maintained at constant (125 m$^3$/h). The recovery rate or operating pressure is designed to be constant, depending on the variation in sea water temperature. When the temperature is below 17°C, the pressure is constant at a maximum pressure of 6.8 MPa. At this time, the amount of desalted water depends on the sea water temperature. When the temperature is above 17°C, the pressure decreases to obtain a constant amount of desalted water (1200 m$^3$/d).

3.1.5. Operation and maintenance

Table V shows the operational records of the sea water RO desalination plant in Ikata-III between 1992 and 1994. The conductivity of the desalted water, shown in Table VI, is about 60–70% of the design value.
TABLE V. OPERATIONAL RECORDS OF THE SEA WATER RO DESALINATION PLANT IN IKATA-III

<table>
<thead>
<tr>
<th>Operating months</th>
<th>1992</th>
<th>1993</th>
<th>1994</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water produced (m³/a)</td>
<td>222 000</td>
<td>457 000</td>
<td>435 000</td>
<td>1 114 000</td>
</tr>
<tr>
<td>Load factor (%)</td>
<td>62</td>
<td>63</td>
<td>65</td>
<td>63</td>
</tr>
</tbody>
</table>

TABLE VI. CONDUCTIVITY OF THE DESALTED WATER (AT 25°C) IN IKATA-III

<table>
<thead>
<tr>
<th>Conductivity (µS/cm)</th>
<th>Initial value</th>
<th>After 1 year</th>
<th>After 2 years</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design value</td>
<td>420</td>
<td>470</td>
<td>550</td>
</tr>
<tr>
<td>Operating value</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unit A</td>
<td>194</td>
<td>261</td>
<td>350</td>
</tr>
<tr>
<td>Unit B</td>
<td>207</td>
<td>343</td>
<td>430</td>
</tr>
</tbody>
</table>

Maintenance was carried out after plant startup and, according to schedule, about 20% of the membranes were exchanged annually. This percentage could be reduced if fine control of several membranes is carried out during operation; a lifetime evaluation will be undertaken in the future. Minor corrosion was found in the stainless steel pump casing, therefore some countermeasures will have to be taken.

3.2. The MSF desalination plants in Ikata-I and II

3.2.1. System

The MSF process is being used for the desalination plants in Ikata-I and II. As the sea water has to be heated to 116°C, the heat energy from the nuclear power plant is used for the desalination process.
3.2.2. **Operation and maintenance**

Operation of the desalination plants in Ikata-I and II started in November 1975. They were operated for about 20 years and contributed to the supply of fresh water. During operation, no problems arose in the control of the system. However, some difficulties have occurred with repairs and maintenance, e.g. as a result of corrosion there was a reduction in thickness of the inside of the tubes of the brine heater, the evaporator and the sea water piping. To date, the following parts have been repaired or replaced:

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Status</th>
<th>Countermeasure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brine heater</td>
<td>Reduction in the thickness of the inside tube</td>
<td>Exchange of tube</td>
</tr>
<tr>
<td>Evaporator</td>
<td>Reduction in the thickness of the inside tube, Corrosion of the internal structure</td>
<td>Exchange of tube, Replacement of the stainless steel lining, paint or exchange</td>
</tr>
<tr>
<td>Piping</td>
<td>Corrosion, Reduction in the thickness of the piping</td>
<td>Exchange of the material, Replacement of carbon steel with CuNi steel and of the fibreglass reinforced plastic tube with a polyethylene lined tube</td>
</tr>
</tbody>
</table>

4. **THE GENKAI NUCLEAR POWER STATION [4]**

The fresh water required for units I and II of the Genkai nuclear power station is taken from a nearby river. With the addition of units III and IV, sea water desalination plants were installed to secure the required fresh water. For the fresh water needed during construction, one RO plant was installed that did not require steam. Also, one MED desalination plant began operating after the startup of unit III. A plant of this type uses steam from a nuclear power station and produces water that has a higher purity than that from an RO plant. In the following subsections, an outline of the desalination plants, mainly MED, is given and the state of operation is described.
4.1. Specifications

The MED plant consists of evaporators with preheaters called the 'effect section' and condensers called the 'heat rejection section'. One train consists of the first, third, fifth and seventh effects, and a heat rejection section. Another train consists of the second, fourth, sixth and eighth effects. Thus, the MED plant is a configuration of eight effects in a dual stack arrangement.

4.2. Main materials

Regarding the corrosion resistance, the shells of the condensers and preheaters are made of a carbon steel plate with rubber lining. The shells of the evaporator are made of stainless steel clad on carbon steel (the bottom plates are rubber lined) to prevent any contact between the salt water and the carbon steel. The heat exchanger tubes are made of titanium or aluminium-brass, depending on the operating conditions.

4.3. Control of operation

Centralized monitoring and control (or start and stop) of the facilities can be made through cathode ray tube displays in the central control room. Load following is controlled automatically by the flow rate of the steam.

4.4. Standard of operation

The production rate of the desalted water is adjusted to the water consumption of the nuclear power station. The basic standard is as follows. When the nuclear power station is in operation, priority is given to the operation of the MED plant, where the water quality is better. When the station is shut down and no steam is available, the RO plant is operated. Two water storage tanks have been installed: water produced by the RO plant is stored in the normal water tank, and that produced by the MED plant is stored in the high quality water tank.

4.5. Operating records

The RO plant started operation in 1988, and the MED plant in February 1992. The desalted water production rate of the MED plant ranges between 540 and 1000 m³/d, and that of the RO plant, between 400 and 1000 m³/d. To date, there have been no significant changes in the performance parameters (conductivity, TDS, iron content, etc.) from the values obtained at the time of startup of the nuclear power station.
4.6. Maintenance

Since startup of the MED plant in 1992, periodic inspections (1 month per year) have been carried out. The findings were satisfactory. Slight peeling was found on the rubber lining inside the evaporator; the lining has since been replaced.

5. CONCLUSIONS

(1) The sea water desalination plants owned by the electric power companies in Japan have been operated for more than 20 years. They have been free of any serious problems caused by the migration of radioactive materials into the desalted water, and operation has been satisfactory. The desalination plants have become very important and effective facilities for nuclear power stations, e.g. for supplying plant make-up water.

(2) The capacity of the desalination plants operated by each electric power company is small, but the operating data obtained so far are very valuable. These data will be of much use in promoting sea water desalination projects with nuclear power.

(3) In the case of a desalination plant coupled to a nuclear power plant, the plastic casings of the RO membranes were replaced by carbon steel. Apart from this replacement, there have been no other design changes in the desalination plant compared with those plants coupled to fossil fuelled power plants.

(4) The water produced by desalination plants is used for the make-up water of nuclear power plants. Moreover, in some plants it is used for household water after appropriate treatment, including the addition of minerals.

ACKNOWLEDGEMENT

The valuable contribution of Y. Shiota, Sasakura Engineering Co., in reviewing this paper is highly appreciated.

REFERENCES


EXPERIENCE GAINED IN THE ASHDOD PLANT AND OTHER DUAL PURPOSE DESALINATION PLANTS USING MULTI-EFFECT DISTILLATION WITH ALUMINIUM TUBES

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Abstract

EXPERIENCE GAINED IN THE ASHDOD PLANT AND OTHER DUAL PURPOSE DESALINATION PLANTS USING MULTI-EFFECT DISTILLATION WITH ALUMINIUM TUBES.

In the early 1980s, the Ashdod plant project demonstrated the coupling of a multi-effect distillation (MED) plant to a steam turbine through the cooling water stream. Such a dual purpose plant simulated connection of a nuclear reactor to a MED plant. The experience gained in the Ashdod plant and other dual purpose plants is outlined, using the MED process with aluminium tubes. Current activities with the coupling of a 10 MW nuclear reactor to MED, vapour compression (VC) or reverse osmosis (RO) units are presented. A description is also given of large MED plants, up to $75 \times 10^6$ gal(US)/d per module, based on vertical aluminium enhanced heat transfer tubes, recently developed by the Metropolitan Water District of southern California.

1. ASHDOD PLANT

The Ashdod plant was based on the multi-effect low temperature (MELT) distillation process, which utilizes horizontal tube evaporators built of aluminium tubes and coated steel vessels. The purpose of the Ashdod plant project was to demonstrate and simulate the feasibility of coupling a large multi-effect distillation (MED) unit to a steam turbine in a nuclear power station. To achieve this, a $4.6 \times 10^6$ gal(US)/d, six effect evaporator was constructed in Ashdod, Israel, and coupled to an existing 50 MW fossil fuel fired power unit.1 Operating at a relatively low temperature, this MED plant could be defined as a MELT type process plant.

The project, completed in the early 1980s, enabled the dual purpose desalination plant to be operated for approximately 2 years, yielding meaningful and

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1 $1 \text{ gal (US)} = 3.785 \times 10^{-3} \text{ m}^3$. 
encouraging results on the operation and performance of the complex. Details of this plant are given in Refs [1, 2].

1.1. Main characteristics

The main characteristics are as follows:

Nominal fresh water production: $4.6 \times 10^6$ gal/d (725 t/h)
Fresh water quality: Less than 50 ppm total dissolved solids (TDS)
Economy ratio: 5.7 (for six effects)
Yield: 35%

Heat source:
Circulated saline cooling water from the turbine condenser:
  Flow: 10 000 t/h
  Temperature in: 62.9°C
  Temperature out: 55.4°C
  Salinity: 5.68 wt% TDS

Heat sink:
Sea water coolant: 8600 t/h
  Temperature in: 26°C
  Temperature out: 34°C
  Salinity: 4.20 wt% TDS

1.2. Running targets

Since this was a demonstration plant, it was properly instrumented to achieve the following targets: performance of the plant in accordance with the design criteria; coupling of the turbine to the desalination plant through the cooling water system, causing no interference with the power station; durability of the construction materials; and prevention of scaling to maintain clean heat transfer surfaces.

1.3. MED process

The MED process is based on a train of horizontal tube evaporators–condensers. The source energy supplied to the first effect is repeatedly used in successive effects, while each effect works at a slightly lower temperature, producing almost the same amount of steam/vapour. The Ashdod plant is different from a plain MED plant because of the way in which its heat source and sink are utilized; this is also the origin of its definition as a MELT process.
1.4. MED at Ashdod (MELT)

The Ashdod plant uses the hot cooling water from the power plant condenser (Figs 1 and 2).

Such a coupling scheme is suitable for both fossil fuel fired dual purpose plants and nuclear dual purpose plants. Utilization of the heat from the cooling water of the turbine condenser, rather than the exhaust steam from the turbine, simulates coupling of the desalination plant to a nuclear power station, where a phase barrier is needed. The phase barrier is a form of isolation between the nuclear and the water sections of a nuclear dual purpose plant.
1.5. Results of 2 years of operation

1.5.1. Plant production

Most of the time, the plant was operated at 650–750 t/h.
The economy ratio ranged between 5.8 and 6.2, which is higher than the design criterion of 5.7.
The reason for obtaining a figure that is almost the same as the number of effects is that first effect condensate is not returned to the boiler house. Replenishment of the extracted vapour from the hot cooling water is achieved by the sea water make-up stream connected to the cooling water circulation line.

Regarding thermal efficiency, performance of the plant was very similar to that of the design criteria.

The heat transfer coefficients of each of the effects and the condenser are summarized below.

<table>
<thead>
<tr>
<th>Effect No.</th>
<th>Temperature (°C)</th>
<th>Heat transfer coefficients (kcal·m⁻²·h⁻¹·°C⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>50–54</td>
<td>2100–2300</td>
</tr>
<tr>
<td>2</td>
<td>46–50</td>
<td>2000–2100</td>
</tr>
<tr>
<td>3</td>
<td>41–45</td>
<td>2000–2100</td>
</tr>
<tr>
<td>4</td>
<td>38–40</td>
<td>1900–2100</td>
</tr>
<tr>
<td>5</td>
<td>36–38</td>
<td>1900–2000</td>
</tr>
<tr>
<td>6</td>
<td>34–37</td>
<td>1900–2000</td>
</tr>
<tr>
<td>Condenser</td>
<td>33–35</td>
<td>1600–1800</td>
</tr>
</tbody>
</table>

1.5.2. Energy consumption and product water quality

The energy consumption of the desalination plant was as follows:

- Specific energy for the process: 7.00 kW·h/t
- Equivalent steam for the ejectors: 0.15 kW·h/t
- Electric energy consumption of the pumps: 1.60 kW·h/t
- Total energy consumption: 8.75 kW·h/t

The quality of the product water was:

- Turn down: 300–350 t/h; 10–40 ppm TDS
- Nominal load: 700–750 t/h; 40–80 ppm TDS
- Above the design load: 750–800 t/h; 50–100 ppm TDS
During 2 years of operation, the Ashdod plant showed steady performance of the evaporator and condenser. The thermal efficiency, the steady operational behaviour while coupled to an existing 50 MW turbine, and the prevention of scaling and corrosion in the evaporators allow this type of dual purpose system to be considered as a future way of using nuclear energy for desalination. The expected energy consumption for a new dual purpose plant is 6 kW-h/t, and for a combined cycle, 4.5–5 kW-h/t.

2. CURAÇAO DUAL PURPOSE PLANTS

Multi-stage flash (MSF) plants are usually operated with extraction steam (2.5 bar) from the steam turbines in dual purpose complexes. Because the MED system requires a low steam inlet pressure (only 0.3 bar), it is possible to install another turbine that produces extra power, in addition to that of the existing backpressure turbine.

For a MED 10 000 t/d unit coupled to a 20 MW steam turbine system with a 2.5 bar backpressure, a second turbine can be installed that produces an additional 3.2 MW. This was the case in Curaçao, where MSF units were replaced by MED in an existing power station. The Water and Electricity Company of Curaçao, Netherlands Antilles, adapted such dual purpose plants in the late 1980s and studied the best operational regime of such systems. The experience gained with such plants is described in Ref. [3].

2.1. Main characteristics

The main characteristics are:

- Nominal fresh water production: $2.65 \times 10^6$ gal/d (417 t/h)
- Fresh water quality: Less than 1 ppm TDS (for the first effect);
  - 5–20 ppm TDS (in the rest of the plant)
- Economy ratio: 8.7 (for 12 effects)
- Yield: 45%
- Power generated in the low pressure turbine: 3.2 MW

The Curaçao plant is shown in Fig. 3.

2.2. Results and conclusions

The plant was run to the satisfaction of the operators. One question that was raised during the first few years of operation was whether the large backpressure
FIG. 3. The Curaçao plant ($2.65 \times 10^6$ gal/d).
steam turbine should dictate the conditions of the first effect of the MED, or vice versa. Experience showed that the backpressure in the large turbine should be fixed, likewise the pressure in the first MED effect. Operating the dual purpose plant in this way resulted in steady operation of the small second turbine and the MED plant, whereas the output of the first turbine power fluctuated.

3. COUPLING OF DESALINATION PLANTS TO NUCLEAR REACTORS

The successful experience accumulated with aluminium tubes in plants, two of which are described here, led to further opportunities, e.g. coupling of desalination plants to nuclear reactors, producing the heating media for the evaporators. A demonstration plant is proposed (for arid and semi-arid regions) that desalts saline water by utilizing the heat from a nuclear reactor to drive both a low pressure turbine and, with the steam leaving the turbine, a MED plant. The turbine can drive the compressor of a vapour compression (VC) unit, or the high pressure pump of an RO unit, and all the pumps in the desalination units. The nuclear dual purpose plant is given in Fig. 4. Selection of either a VC or an RO unit (in addition to the MED unit) depends very much on the quality of the product water needed. Two possible methods for utilizing the heat from the nuclear reactor are given in Fig. 4.

3.1. Heat and mass balance

The demonstration plant will be based on the following thermal performance and efficiency:

Steam produced by flashing the hot water
- from a 10 MW nuclear reactor: 15 t/h at 1.7 bar, dry saturated (130°C)
Condensate return at 70°C: 15 t/h
Nuclear reactor rating: 10 113 kW
Steam turbine output at 85% efficiency: 1242 kW
Generator output at 96.5% efficiency: 1200 kW
Output of a MED unit with 14 effects:
- Economy ratio: 10
- Product: 3600 t/d
Output of a VC unit:
- Compressor energy consumption: 6.7 kW·h/t
- Product: 2200 t/d
VC unit compressor motor:
- Power consumption: 614 kW
- Motor name plate: 750 kW
FIG. 4. Nuclear dual purpose plant showing two possible methods for utilizing heat (R = reactor; F = steam release by a flashing device; T = turbine; G = generator; M = motor; P = product; SW = sea water; B = brine).
Descriptions are given in the following subsections of each of the major possibilities for combining a nuclear reactor with desalination plants.

### 3.1.1. Combining MED with VC units

The 10 MW nuclear reactor drives:

- One MED unit: 3600 t/d
- Two VC units: 4400 t/d
- **Total:** 8000 t/d

The electric power consumption is:

- Two VC motors: 1228 kW
- MED and VC pump motors: 500 kW
- Supply by the turbine: 1200 kW
- **Backup power from the grid:** 528 kW

The product will be of high quality (less than 20 ppm TDS).

### 3.1.2. Combining MED with RO units

The 10 MW nuclear reactor drives:

- One MED unit: 3600 t/d
- One RO unit: 4400 t/d
- **Total:** 8000 t/d

The electric power consumption is:

- RO high pressure pump block: 734 kW
- MED and RO (other) pump motors: 500 kW
- Supply by the turbine: 1200 kW
- **Backup power from the grid:** 34 kW

### 3.2. Summary

The characteristics of a dual purpose plant coupled to a nuclear reactor are as follows:

- Nuclear reactor: 10 MW
- Steam release by a flashing device: 15 t/h
FIG. 5. Flow diagram of the vertical MED process.
Fresh water by the MED unit: 3600 t/d
Plus two VC units: 4400 t/d
Total product water: 8000 t/d
Water quality: less than 20 ppm TDS

Alternative desalination units:

Fresh water by the MED unit: 3600 t/d
Plus an RO unit: 4400 t/d
Total product water: 8000 t/d
Water quality: 250 ppm TDS

4. VERTICAL MED PROCESS

In the early 1990s, a new version of the MED process was introduced in the United States of America. This is a configuration of the MED with vertically stacked effects and double fluted, vertical aluminium tubes. Two pilot plants based on this process have been in operation for a few years in Huntington Beach, southern California. This process can fit into a power station with a nuclear reactor, directly using its steam. The features of the vertical MED are as follows:

Heat transfer tubes: Double fluted, vertical
Materials: Special aluminium alloy
Advantages: High heat transfer coefficients
Shell: Reinforced concrete tower slip form construction, vacuum tight
Economy ratio: 23 (for 30 effects)
Typical size: $75 \times 10^6$ gal/d (11 830 t/h)
Size of plant: 520 ft (160 m) high, 80 ft (25 m) diameter
Size of caisson: 80 ft (25 m) deep, 130 ft (40 m) diameter
Nuclear reactor needed: 350 MW or $2 \times 200$ MW

There is a serious need for technology in regions of dense population with water shortage problems and expensive land. References [4, 5] describe this new technology, developed by the Metropolitan Water District of southern California. A flow diagram of vertical MED is given in Fig. 5.

REFERENCES


DESIGN AND OPERATION
OF THE LAAYOUNE SEA WATER
REVERSE OSMOSIS PLANT

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Abstract

DESIGN AND OPERATION OF THE LAAYOUNE SEA WATER REVERSE OSMOSIS PLANT.

The largest desalination plant currently in operation in Morocco is the Laayoune sea water reverse osmosis (RO) plant. It is operated by the Office national de l’eau potable and has a capacity of 7000 m³/d. Pretreatment consists of chlorination; the acidification (H₂SO₄) required for adequate coagulation; coagulation using ferric chloride; pressure filtration through a sand filter; acidification (H₂SO₄) to reduce the precipitation of calcium carbonate at the membrane level; injection of an anti-scalent agent (Flocon 100) to reduce the precipitation of sulphates at the membrane level; microfiltration using 5 µm cartridge filters; and dechlorination using sodium metabisulphite. The plant uses a brine staging design concept, and has four trains, each with a capacity of 1750 m³/d. The RO section of the plant uses Dupont polyamide hollow fine fibre membranes. The design specifications are as follows: sea water total dissolved solids (TDS) of 40 000 ppm; a silt density index of <3; a maximum pressure of 70 bar; a recovery ratio of 45%; and a desalinated water TDS (product) of 1000 ppm. The plant was commissioned in November 1995 and has been in operation ever since, operating at a constant production of 1750 m³/d per train. After 7000 hours of operation, the key operating conditions are as follows: an operation pressure of 60 bar; a product salinity of 750 ppm; and a power consumption of 5.52 kW-h/m³. The main design features of the plant and the experience gained in the first year of operation are outlined.

1. INTRODUCTION

To solve water shortage problems in the Saharan provinces (especially in Laayoune City), the Office national de l’eau potable (ONEP) formed a committee which, at the end of the 1990s, visited several countries that had accumulated experience on the research and operation of a sea water desalination plant producing potable water (the Middle East, the Canary Islands, Malta, etc.). The objective of these visits
was to choose a reliable technology that could be adapted to the capacities and specificities (energy costs) required. As a result, desalination using the reverse osmosis (RO) process was adopted.

The Laayoune sea water RO plant produces 7000 m$^3$/d of drinking water. If brackish underground water (5616 m$^3$/d, with a total dissolved solids (TDS) value of 1600 mg/L) is included, the total capacity rises to 12 600 m$^3$/d of drinking water supplied to the inhabitants of Laayoune City and its neighbouring population. In April 1993, a contract was awarded to a group that comprised Polymetrics (United States of America), Hydrex and Sogea (both France) for the design, supply, construction and commissioning of the plant on a turnkey basis.

The contractor’s tender, as well as the control and supervision of the project, were ensured by ONEP. Plant operation (even during the testing period) was carried out by ONEP technicians, with the assistance of the contractor.

2. DESIGN CONCEPT

The design concept of the plant is as follows:

(1) The water intake is ensured through beach wells;
(2) The daily nominal production of the installation is 7000 m$^3$/d, divided into four trains of 1750 m$^3$/d each; extension is possible by adding two similar trains;
(3) The water produced has a total salinity (TDS) of 1000 mg/L; a peak of 1100 mg/L is tolerated;
(4) The RO plant works continuously;
(5) The design of the RO modules is based on a daily nominal capacity of 7000 m$^3$/d and a maximum ratio conversion of 45%; there are four trains and energy recovery of the brine;
(6) Maintenance of the components is easy, and module replacement is possible while production is in progress;
(7) Choice of a material that is resistant to the aggressivity of the fluids and medium with which it is in contact;
(8) Control and supervision by a synoptic control panel installed in the command room.

The design conditions for raw sea water are given in Table I, and a block flow diagram of the sea water RO facility is shown in Fig. 1.
TABLE I. DESIGN CONDITIONS OF THE LAAYOUNE SEA WATER RO PLANT

<table>
<thead>
<tr>
<th>Chemical composition</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total dissolved solids (mg/L)</td>
<td>40 077</td>
</tr>
<tr>
<td>pH</td>
<td>8</td>
</tr>
<tr>
<td>Total alkalinity as HCO$_3^-$ (mg/L)</td>
<td>162</td>
</tr>
<tr>
<td>Calcium (Ca$^{2+}$) (mg/L)</td>
<td>464</td>
</tr>
<tr>
<td>Magnesium (Mg$^{2+}$) (mg/L)</td>
<td>1 477</td>
</tr>
<tr>
<td>Sodium (Na$^+$) (mg/L)</td>
<td>12 255</td>
</tr>
<tr>
<td>Potassium (K$^+$) (mg/L)</td>
<td>441</td>
</tr>
<tr>
<td>Strontium (Sr$^{2+}$) (mg/L)</td>
<td>15.4</td>
</tr>
<tr>
<td>Barium (Ba$^{2+}$) (mg/L)</td>
<td>0.4</td>
</tr>
<tr>
<td>Silica (SiO$_2^-$) (mg/L)</td>
<td>1.4</td>
</tr>
<tr>
<td>Sulphate (SiO$_2^2-$) (mg/L)</td>
<td>3 075</td>
</tr>
<tr>
<td>Chloride (Cl$^-$) (mg/L)</td>
<td>22 109</td>
</tr>
<tr>
<td>Bromide (Br$^-$) (mg/L)</td>
<td>75.5</td>
</tr>
<tr>
<td>Fluoride (F$^-$) (mg/L)</td>
<td>1.5</td>
</tr>
</tbody>
</table>

*a The average temperature of the sea water is 17–20°C; the design temperature is 18°C.

3. LAYOUT

The raw sea water from the beach wells flows into the sea water reservoir (2 x 750 m$^3$). It is then sent to the pretreatment unit, the high pressure pumps and the RO modules. The permeate (product water) is stored in the product water tanks, which are located outside of the building.

The total plant space is: from West to East, 180 m; and from North to South, 164 m.

4. DESCRIPTION

The plant consists of the following systems: a sea water supply system; a pretreatment unit; high pressure pumps and RO trains; a post-treatment unit; product delivery; an electric power supply; a central control room; and auxiliary systems.

4.1. Sea water supply system

Raw sea water is taken from the Atlantic Ocean through 12 beach wells, of which only six are equipped with 144 m$^3$/d submerged pumps. Six other
FIG. 1. Block flow diagram of the sea water RO facility.
beach wells have been drilled to reinforce (for the mid-term) the plant capacity, which will rise to 14 000 m³/d of desalinated water. Of the six equipped beach wells, five are in operation and the sixth is on stand-by. The average well depth is 40 m. In general, the material used was stainless steel 316L. The raw sea water pumped from the beach wells flows through concrete canalization (diameter of 500 mm; length of 6797 m) before being stored in the sea water reservoir. The sea water is pumped from the above reservoir to the pretreatment unit by five booster pumps, four of which are in operation and the fifth is on stand-by. Two additional pumps are to be installed during the foreseen short term extension, which will raise the total production to 10 500 m³/d of drinking water.

4.2. Pretreatment unit

The raw sea water is pretreated through the following stages:

1. Prechlorination, using chlorine gas (fed at the entry to the reservoir);
2. Acidification (H₂SO₄), eventually required for adequate coagulation of the suspended matter;
3. Coagulation, using FeCl₃;
4. Pressure filtration through a sand filter in four horizontal cells (total length of 9 m; diameter of 2.9 m; material of glass reinforced plastic (GRP)); all the cells are backwashed (in sequence) with raw sea water and air; two additional cells could be installed to raise the total production to 10 500 m³/d;
5. Acidification (H₂SO₄), to attenuate the precipitation of CaCO₃ at the membrane level;
6. Injection of an anti-scalent reagent (Flocon 100), to reduce the precipitation of sulphates at the membrane level;
7. Microfiltration through four cartridge filters (diameter of 5 μm) that remove particles larger than 5 μm and provide final protection for the high pressure pumps and RO section; two additional cells could be installed within the foreseen extension;
8. Injection of sodium metabisulphite (SBS), to neutralize the remaining residual chlorine for protection of the membranes.

The construction material of the low pressure canalization and equipment is GRP.

4.3. High pressure pumps and RO trains

The high pressure pump and RO section of the plant is divided into four trains with a production capacity of 1750 m³/d each. One stand-by high pressure pump (the
fifth) is installed and connected to the four trains. Adequate space has been reserved for two additional high pressure pumps and two trains in order to increase production to 10 500 m$^3$/d of drinking water. The pretreated (clean) water is pumped at a pressure of up to 60 bar by four high pressure, eight stage centrifuge pumps with a capacity of 3888 m$^3$/d each. The maximum design pressure is 70 bar. Each pump is coupled to a turbine for brine energy recovery. The recovered power is around 40% of the total energy required by the high pressure pumps. The latter are made of Duplex stainless steel (chrome = 24–26%; nickel = 7–9%; molybdenum = 2–3%).

The RO section is the heart of the plant. Here, 45% of the feedwater is recovered as product water. The remaining 55% (brine) is depressurized through the turbine and returned to the ocean through a brine pumping station, which is equipped with three submerged pumps, two of which are in operation and one is on stand-by; the capacity of each pump is 12 960 m$^3$/d.

At present, the four RO trains are equipped with 94 Dupont B10-6845T (hollow fine fibre) RO modules arranged in two stages (brine staging: 47/47 or 1/1). Sixteen additional modules per train will be connected progressively over the next 4 years in order to maintain a production of 1750 m$^3$/d per train by the end of the fifth operating year (as agreed with the contractor). The permeate flows to the post-treatment unit. The construction material of the high pressure canalization is AVESTA 254 SMo (high resistance against corrosion).

4.4. Post-treatment unit

Caustic soda is added (for pH adjustment) to minimize corrosion in the product water delivery pipes and the distribution network, and then chlorine is added to disinfect the product water before its distribution for human consumption.

4.5. Product delivery

The drinking water produced in the RO plant flows to a product water reservoir and is then pumped to the ‘carrefour reservoir’ (located 9 km from the plant) by two product water pumps, one in operation and one on stand-by; each pump has a nominal capacity of 10 800 m$^3$/d. A third pump, with a capacity of 3500 m$^3$/d, has been installed and is used when production is ensured only by two trains. The drinking water from the RO plant is mixed with the brackish underground water (in the above mentioned reservoir), and then pumped to Laayoune City.

4.6. Electric power supply

The electric power supply of the plant is ensured through a 22 kV electrical line belonging to the Office national de l'électricité. The high pressure pumps have
three electrical transformers (1000 kV·A capacity) (22 kV/5.5 kV), two in operation and one on stand-by. The low pressure pumps have three other transformers (315 kV·A) (22 kV/220–380 V), one of which is on stand-by. The RO plant needs a nominal power supply of 2 MW.

4.7. Central control room

The entire process of the plant is automated, and visualization of the status of plant equipment (in operation or in the stop mode) is provided by a synoptic control panel. A computer with printer operates the automated plant; dates the operations; and displays, stores and prints all the operational data.

4.8. Auxiliary systems

These include instrument and service air; air conditioning; a chemical cleaning system for the RO modules; a chemical waste disposal system; and a chemical laboratory.

<table>
<thead>
<tr>
<th>TABLE II. PERFORMANCE PARAMETERS ON 8 NOVEMBER 1995 (TRAIN 2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameter</td>
</tr>
<tr>
<td>----------------------------</td>
</tr>
<tr>
<td>Pressure (bar)</td>
</tr>
<tr>
<td>Flow rate (m³/h)</td>
</tr>
<tr>
<td>Temperature (°C)</td>
</tr>
<tr>
<td>pH</td>
</tr>
<tr>
<td>Conductivity (µS/cm)</td>
</tr>
<tr>
<td>TDS (mg/L)</td>
</tr>
<tr>
<td>Silt density index (SDI)</td>
</tr>
<tr>
<td>Residual chlorine</td>
</tr>
<tr>
<td>Chloride (Cl⁻) (mg/L)</td>
</tr>
<tr>
<td>Bicarbonate (HCO₃⁻) (mg/L)</td>
</tr>
<tr>
<td>Sulphate (SO₄²⁻) (mg/L)</td>
</tr>
<tr>
<td>Sodium (Na⁺) (mg/L)</td>
</tr>
<tr>
<td>Potassium (K⁺) (mg/L)</td>
</tr>
<tr>
<td>Calcium (Ca²⁺) (mg/L)</td>
</tr>
<tr>
<td>Magnesium (Mg²⁺) (mg/L)</td>
</tr>
</tbody>
</table>

ᵃ This value had to be confirmed.
5. OPERATION

The commissioning activities were completed in October 1995. These were followed by trial operation and demonstration tests. A reliability test (for 1 month) was started on 5 November 1995. It was confirmed that startup and shutdown of the entire plant were accomplished without any problems.

The performance parameters on 8 November 1995 are given in Table II. A comparison of current performance (after 7000 hours of operation) with the design requirements is made in Table III.

6. PLANT OPERATION

Performance of the plant was assessed using the standard procedures outlined in the following subsections.

6.1. Production

Using the Dupont PC, NORM-PAC III, the production for each train is normalized to the design conditions: a pressure of 70 bar; a temperature of 18°C; a sea water salinity (TDS) of 40 000 ppm; and a recovery ratio of 45%.

Figure 2 gives the results for a typical train: after 7000 hours of operation, the current normalized flow is 96 m³/h versus the design requirement of 73 m³/h. The figure also shows the projections originally made for plant performance.

6.2. Product water salinity

Using the same procedure, the TDS for each train is normalized according to the design conditions cited in Section 6.1. Figure 3 gives the product water TDS from initial startup to the end of the first year of operation. The projected TDS specification of 1000 ppm is also given. As shown, after 1 year of operation the product water TDS is 240 ppm, which is well below the project specification.

6.3. Pretreatment conditions

Biological contamination and a rapid drop in pressure in some trains occurred many times during 7 months of operation without prechlorination dosing. An inspection of the installations was carried out and a large amount of white gelatinous
TABLE III. PERFORMANCE OF THE LAAYOUNE SEA WATER RO PLANT AFTER 7000 HOURS OF OPERATION

<table>
<thead>
<tr>
<th>Train</th>
<th>Actual pressure (bar)</th>
<th>Actual product flow (m³/h)</th>
<th>Flow at design conditions (m³/h)</th>
<th>Actual flow at design conditions (m³/h)</th>
<th>Actual product conductivity (µS/cm)</th>
<th>Actual product conductivity (µS/cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>First stage</td>
<td>Second stage</td>
<td>Total</td>
<td>First stage</td>
<td>Second stage</td>
</tr>
<tr>
<td>First stage</td>
<td>Second stage</td>
<td>First stage</td>
<td>Second stage</td>
<td>Total</td>
<td>First stage</td>
<td>Second stage</td>
</tr>
<tr>
<td>1</td>
<td>54.00</td>
<td>51.65</td>
<td>42.90</td>
<td>26.40</td>
<td>69.30</td>
<td>73.00</td>
</tr>
<tr>
<td>2</td>
<td>65.00</td>
<td>62.00</td>
<td>45.42</td>
<td>27.96</td>
<td>73.38</td>
<td>73.00</td>
</tr>
<tr>
<td>3</td>
<td>63.00</td>
<td>60.08</td>
<td>44.76</td>
<td>27.55</td>
<td>72.31</td>
<td>73.00</td>
</tr>
<tr>
<td>4</td>
<td>64.00</td>
<td>61.08</td>
<td>45.46</td>
<td>27.98</td>
<td>73.44</td>
<td>73.00</td>
</tr>
<tr>
<td></td>
<td><strong>Average</strong></td>
<td></td>
<td></td>
<td><strong>72.10</strong></td>
<td></td>
<td><strong>73.00</strong></td>
</tr>
</tbody>
</table>

*Notes:* Design conditions: pressure 70 bar; recovery ratio = 45%; temperature = 18°C; and TDS = 40 000 mg/L. Train No 1: in operation for 6000 hours.

*Product purity TDS*

<table>
<thead>
<tr>
<th>Design</th>
<th>Actual</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000 mg/L</td>
<td>750 mg/L</td>
</tr>
</tbody>
</table>

*Electric power consumption*

<table>
<thead>
<tr>
<th>Design</th>
<th>Actual</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.82 kW h/m³</td>
<td>5.52 kW h/m³</td>
</tr>
</tbody>
</table>

*Chemical consumption*

<table>
<thead>
<tr>
<th>Chemical</th>
<th>Design</th>
<th>Actual</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cl₂</td>
<td>22 g/m³</td>
<td>3 g/m³</td>
</tr>
<tr>
<td>FeCl₃</td>
<td>23 g/m³</td>
<td>0</td>
</tr>
<tr>
<td>H₂SO₄ (92%)</td>
<td>65 g/m³</td>
<td>20 g/m³</td>
</tr>
<tr>
<td>Flocon 100</td>
<td>15 g/m³</td>
<td>10 g/m³</td>
</tr>
<tr>
<td>SBS</td>
<td>7 g/m³</td>
<td>10 g/m³</td>
</tr>
<tr>
<td>NaOH (35%)</td>
<td>69 g/m³</td>
<td>50 g/m³</td>
</tr>
</tbody>
</table>
FIG. 2. Flow at the Laayoune sea water RO plant (train 2).

FIG. 3. Product water TDS at the Laayoune sea water RO plant (train 3).

material was found on the bottom and walls of the concrete sea water reservoir. On the basis of these observations, the following actions were taken:

(1) Complete disinfection, from the raw sea water reservoir to the high pressure pumps, with about 10 ppm of chlorine for 24 hours;
(2) Extended flushing of the system following disinfection;
(3) Hypochlorite cleaning at a high pH (11.8–12.0);
(4) Citric acid cleaning (pH4);
(5) On-line PT-B of the trains;
(6) On-line PT-A of the trains.

As a result, the system pressure dropped from 4.5 to 2.7 bar (across the system) and coliform in the product water was removed. Prechlorination dosing has been in operation since this time.

After the first year of operation, the most suitable pretreatment conditions were found to be:

- Chlorine: 2 ppm
- Sulphuric acid: 20 ppm
- Flocon 100: 15 ppm
- SBS: 10 ppm
- pH of feedwater: 6.9
- Backwash cycle for the sand filter cells: 20 days
- Replacement of the cartridge microfilters: Every 2 months
- Chemical cleaning of the RO trains: Every 3 months is adequate

### TABLE IV. DATA USED AS A BASIS FOR THE ECONOMIC ANALYSIS

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total investment costs</td>
<td>230 000 000 dhs</td>
</tr>
<tr>
<td>Civil work</td>
<td>46 000 000 dhs</td>
</tr>
<tr>
<td>Equipment</td>
<td>184 000 000 dhs</td>
</tr>
<tr>
<td>Actualization rate</td>
<td>10%</td>
</tr>
<tr>
<td>Availability of the plant</td>
<td>90%</td>
</tr>
<tr>
<td>Amortization period for the civil work</td>
<td>40 years</td>
</tr>
<tr>
<td>Amortization period for the equipment</td>
<td>15 years</td>
</tr>
<tr>
<td>Electric power</td>
<td>1 dhs/kW-h</td>
</tr>
<tr>
<td>Chlorine</td>
<td>6500 dhs/t</td>
</tr>
<tr>
<td>Sulphuric acid</td>
<td>4560 dhs/t</td>
</tr>
<tr>
<td>Flocon 100</td>
<td>68 400 dhs/t</td>
</tr>
<tr>
<td>Caustic soda</td>
<td>5700 dhs/t</td>
</tr>
<tr>
<td>SBS</td>
<td>17 100 dhs/t</td>
</tr>
</tbody>
</table>

a 10 dirham (dhs) = US $1.
Under the above conditions, an SDI of less than one is consistently maintained in the feedwater without ferric chloride dosing.

6.4. Post-treatment conditions

The aggressivity correction facility of the produced water, actually ensured by caustic soda dosing, is inefficient because it does not allow this water to be brought to its calco-carbonic equilibrium. In fact, the water produced damages the equipment and attacks the canalization. This has been confirmed through a pH increase in the product water, which reaches 10 at the level of the ‘carrefour reservoir’, whereas it was 9 at the outlet of the plant.

The only way of solving this problem is to remineralize the product water with calcium (Ca$^{2+}$) and bicarbonates. A study is being carried out on whether to introduce filtration on a medium consisting of calcium and magnesium in order to correct the aggressivity of the water before it is transported.

<table>
<thead>
<tr>
<th>TABLE V. WATER PRODUCTION COSTS$^a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plant conditions</td>
</tr>
<tr>
<td>Chemical consumption</td>
</tr>
<tr>
<td>Chlorine</td>
</tr>
<tr>
<td>Sulphuric acid</td>
</tr>
<tr>
<td>Ferric chloride</td>
</tr>
<tr>
<td>Flocon 100</td>
</tr>
<tr>
<td>SBS</td>
</tr>
<tr>
<td>Caustic soda</td>
</tr>
<tr>
<td>Power consumption</td>
</tr>
<tr>
<td>Recovery ratio</td>
</tr>
<tr>
<td>Production</td>
</tr>
<tr>
<td>Chemical costs</td>
</tr>
<tr>
<td>Electrical costs</td>
</tr>
<tr>
<td>Amortization costs of the civil work</td>
</tr>
<tr>
<td>Amortization costs of the equipment</td>
</tr>
<tr>
<td>Operation and maintenance labour</td>
</tr>
<tr>
<td>Membrane replacement</td>
</tr>
<tr>
<td>Cartridge filter replacement</td>
</tr>
<tr>
<td>Water production costs</td>
</tr>
<tr>
<td>(US $2.48/m^3$)</td>
</tr>
</tbody>
</table>

$^a$ 10 dirham (dhs) = US $1$. 
7. ECONOMIC ANALYSIS

A product water cost analysis was made on the basis of the original design conditions and the conditions observed after 1 year of operation. Table IV gives the data used as a basis for this analysis, and Table V outlines the water production costs.

8. CONCLUSIONS

Given the results of 1 year of operation, the following conclusions can be made. The performance of the Laayoune sea water RO plant exceeds projections, both for production and for product salinity. Calcium and bicarbonates should be used to correct aggressivity. The economics of sea water RO seem to be favourable.
REVERSE OSMOSIS MEMBRANES IN THE POWER INDUSTRY

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Abstract
REVERSE OSMOSIS MEMBRANES IN THE POWER INDUSTRY.
A description is given of two applications of reverse osmosis (RO) membranes in the power industry. These are sea water RO for potable and boiler feedwater use, and for the control of cooling tower water chemistry, with side stream RO processing.

1. CASE STUDY 1 — DIABLO CANYON SEA WATER REVERSE OSMOSIS (RO) SYSTEM

The first application of sea water RO for the production of boiler feedwater in the United States of America took place at the Diablo Canyon nuclear power plant, which is owned by Pacific Gas and Electric (PG&E). This plant is a 2200 MW PWR located along the Pacific Ocean on the California central coastline near the town of San Louis Obispo. In 1985, the RO system was installed by Hydranautics, and has been continuously operated since that time.

While sea water is used for reactor cooling, additional fresh water is required to supplement the plant’s steam generation and for other uses such as potable water and fire suppression. The primary source of fresh water, Diablo Creek, is not a dependable supply all year round. Consequently, PG&E selected a sea water RO desalination plant as the best option for supplying additional fresh water to this facility. Hydranautics was selected to supply an RO plant with a capacity of 2200 m³/d, on a ‘build, install and operate’ basis.

The design of the Diablo Canyon RO plant is a two stage (permeate) system, as shown in Figs 1 and 2. The major design parameters are given in Table I.

The pretreatment system consists of primary and secondary pressure media filters followed by ultraviolet (UV) sterilizers and cartridge filters. The raw sea water is pumped from the intake structure to a storage tank. Coagulant and polyelectrolyte are added upstream of the primary filters to aid filtration.
An organic scale inhibitor is added to the filtered water to prevent precipitation of the calcium salts on the membrane surface. The filtered sea water then passes through the UV sterilizers and cartridge filters. The system has provisions to shock chlorinate the sea water and to dechlorinate prior to RO with sodium metabisulphite.

The two stage RO design was selected to optimize the quality of the product water and the flexibility of operation. The pretreated sea water is pressurized to 70 bar and delivered to the first stage sea water system. This system typically operates at 50% recovery, producing 2420 m$^3$/d of desalted water with a salinity of less than 600 ppm total dissolved solids (TDS).

The second stage of the Diablo Canyon desalination plant is a brackish RO system operating at high recovery. This system typically operates at a feed pressure of 25 bar and 90% recovery. It is capable of treating up to 1550 m$^3$/d from the primary stage. The product water quality from the brackish water RO system is typically less than 100 ppm. A blend of first stage and second stage permeates enables the production of various quantities and qualities of product water. This flexibility allows the owner of the plant to obtain high quality water (if desired) at a reduced capacity, or larger flow rates at the design capacity.
The performance of the sea water RO system at Diablo Canyon has been very successful. The operating data for the first 4.5 years are shown in Figs 3 and 4. Figure 3 shows the permeate flow rate over this period. For most of this period, the plant was not required to deliver the full capacity of 2180 m$^3$/d. However, when required, a capacity in excess of design was possible because of the flexibility of the two stage design. Figure 4 shows the feedwater quality, measured in units of conductivity ($\mu$S/cm). The design quality of 350 ppm corresponds to a conductivity of approximately 600 $\mu$S/cm. For most of the operating period, the product water quality was above that of the design levels.

2. CASE STUDY 2 — BAYSWATER/LIDDELL POWER STATION COMPLEX

The Bayswater/Liddell power station complex contains the largest RO system in the Southern Hemisphere. It is used to control the cooling water chemistry in a large scale ‘zero discharge’ system.
CHMIELEWSKI


This complex, located in the Hunter Valley of New South Wales, Australia, is a 4640 MW, coal fired complex. It consists of the Liddell station, commissioned in 1971 (4 x 500 MW), and the Bayswater station, consisting of 2640 MW (4 x 660 MW), commissioned in 1986. This complex contains one of the world’s largest power station water management systems with zero discharge of aqueous streams.

To achieve zero discharge, the approximately 24,000 tonnes of dissolved salts per year must be removed from the combined power complex water systems. The treatment system to accomplish this task is truly an engineering and operation masterpiece. The major processes incorporated into this water treatment system include: conventional lime softening; dual media filtration; alkalinity reduction via ion exchange; RO; solar evaporation ponds; and vapour compression evaporators.

A simplified flow diagram of the Bayswater/Liddell waste water treatment system is shown in Fig. 5. Two sets of large parabolic wet cooling towers provide cooling to the generating station condensers. Loss of water from evaporation and drift result in an increase in TDS in the main cooling water loop. A combination of fresh water make-up and side stream cooling water processing is necessary to maintain the proper chemistry in the main cooling water loop. The maximum limits for the cooling tower water chemistry are as follows: water pH: 7–8.5; Langelier

FIG. 5. Bayswater/Liddell waste water treatment system.
index: +1.0; calcium: 170 mg/L; sulphate: 1200 mg/L; silica: 150 mg/L; and TDS: 2500 mg/L.

The major components of the cooling water control system are alkalinity reduction using weak acid ion exchange and TDS reduction with lime softening and RO. In addition, the concentrate or reject from each of these major processes is treated in a common water reclamation plant, which consists of a vapour compression evaporator and solar ponds.

2.1. Design of the TDS reduction system

Focus is placed on the design and operation of the RO system used to control the TDS in side stream processing of the cooling water loop.

Pretreatment to the RO system consists of conventional lime and soda softening clarifiers. Each of these four units has a capacity of 400 m³/h. Partial softening is accomplished with the addition of lime and soda ash. Total hardness reductions of the order of 60% are achieved, as well as approximately 50% reductions in silica. Ferric chloride is used as a flocculent aid in the clarification units. Water from the clarifiers is filtered with dual media filters to remove the suspended solids. Sulphuric acid is added before the filters to reduce the pH to approximately 7.

Filtered water is collected in clear water sumps, from where it is pumped to the RO systems. Chemical treatments include scale inhibitors, and additional acid and chlorine to control the potential for biological fouling of the membranes. The RO systems at the Bayswater/Liddell station consist of a total of eight trains, each with a feed capacity of 185 m³/h. Each train consists of a 16–8–4 array, with a total of 168 model 8540-MSY-CAB2 Hydranautics cellulose acetate membranes. The design recovery of each unit is 82.5%. Permeate is produced at a rate of 152 m³/h, and the concentrate stream is 33 m³/h. During operation, the units have operated at recovery levels ranging from 75 to 90%.

Cellulose acetate membranes were selected for this application, since they show tolerance to chlorine and good rejection, and have demonstrated low fouling tendencies in a number of waste water applications. The ability to tolerate chlorine has proved to be of great benefit to this plant, as well as in similar applications in North America, where the potential for biological activity is high. Biological fouling has never been a problem in the Bayswater/Liddell RO system.

2.2. Performance of the RO systems

The overall reduction in TDS from the RO system has been excellent. The initial salt rejection upon startup was approximately 99%, which was better than expected. The performance of the plant over its first 10 years of life has exceeded expectations. Membranes have been replaced twice during this period, also exceed-
ing expectations. The typical feedwater to the RO system has been within specifications, with an average feed TDS of about 2200 ppm. The permeate quality, initially less than 100 ppm TDS, has gradually risen to about 250 ppm TDS. The total brine flows have, when all eight units are operating, a total of 260 m³/h, with a TDS in excess of 10 000 ppm. Total salt removal via the RO system concentrate stream is therefore more than 60 000 kg/d, or almost $20 \times 10^6$ kg/a.

3. CONCLUSIONS

These case histories of the application of RO membranes in the power industry include sea water RO for potable water and boiler feedwater, and control of the cooling water chemistry.

These systems show that in the long term performance is satisfactory with proper system design and operation. Membrane technology has proved to be capable of meeting the reliability and durability requirements of the power industry. This has been demonstrated in more than 10 years of operating experience.

Membrane technology for boiler feed and cooling tower applications should no longer be considered novel, or for demonstration purposes only. Most users can benefit from the advantages of membrane technology in the design and operation of today’s power generation systems.
IMPORTANCE OF THE POWER TO WATER RATIO IN SELECTING POWER-DESALINATION TECHNOLOGY

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Abstract

IMPORTANCE OF THE POWER TO WATER RATIO IN SELECTING POWER-DESALINATION TECHNOLOGY.

Today, fresh water, which is the 'essence of life', can be reliably produced by desalination, particularly from unlimited sea water. Large dual purpose power-desalination plants are being built to reduce the production costs of electricity and water. Over 25 000 MW of power are combined with desalination plants in the largest use of co-generation concepts. In many countries, particularly in the Middle East, the demand for water is growing at a pace that is greater than that of electricity. Also, the peak demand occurs in summer, and then drops dramatically to 30-40%; in contrast, the demand for desalinated water is almost constant. Therefore, the design of future plants requires careful consideration of the power (MW) to water (10^6 gal/d) ratio. An examination is made of the possible choices of steam turbine technology in relation to the selection of desalination process (multi-stage flash (MSF), multi-effect distillation (MED), reverse osmosis (RO) and vapour compression (VC)). Using both a simple and an integrated approach, a hybrid system was assessed with a view to taking full advantage of thermal and electric energy. Water can be stored, whereas electricity storage is not practical. In this case, excess electricity can be diverted to water production, incorporating electrically driven sea water RO and/or VC combined with the low pressure steam driven technology of MSF or MED, which is advantageous to the design of an integrated hybrid plant. A review of the large scale power-desalting projects undertaken in recent years underlines the importance of the power to water ratio in selecting the appropriate technology.

1. INTRODUCTION

Today, fresh water can be reliably produced by desalination, particularly from unlimited sea water. Large dual purpose power-desalination plants are being built to reduce the production costs of electricity and water. Over 25 000 MW of power are combined with desalination plants in the largest use of co-generation concepts. Dual purpose power-desalination plants make use of the thermal energy extracted or exhausted from power plants in the form of low pressure steam to provide heat input to the thermal desalination plants for the multi-stage flash (MSF) or multi-effect distillation (MED) processes. Electric energy can also be effectively used in
electrically driven desalination processes such as reverse osmosis (RO) and vapour compression (VC).

The important issue facing planners, designers and operators of power–desalination projects is optimum selection of the power and desalting technology in order to optimize the joint production of water and power by the utility. In the past, the choice was based on minimizing the costs for stand alone, base load production of power and water.

The Middle East countries, particularly the Gulf Co-operation Council (GCC) States, are the largest users of desalination technology, with about 50% of the world's capacity installed in the area. The demand for water in the Gulf region is rising at a pace that is greater than that of electricity, increasing at a rate of 10% per year in some countries.

Unique conditions exist in the Gulf, where the peak demand for electricity rises significantly during the summer, mainly because of the use of air-conditioning, and then drops dramatically to 30–40%. This creates a situation where over 50% of the power generated is idle. In contrast, the demand for desalinated water is almost constant. Water can be stored, whereas electricity storage is not practical. In this case, excess electricity can be diverted to water production, incorporating the electrically driven technologies of sea water RO and/or VC combined with the low pressure steam driven technology of MSF or MED, making it advantageous to the design of an integrated hybrid plant.

Because the annual water demand is growing at a pace that is greater than that of electricity, the design of future plants requires careful consideration of the power (MW) to water (10^6 gal/d) ratio.\(^1\)

2. RECENT POWER–DESALINATION PROJECTS

Some examples of the large scale projects undertaken in recent years are given. The Phase I and Phase II Jeddah sea water RO plants, each with 15 x 10^6 gal/d, are combined with an 80 x 10^6 gal/d MSF plant at the Saline Water Conversion Corporation (SWCC) complex and have an installed power capacity of 924 MW. The Yanbu–Medina Phase II project is a 150 MW backpressure steam turbine power plant (BTG) combined with 30 x 10^6 gal/d of sea water RO and over 30 x 10^6 gal/d of MSF. Also, in Saudi Arabia SWCC was awarded (in the Eastern province) Al Khobar III, a 475 MW BTG combined with a 72 x 10^6 gal/d MSF plant, and (at the Red Sea) Shoiba Phase II, a 575 MW BTG plant combined with a 120 x 10^6 gal/d MSF plant featuring ten desalination units, each with a capacity of 12 x 10^6 gal/d.

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\(^1\) 1 gal (UK) = 4.546 x 10^{-3} \text{ m}^3.
In Abu Dhabi, the Water and Electricity Department is successfully completing a six unit 732 MW extracting steam turbine (EST), $86.4 \times 10^6$ gal/d MSF plant featuring the six largest MSF units in the world, each with a capacity of $14.4 \times 10^6$ gal/d.

In Dubai, the Jebel Ali Station G is a 450 MW, $72 \times 10^6$ gal/d power–desalting plant that originally used a combination of four gas turbines (GTs) with heat recovery steam generators (HRSGs) and MSF desalination units. Recently, the Dubai Water and Electricity Department converted a simple cycle GT to a combined cycle by adding low pressure steam turbines between the HRSG and the MSF units, making this facility the largest combined cycle–desalting plant in the world.

In Kuwait, the recently announced Az Zour North Power Station will comprise eight 300 MW ESTs combined with eight $7.2 \times 10^6$ gal/d MSF units, ultimately to be expanded by an additional eight MSF or RO units of identical capacity.

It is obvious that each of these solutions was dependent on numerous factors, including the local conditions and experience, the availability of fuel, and the willingness to take the risk of using new technology.

The Power and Water Master Plan of Abu Dhabi to the year 2010, completed recently by Bechtel International Inc. for the Abu Dhabi Water and Electricity Department, required very careful selection of the power and water technology for future plants. To optimize selection, Bechtel developed a unique programme that took into account the individual site demands for electricity and water (power to water ratio), the total network situation, the cost of energy and the capital costs of the plants (optimized for the lowest cost solution, depending on the ratios of water to base load power and peak to base load electricity demand).

In view of the high cost of power–desalting plants, the GCC States are considering possible alternatives. Ongoing considerations are expected to include the feasibility of installing power–desalination units that use various improved methods of generation. The chief objective is to minimize the investment and operating costs and to ensure an optimum supply of energy and water.

3. AVAILABLE DUAL PURPOSE FACILITIES

The importance of the power to water ratio becomes more relevant after assessing the comparative advantages of the currently available power and water technologies. In this paper, the nuclear option for power generation is excluded.

(1) Gas turbine technologies: These include GTs with HRSGs (GT–HRSG); GTs in the combined cycle mode: HRSGs with BTGs (CC–BTG); GTs in the combined cycle mode: HRSGs with ESTs (CC–EST); and simple cycle GTs with no waste heat recovery (GT).
(2) **Boiler–steam turbine technologies**: These include ESTs, BTGs and stand alone auxiliary boilers.

(3) **Thermally driven desalination technologies**: These include MSF, MED and MED with thermal compression (MED–TC).

(4) **Electrically driven desalination technologies**: These include RO and VC.

The above options differ significantly with respect to several key characteristics: the efficiency, the heat rate of power production and the maximum power to water ratio. Each combination differs in the maximum performance ratio (PR), the electricity consumption of the desalination process and the capital costs.

4. **CHARACTERISTICS OF THE TECHNOLOGIES**

(1) **Gas turbines**: The GTs are efficient in base load operation in that the HRSGs provide waste heat without sacrificing performance, but they have relatively low water to power ratios. Moreover, their efficiency falls off rapidly in the turndown mode. Their efficiency is 29–30%, the capital costs are US $450–600/kW and the design air temperature is 50°C.

(2) **Steam turbines (backpressure)**: These steam turbines are much less efficient when assessed as a stand alone, base load option, but they can produce far more water in relation to power. Their efficiency is 21–27% and the capital costs are US $750–1000/kW.

(3) **Combined cycle units**: These units are the most efficient for producing base load electricity, but their water ratio is very much lower. Combined cycle with BTGs has an efficiency of 35–39% and the capital costs are US $550–850/kW. Combined cycle with ESTs has an efficiency of 37–40%, the capital costs are US $500–800/kW and the design temperature is 50°C.

(4) **Steam turbines (extraction)**: These steam turbines are flexible and efficient in power production, but they produce about half the amount of water compared with BTGs. Their efficiency range is 24–30% and the capital costs are US $650–900/kW.

(5) **MSF**: This is a well established, reliable technology with a PR limit of 10 (typically 8), an internal power consumption of 4 kW·h/t of water, a turndown ratio of 110–70% of the nominal capacity and capital costs of US $4–12 · gal⁻¹·d⁻¹.
(6) **MED**: This process has a PR of 8–16 (typically 12), an internal power consumption of 1.8 kW-h/t of water, a turndown ratio of 120–45% of the nominal capacity and capital costs of US $3.50–8 · gal⁻¹·d⁻¹.

(7) **MED-TC**: This technology is similar to MED, but it requires higher pressure steam for the steam jet compressor that acts as the heat pump. It is designed to have 2–10 atm (abs) of steam, and the water vapour is thermally compressed across several effects. MED-TC is most often used with GTs.

(8) **Sea water RO**: This has become a mature technology, with a high degree of reliability. It uses electric energy to operate, and energy recovery devices can recover 24–30% of the total energy from the high pressure RO reject brine stream. As a result, the total plant energy requirements can vary between 4.2 and 7.4 kW-h/t of product. The RO system can vary in output, but the great advantage is its quick startup, which allows shutdown during peak power operation. The capital costs of the RO plant vary between US $3.50 and 9 · gal⁻¹·d⁻¹.

(9) **VC**: This is a simple, reliable and efficient process requiring electric power only and is inherently the most efficient distillation process. High performance VC units have a specific electricity consumption of 7.5–10 kW-h/t of product, which is equivalent to a PR of 23 using an efficiency of power conversion of 30%. VC, like RO, is a quick startup system because of the very limited mass of water circulating, therefore it is able to be shut down during peak and off-peak operation and can use the available electric power generation for water production. In contrast to RO, VC produces high quality distilled water (10 ppm total dissolved solids). The capital costs can vary between US $6 and 12 · gal⁻¹·d⁻¹.

The above examples give a good indication of the complexity of selecting the proper technology for combined water and power production. Given that the water and power requirements of a real utility vary significantly by season, the optimal choice for a power–desalting plant is not obvious when operation extends beyond base load.

5. **TYPICAL POWER TO WATER RATIOS FOR DIFFERENT TECHNOLOGIES**

The typical power to water ratios for different technologies are given in Table I. It is interesting to note that the more efficient the base load operation for generating electricity, the less effective the production of water and power in the peaking and intermediate modes. The most advanced combined cycle desalination plants have
TABLE I. TYPICAL POWER TO WATER RATIOS FOR DIFFERENT TECHNOLOGIES

<table>
<thead>
<tr>
<th>Technology</th>
<th>Power to water ratio$^a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steam turbine BTG–MED</td>
<td>3.5</td>
</tr>
<tr>
<td>Steam turbine BTG–MSF</td>
<td>5</td>
</tr>
<tr>
<td>Steam turbine EST–MED</td>
<td>7</td>
</tr>
<tr>
<td>Steam turbine EST–MSF</td>
<td>10</td>
</tr>
<tr>
<td>GT–HRSG–MED</td>
<td>6</td>
</tr>
<tr>
<td>GT–HRSG–MSF</td>
<td>8</td>
</tr>
<tr>
<td>Combined cycle BTG–MED</td>
<td>10</td>
</tr>
<tr>
<td>Combined cycle BTG–MSF</td>
<td>16</td>
</tr>
<tr>
<td>Combined cycle EST–MED</td>
<td>12</td>
</tr>
<tr>
<td>Combined cycle EST–MSF</td>
<td>19</td>
</tr>
<tr>
<td>RO</td>
<td>0.8–1.5</td>
</tr>
<tr>
<td>VC</td>
<td>1.4–1.6</td>
</tr>
</tbody>
</table>

$^a$ Power to water ratio = MW required per $10^6$ gal/d.

a very high power to water ratio. However, the choice is which combined cycle would provide a significant surplus of unused power capacity during winter.

To determine the optimum mix of generating plants, Bechtel has developed a simulation model that determines the size, type and operating cycle of each of the possible combinations of power and steam generation options.

The optimum configuration for dual purpose power and water depends greatly on the power to water ratio at different periods of electricity and water demand. In winter, when the power demand is low and the water demand is continuously high, selection of an efficient electric plant will result in a significant amount of idle power because of the high power to water ratio. The marginal cost of water will rise significantly if auxiliary boilers or bypass steam turbines have to be used by the pressure reducing station to keep the desalination plant at full capacity.

The above data show that electrically driven desalination processes such as RO and VC clearly require minimum investment in the power plant. At the same time, where seasonal and daily variations occur, electrically driven technology can be an excellent choice for hybridization with more conventional dual purpose plants. The hybrid approach could achieve the lowest total investment costs, flexibility in production, and the lowest power and water production costs.
EXPRESSX IN AND FUTURE PROSPECTS FOR SEA WATER DESALINATION IN SAUDI ARABIA

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Abstract

EXPERIENCE IN AND FUTURE PROSPECTS FOR SEA WATER DESALINATION IN SAUDI ARABIA.

The national programme for sea water desalination in Saudi Arabia is assigned to the Saline Water Conversion Corporation (SWCC), a government entity loosely affiliated with the Ministry of Agriculture. In addition to water production, SWCC generates considerable electric power in its dual purpose power/water plants, selling excess power to the national grid. SWCC also builds and maintains certain major fresh water pipelines that connect its plants to important municipal water systems. SWCC’s pride is the Research, Development and Training Center (RDTC) located in Al-Jubail. The goals at RDTC include improving plant efficiency and minimizing scale formation and corrosion problems. It also trains Saudi engineers and technicians in the operation and management of SWCC plants. As a result, Saudi nationals now represent 65% of the workforce and are heavily involved with all aspects of plant specification and tender analysis. Working at the plant site, SWCC has been able to optimize the power/water production ratios to minimize the cost of base load plants; use multi-stage flash (MSF)/reverse osmosis (RO) hybrid plants to further reduce water costs; optimize the selection and design of materials; make improvements in the process of site selection and intake design; reduce operation and maintenance costs through the field testing of new process concepts; continue the development and training of plant operators; use local workshops and suppliers whenever possible; field test new products, processes and materials; and, in total, reduce water costs to as low as US $0.53/m³. Looking to the future, SWCC is aware that it must adopt new policies with respect to pricing and consider the long term implications of subsidized water. It also recognizes that desalination costs will continue to decrease because of economies of scale; use of lower cost materials; more efficient operation; increased use of automation and sophisticated controls; and continuing high competition among suppliers. All these points are, of course, of benefit to the eventual customer. In terms of technical developments, MSF is mature and will see only incremental improvements in cost and performance. Multi-effect distillation (MED) and thermal vapour compression (TVC) are still developing towards larger unit sizes, better efficiency and greater reliability. RO will continue to advance through longer operating histories from which to learn; improved pretreatment techniques, including membrane pretreatment; and improved membranes with lower operating pressures, a higher flux and higher salt rejection. Overall, 50% water recovery will become the norm. Beyond this, new versions of hybrid plants will appear, including membrane/membrane,
membrane/adsorption and membrane/electrochemical systems. The eventual result will be plants with 100% recovery (zero discharge). The prospects for desalination with nuclear energy are bright, but it must be remembered that most coupling options are not unique to nuclear. Social and political issues are critical and must be addressed early and often. It can be concluded that sea water desalination is now reliable and of reasonable cost; desalination costs will continue to decrease; MSF is close to optimization; MED and TVC are growing in competitiveness to MSF, especially in smaller sizes; RO continues to strengthen as a viable candidate under nearly all conditions; the final choice of technology should be reached by an educated customer, not dictated by suppliers; and international co-operation is vital to the further productive reset that is so critical to success.

1. INTRODUCTION

Saudi Arabia has accumulated considerable experience in operating and maintaining various desalination processes. It has developed and exploited the Research, Development and Training Center in Al-Jubail for the purpose of improving efficiency, controlling scale formation, minimizing corrosion effects and reducing water costs. It has also developed training courses for engineers and technicians, as well as intensive on the job training in operation and maintenance tasks. There are now well qualified Saudi engineers and technicians who operate and maintain all the plants. Furthermore, there are also well experienced Saudi engineers who are involved in preparing plant specifications, evaluating and analysing tender documents and supervising construction.

At present, a large percentage (over 65%) of Saudis dominate the operation and maintenance staff. Furthermore, training centres and technical seminars have also greatly contributed to the development of their technical and administrative skills. Consequently, with great confidence Saudis have begun to manipulate the major design and operation parameters, and to modify the maintenance techniques. This has resulted in a reduction in the operation and maintenance costs and a minimization of the water costs to as low as US $53/m³ for large multi-stage flash (MSF) plants.

The Saudi experience in improving the design of new plants and the operation of existing desalination plants can be summarized as follows:

(1) Co-generation of water and power using large multi-purpose plants reduces the cost of water when such plants are utilized to supply the base load electric power demand;
(2) Use of hybrid distillation and reverse osmosis (RO) processes can achieve lower water costs than multi-purpose plants using only distillation;
(3) The energy efficiency and recovery should be maximized to achieve the lowest water costs over the life of the plant;
(4) Proper selection of material and design parameters is essential to optimize the capital costs and to minimize the water costs;
(5) Appropriate site selection and intake design greatly influence the feedwater quality, and the capital costs and operation and maintenance costs;
(6) Operation and maintenance costs can be greatly reduced through field experience and trials to select the proper operating parameters and maintenance techniques that fit the existing requirements for the feedwater, plant design, operator skills and production;
(7) Continuous development and training of operators and technical staff are essential to control and reduce the water production costs and to extend the useful life of plants;
(8) Local workshops and suppliers should be encouraged to manufacture and supply parts and chemicals to minimize the costs and down time;
(9) Field testing and the development of new products, processes and materials should be a continuous task to reduce costs and to train staff.

2. FUTURE PROSPECTS FOR SEA WATER DESALINATION TECHNOLOGY

2.1. Water costs and pricing

The most critical factor for the future development of desalination technology and the degree of unit cost reduction is the water pricing policy. Desalination plants will continue to require major capital investment if they are to achieve the desired economy of scale. Most arid countries, which most need desalination technology, will not be able to afford such investments as long as they continue to subsidize water. Proper water pricing is essential, not only to facilitate and sustain its availability but also to reduce waste and environmental degradation. The cost of good quality water has been increasing in most free market countries at twice the rate of local inflation. This is expected, since the lower cost water sources are being depleted and new sources require larger investments.

The unit cost of desalted water has decreased over the past 20 years and will continue to do so in the future in order to be more attractive than alternative sources of water supply. This decrease in unit cost can be achieved through larger units (economy of scale), lower cost materials, improved products, more efficient utilization of energy, more automation, more competition among suppliers and more privatization of the water supply market.
2.2. Technical prospects

There is a consensus in the desalination industry that MSF distillation has matured and that no major breakthrough can be expected in the process with the exception of building larger sized units. Continued development is expected, however, in other thermal processes. Equipment suppliers are working to build reliable and larger low temperature alternatives using multi-effect distillation (MED) or thermal vapour compression (TVC) units.

Further technical developments are expected in membrane processes as desalination benefits from the extensive R&D efforts under way in many countries in membrane separation fields. The continuing operational experience gained by owners and manufacturers of existing sea water RO plants will also lead to improved products, process designs and operational procedures. More improvements are needed in the pretreatment of feedwater, especially for surface sea water. Development of low cost microfiltration membranes is expected to provide an economic alternative to the problems of RO pretreatment.

New generations of membranes have recently come into use that have a lower energy requirement, higher salt rejection, better chemical stability over a wider pH range, higher temperature tolerance and better stability against compaction. These new membranes are expected to lower the production costs and to make RO more reliable. New membrane manufacturing techniques such as plasma polymerization or radiation induced grafting may be available within the next 10 years, as well as new classes of membranes with higher specific fluxes, a higher temperature tolerance, and high chemical stability and anti-fouling behaviour. Improved backing materials will allow the production of membranes with a higher resistance to compaction, allowing operation at higher pressures. Hence, conversions of 50% or more will become common, resulting in a reduction in the water production costs.

Major improvements in existing desalination technology costs and reliability are expected with the use of innovative hybrid processes. Use of chemical separation processes, such as adsorption or ion exchange in combination with a physical process such as a membrane, can improve the efficiency of desalination and reduce or eliminate waste streams from plants by achieving close to 100% water recovery, even for sea water plants. Also, there is evidence that using an electric or electromagnetic field may achieve similar benefits, especially with the development of electrically charged membranes.

Unfortunately, it will take many years before the benefits of all the technical developments in desalination are available to users, since no major R&D programme in desalination is under way in any part of the world. Between 1952 and 1982, United States Government funding for desalination R&D and demonstration averaged about US $30 million per year (in 1985 US dollars) [1]. This research programme was
primarily responsible for the development of RO, and many advances in distillation technologies.

Between the mid-1970s and mid-1980s, the Japanese Government co-ordinated major efforts by its industry to develop Japanese desalination technologies. All countries of the world continue to benefit from these major efforts, while US and Japanese suppliers maintain their world leadership in the desalination industry.

It is worth noting that the R&D efforts being made by the Al-Jubail Research, Development and Training Center of the Saline Water Conversion Corporation, as well as the excellent plans of the Middle East Desalination Research Center at Muscat, Oman, and the Kuwait Institute for Scientific Research are expected to produce benefits to all users of desalination technology.

2.3. Nuclear energy

The prospect of using nuclear energy for sea water desalination on a large scale remains very attractive, since desalination is an energy intensive process that can utilize the waste heat from a nuclear power plant, or the electricity produced by such plants. It makes no difference to the desalination process how the energy is produced. However, the need to avoid any possible radioactive contamination of the product water, and the need to co-ordinate the implementation of major capital intensive power and water projects, are some of the important aspects that need to be considered.

It is well known that nuclear reactors are most competitive for large electric plants (900 MW(e) or more) if both low interest rates for capital (i.e. government subsidies) and a national or regional power grid are available [2]. Very small reactors suitable for dedicated use for a desalination plant may be commercially available, but none has yet been built or commissioned. The availability, safety and security of nuclear fuel and the disposal of waste material need to be ensured before the market is opened to such applications.

To improve the potential of utilizing nuclear energy for desalination, other energy intensive processes such as the production of salts from sea water have to be considered and evaluated as a cornerstone for the development of a new industrial zone that supports energy intensive industries.

3. CONCLUSIONS

(1) Sea water desalination technology has been developed to the point where it is considered to be a reliable source of fresh water at a reasonable cost. Most
often, the desalination option is proving to be cheaper than building new dams or pipelines to provide water to urban centres, and to have a more positive environmental impact.

(2) The desalination costs are expected to continue to decrease and to become more attractive than most other options. The actual experience accumulated by Saudi Arabia indicates that for very large sea water desalination plants a unit water production cost of US $0.53/m³ is achievable. The water costs depend on the plant size, the feedwater salinity and quality, the plant material and specifications, the energy costs, the location, the operating skills, the cost allocation assumptions for dual purpose plants, and many other location and time specific factors.

(3) The MSF process is cost competitive in large scale dual purpose plants that produce water and power and operate close to their optimum design conditions. The low running costs of MSF compensate for its high capital costs. Proper selection of corrosion resistant materials should be made to ensure a long plant life and low maintenance costs. This process is well developed and its future growth will be based mostly on the development of larger units and a once through design.

(4) The MED process is cost competitive when low pressure steam is available. The scaling problems of high temperature MED can be avoided using low temperature MED, especially as hybrid MED. The low temperature vertical tube MED–TVC process holds the greatest potential for future large thermal desalination plants with a low unit cost.

(5) The RO process should always be considered and compared with other alternative processes, regardless of the size of the desired plant. RO plants should be well designed and operated to achieve their cost competitive advantage. Proper process design and proper sea water intake and pretreatment design and operation are essential to reduce the fouling and scaling of sea water RO plants.

(6) The choice of desalination process is subject to many interactive variables and should not be left to the influence of suppliers. Proper choice of the process materials, the plant location, the sea water intake design, the pretreatment, the operation and maintenance requirements, the degree of flexibility and reliability of the plant, and the desired quality and quantity of product water should be considered and analysed by experienced independent professionals to obtain a long plant life with minimum water costs.

(7) International and regional co-operation is needed to promote desalination R&D and to assist owners of desalination plants in their choice, installation and management. More funding for research, education and training programmes is needed to reduce the desalination costs and to increase the benefits to world populations.
REFERENCES


OPPORTUNITIES FOR DESALINATION SYSTEMS USING NUCLEAR ENERGY

(Session 5)

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TECHNOLOGY TRANSFER IN NUCLEAR DESALINATION

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Abstract

TECHNOLOGY TRANSFER IN NUCLEAR DESALINATION.

A recent technical and economic feasibility study on use of nuclear desalination as a source of low cost potable water in North Africa indicated that it would be technically feasible and economically competitive in a range of situations. This opened the door for a demonstration plant to be selected from several options that have been identified. Most developing countries in a water stress or water scarce situation do not have a sufficient nuclear fuel cycle technology base, including reactors. Therefore, the introduction and development of a sustainable nuclear programme for the safe, reliable and economic production of desalted water alone, or water and electricity, in developing countries should involve considerable technology transfer and technical co-operation at the international and bilateral levels. Technology transfer and technical co-operation are challenging tasks that require strong national will and determination to maximize local participation with a view to enhancing the national capability of managing nuclear desalination and solving problems. The issues discussed are for the benefit of those countries that are starting out in nuclear energy, and include establishing an organization culture and formulating guidelines for technology transfer on the basis of the advanced experience accumulated in the Republic of Korea. Finally, an action plan is proposed.

1. INTRODUCTION

Considerable parallel technological and industrial development and growth have taken place in nuclear and desalination industries since their take-off in the early 1960s. To a large extent, both have similar growth patterns, as shown in Fig. 1 [1]. The growth and development of nuclear technology and its utilization have taken place mainly in industrialized countries for electricity generation. On the other hand, desalination technology is used widely in the Arab world, which has about 60% of the world's desalination capacity; the Arabian Peninsula alone has about 46% of this capacity.

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FIG. 1. Contracted capacity of all land based desalination plants capable of producing 100 m$^3$/d or more of fresh water versus the contract year and nuclear electricity generation during the period 1964–1993 [1].

The technical and economic feasibility of nuclear desalination as a source of low cost potable water in North Africa [2, 3] was studied by the IAEA and five of its North African Member States. The assessment, which has received wide attention, indicated that nuclear desalination would be technically feasible and economically competitive with fossil and renewable energy in a range of situations. Furthermore, options were identified for demonstration [4]. The suitable reactor options include PHWRs and PWRs, preferably of medium size coupled to reverse osmosis, as well as multi-effect desalination units coupled to small reactors.

Table I [5] lists the water scarce and water stressed countries in 1990 and 2025 (projected). Only one country (South Africa) operates nuclear power reactors and a research reactor, and one (Islamic Republic of Iran) is constructing a power plant and operates several research reactors. Four countries operate research reactors only (Algeria, Egypt, Libyan Arab Jamahiriya and the Syrian Arab Republic) [6, 7]. One country (Israel) has a plutonium producing reactor and a research reactor. Thus, most of the countries that are now in a water scarce situation or are moving towards this situation do not have an adequate nuclear infrastructure.

The introduction and development of a sustainable nuclear programme for the safe, reliable and economic production of desalted water alone, or electricity and water, in developing countries are challenging tasks. They require unambiguous national, legal, financial and technical commitments, and the establishment of
TABLE I. COUNTRIES EXPERIENCING WATER SCARCITY AND WATER STRESS IN 1990 AND 2025 (PROJECTED) BASED ON THE ANNUAL RENEWABLE FRESH WATER AVAILABLE (m³) PER PERSON [5]a

<table>
<thead>
<tr>
<th>Countries</th>
<th>1990</th>
<th>2025</th>
<th>Nuclear reactors</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Water scarcity</strong></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Djibouti</td>
<td>23</td>
<td>9</td>
<td></td>
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<tr>
<td>Kuwait</td>
<td>75</td>
<td>57</td>
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<td>Malta</td>
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<td></td>
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<tr>
<td>Qatar</td>
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<td></td>
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<tr>
<td>Bahrain</td>
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<td>89</td>
<td></td>
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<tr>
<td>Barbados</td>
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<td>164</td>
<td></td>
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<tr>
<td>Singapore</td>
<td>221</td>
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</tr>
<tr>
<td>Saudi Arabia</td>
<td>306</td>
<td>113</td>
<td></td>
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<tr>
<td>United Arab Emirates</td>
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<td>176</td>
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<td>Jordan</td>
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<td>445</td>
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<td></td>
</tr>
<tr>
<td>Israel</td>
<td>461</td>
<td>264</td>
<td>xxx</td>
</tr>
<tr>
<td>Tunisia</td>
<td>540</td>
<td>324</td>
<td></td>
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<tr>
<td>Cape Verde</td>
<td>551</td>
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<td></td>
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<tr>
<td>Kenya</td>
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<td>235</td>
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<td>Burundi</td>
<td>655</td>
<td>269</td>
<td></td>
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<tr>
<td>Algeria</td>
<td>689</td>
<td>332</td>
<td>x</td>
</tr>
<tr>
<td>Rwanda</td>
<td>897</td>
<td>306</td>
<td></td>
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<tr>
<td>Malawi</td>
<td>939</td>
<td>361</td>
<td></td>
</tr>
<tr>
<td>Somalia</td>
<td>980</td>
<td>363</td>
<td></td>
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<tr>
<td><strong>Water stress in 1990 and water scarcity in 2025</strong></td>
<td></td>
<td></td>
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<tr>
<td>Libyan Arab Jamahiriya</td>
<td>1017</td>
<td>395</td>
<td>x</td>
</tr>
<tr>
<td>Morocco</td>
<td>1117</td>
<td>590</td>
<td></td>
</tr>
<tr>
<td>Egypt</td>
<td>1123</td>
<td>630</td>
<td>x</td>
</tr>
<tr>
<td>Oman</td>
<td>1266</td>
<td>410</td>
<td></td>
</tr>
<tr>
<td>Cyprus</td>
<td>1282</td>
<td>996</td>
<td></td>
</tr>
<tr>
<td>Haiti</td>
<td>1696</td>
<td>838</td>
<td></td>
</tr>
<tr>
<td>South Africa</td>
<td>1371</td>
<td>683</td>
<td>xxx</td>
</tr>
<tr>
<td><strong>Water abundance in 1990 and water scarcity in 2025</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Islamic Republic of Iran</td>
<td>2025</td>
<td>816</td>
<td>xx</td>
</tr>
<tr>
<td>Ethiopia</td>
<td>2027</td>
<td>842</td>
<td></td>
</tr>
<tr>
<td>Syrian Arab Republic</td>
<td>2087</td>
<td>732</td>
<td>x</td>
</tr>
</tbody>
</table>

a Water stress = annual fresh water available per person is less than 1667 m³; water scarcity = annual fresh water available per person is less than 1000 m³; x = research reactors; xx = power reactors under construction; xxx = power reactors in operation; and xxxx = plutonium producing reactor.
organizations that need to manage the nuclear technology and to develop the essential organization cultures.

Nuclear energy is an advanced and complex technology that involves risk to workers and society. It could lead to transboundary radiological and legal consequences, and also to global ramifications in terms of reduced public confidence in nuclear energy. This has required a strengthening of the national safety culture and the establishment of a global safety culture [8]. The nuclear safety convention is now in force.

Nuclear technology transfer to developing countries is essential for understanding and absorbing this technology, its adaptation to particular needs, or its adoption and efficient utilization. Black box importation of this demanding technology is not conducive to safe and proper management, and also establishes an undesirable dependence on essential and daily matters, water, or water and electricity production. Some issues related to technology transfer are dealt with in this paper. Technology transfer in the nuclear programme of the Republic of Korea was analysed, and guidelines formulated. Furthermore, an action plan is proposed.

2. ORGANIZATION CULTURE

2.1. Definition [8–11]

The term culture refers to the values, beliefs and perceptions shared by members of an organization(s). It encompasses behavioural norms, expectations, goals, practices and even socialization processes that influence and guide the way in which members think and behave towards each other and approach their work, and how these are accomplished. The term also includes the degree to which the organization and its members use the knowledge gained from past experience to improve future performance. The commitment of the members to and pride in the organization, and the degree to which they take personal responsibility and accountability for their actions and their consequences, are expressions of ownership and belonging to the organization.

2.2. Establishing an organization culture

The establishment of an excellent and sustainable organization culture in the complex and risk ridden nuclear industry should be an overriding priority. In nuclear plants, organizational factors were found to be the root cause of many failures that affect safety and performance [12, 13].

The establishment and development of an excellent organization culture is a product of the integrated pattern of behaviour and thinking of an excellent
management team composed of highly trained and successful professionals who possess a dynamic personality, strong values and commitment, a clear vision of the role of the organization, and the ability to motivate others. Members of the team should have planning and decision making abilities and the will to act in an appropriate manner at all times. The recruitment and training of a team that establishes good management and sustains such excellence is the most important step to be taken by developing countries (or any country), particularly those starting a nuclear programme for desalination, or power, or both. This is also necessary in countries with existing organizations in need of restructuring and reform. The task requires considerable technology transfer.

The senior management of organizations involved in the construction, operation, design, fabrication or regulation of a nuclear power plant has the primary responsibility of achieving safe, reliable and economic performance through an integrated approach towards the management of safety (including the health and environmental impact), quality, reliability and productivity (water, electricity, or both), and of monitoring the performance parameters.

2.3. Safety, quality and performance cultures

It is proposed that the term nuclear culture be used to describe the overall organization culture in nuclear organizations. Nuclear culture is a composite culture composed of safety, quality and performance cultures or subcultures.

Safety and the safety culture are paramount [8, 14]. The term safety culture, introduced by INSAG in 1986 in the aftermath of the Chernobyl accident, was defined as “the assembly of characteristics and attitudes in organizations and individuals which establishes as an overriding priority that nuclear safety issues receive the attention warranted by their significance”.

Related to safety is the quality culture [15, 16]. Malfunctions that lead to poor quality also lead to poor safety. Enhancing quality in all phases of nuclear and related projects (such as desalination plants) by all the organizations involved is necessary, but not sufficient, to enhance safety. Likewise, quality culture can be defined as “the assembly of characteristics and attitudes in organizations and individuals which establishes as an overriding priority that total quality management and quality assurance and control issues receive the attention warranted by their significance”.

The performance culture is defined similarly, the overriding priority being “the efficiency and economical performance of the plant”. This includes all those factors that enhance plant reliability and availability, without compromising safety. In a competitive economic environment between various energy sources, nationally and internationally, the economics of nuclear energy determines the viability of the industry.
In the nuclear culture, which is the overall organization culture, of overriding priority is the integration and optimization of safety, quality and (economic) performance in order to achieve productivity, while ensuring safety and public acceptance. Nuclear culture emphasizes that safety (and quality) and productivity are essential and complementary from the beginning; they are two faces of the same coin. It should ensure from the earliest stage alleviation of impediments to nuclear energy development such as construction delays, cost overruns, interruptions in the programme and public acceptance. The overall objective is to provide society with the benefits of safe nuclear energy at competitive prices and to ensure interaction between nuclear energy and society through a sound public acceptance policy. The interrelation between the overall nuclear culture and its subcultures of safety, quality and performance is shown in Fig. 2.

2.4. Excellent management

Excellent, rigorous and vigilant management with a clear vision is essential [17] to establish and develop these cultures, and to instil and monitor high standards of performance in safety, quality, reliability and economic performance. It is important to ensure that excellence is translated into everyday behaviour and thinking; to be sustained it is essential that, particularly for safety, openness, a questioning attitude and learning from past experience are promoted. It does not take much to destroy a good organization. Excellent management should identify risk and ensure risk reduction in a cost effective manner. It should promote technology transfer and development, and establish an essential and relevant R&D base.

![Interrelation between the overall nuclear culture and its subcultures](image)

**FIG. 2.** The interrelation between the overall nuclear culture and its subcultures of safety, quality and performance. The domain of the subcultures is mainly at the on-site facilities, whereas that of the nuclear culture extends beyond the off-site limits to the local community and society.
3. NUCLEAR TECHNOLOGY TRANSFER

3.1. A case study in the Republic of Korea

Varying degrees of nuclear technology transfer have been achieved in several developing countries. Owing to the success of the Republic of Korea in this endeavour, the country was selected as a case study [18–22]. It has very limited fossil fuel reserves, therefore nuclear power was selected as the prime electricity source to minimize dependence on imported fuel. Furthermore, the country has the largest uninterrupted nuclear power programme in any developing country (and several developed countries) (see Table II) [19]. In the mid-1980s, and after accumulating experience with ten nuclear units in operation or under construction, the Republic of Korea formulated a national policy and programme for nuclear self-reliance.

The programme was launched in 1987 with the aim of achieving 95% nuclear self-reliance by 1995 for Korean standardized nuclear power plants (KNSPPs). The programme consisted of building two nuclear units (KNU 11 and 12) of the proven advanced PWR type, and of achieving self-reliance in architect-engineering (AE), and in the engineering and manufacture of a nuclear steam supply system (NSSS) and a turbine generator (TG). A further aim was to build a series of KNSPPs with the related infrastructure, and in the long term to become an NSSS exporter.

The Korea Electric Power Corporation (KEPCO) concluded contracts with foreign firms to build KNU 11 and 12 (Yonggwang-3 and 4). These contracts included separate technology transfer agreements with Sargent and Lundy (S&L) for AE, ABB Combustion Engineering (ABBCE) for NSSS and General Electric (GE) for TG. A key factor in the selection of these companies as partners was their willingness to help the Republic of Korea achieve nuclear self-sufficiency.

In less than 10 years this unparalleled technology transfer programme has led to the extensive development of nuclear technology. By 1995, KNU 11 and 12 were in operation (the first nuclear units to be manufactured in the Republic of Korea) as well as the reference plants for KNSPP. About 90–95% self-reliance was achieved in AE and NSSS design, and about 74% in equipment localization. Additional contracts with partners have been concluded for KNU 13 and 14 (Ulchin-3 and 4) and KNU 17 and 18 (Yonggwang-5 and 6).

3.2. Early phases of technology transfer

3.2.1. Phase 1, 1969–1974: limited technology transfer

During this phase, the first three units (KNU 1–3) were constructed through turnkey contracts that limited opportunities for technology transfer. KEPCO
<table>
<thead>
<tr>
<th>KNU No.</th>
<th>Station</th>
<th>NSSS vendor</th>
<th>Net power (MW(e))</th>
<th>Contract year</th>
<th>Date of commercial operation</th>
<th>Technology transfer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turnkey contracts</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Kori-1</td>
<td>Westinghouse</td>
<td>556</td>
<td>1969</td>
<td>Apr. 1987</td>
<td>No significant technology transfer</td>
</tr>
<tr>
<td>2</td>
<td>Kori-2</td>
<td>Westinghouse</td>
<td>605</td>
<td>1974</td>
<td>Jul. 1983</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Wolsong-1</td>
<td>AECL</td>
<td>629</td>
<td>1973</td>
<td>Apr. 1983</td>
<td></td>
</tr>
<tr>
<td>KEPCO takes over responsibility for project management and procurement</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>5</td>
<td>Kori-3</td>
<td>Westinghouse</td>
<td>895</td>
<td>1978</td>
<td>Sep. 1985</td>
<td>Gradual technology transfer of project management and design of balance of plant</td>
</tr>
<tr>
<td>6</td>
<td>Kori-4</td>
<td>Westinghouse</td>
<td>895</td>
<td>1978</td>
<td>Apr. 1986</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Yonggwang-1</td>
<td>Westinghouse</td>
<td>900</td>
<td>1978</td>
<td>Aug. 1986</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Yonggwang-2</td>
<td>Westinghouse</td>
<td>900</td>
<td>1978</td>
<td>Jun. 1987</td>
<td></td>
</tr>
</tbody>
</table>
### TABLE II. (cont.)

<table>
<thead>
<tr>
<th>KNU No.</th>
<th>Station</th>
<th>NSSS vendor</th>
<th>Net power (MW(e))</th>
<th>Contract year</th>
<th>Date of commercial operation</th>
<th>Technology transfer</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>Ulchin-1</td>
<td>Framatome</td>
<td>920</td>
<td>1980</td>
<td>Sep. 1988</td>
<td>Reorganization of the</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>nuclear industry and</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>workforce development</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Phase 3**
Planning and formulation of  
a nuclear self-reliance policy

**Phase 4**
Contracting and implementation  
of technology transfer

<table>
<thead>
<tr>
<th>11</th>
<th>Yonggwang-3</th>
<th>KHIC/ABBCE</th>
<th>1000</th>
<th>1987</th>
<th>Mar. 1995</th>
<th>Technology transfer on</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Yonggwang-4</td>
<td>KHIC/ABBCE</td>
<td>1000</td>
<td>1987</td>
<td>Mar. 1996</td>
<td>KNSPP (see Table III)</td>
</tr>
<tr>
<td>15</td>
<td>Wolsong-3</td>
<td>KHIC/AECL</td>
<td>700</td>
<td>1991</td>
<td>1998</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>Wolsong-4</td>
<td>KHIC/AECL</td>
<td>700</td>
<td>1991</td>
<td>1999</td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>Yonggwang-5</td>
<td>KHIC/ABBCE</td>
<td>1000</td>
<td>1995</td>
<td>2001</td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>Yonggwang-6</td>
<td>KHIC/ABBCE</td>
<td>1000</td>
<td>1995</td>
<td>2002</td>
<td></td>
</tr>
</tbody>
</table>
participated in the management of construction. Local participation (8–14%) [20] was limited to site preparation, some civil work and the supply of non-safety related equipment. A number of engineers received training abroad to increase their technical capabilities.

3.2.2. Phase 2, 1975–1987: increased technology transfer and a move towards self-reliance

Six (KNU 5–10) 900 MW(e) PWR units were ordered, and construction started during this phase. The management style was proactive and dynamic. KEPCO took over the responsibility for project management, engineering services and procurement. The units were ordered on a component basis [20]. Contracts were concluded with foreign firms for the supply of AE services, NSSS and TG. Furthermore, the amount of local companies used as subcontractors increased, and industries were encouraged to expand their role in various related activities. It is important to note that KNU 1–10 were procured from three NSSS vendors (Westinghouse, Framatome and Atomic Energy of Canada Ltd (AECL)), and designed by four AE companies (Bechtel, Gilbert, Framatome and AECL); the TGs were supplied by three different companies (GE, Alsthom and Parsons) [21]. This indicates the absence of standardization, particularly of plants in the United States of America.

On the job training took place between 1978 and 1983 [22], increasing with time, and was conducted mainly at various AE offices (Bechtel, Burns and Roe, Stone and Websters, Framatome and AECL) and TG manufacturers (GE and Alsthom), with a steady increase in learning and experience in design, engineering, construction and manufacturing. The degree of local participation increased to 46% in 1980 [21].

1981 witnessed a move towards self-reliance. Localization and self-reliance in CANDU fuel for KNU 3 (Wolsong-1), in co-operation with AECL, started. By 1987, localization was completed with the fabrication of fuel for three PHWRs (KNU 3, 4 and 16).

Through the knowledge and experience gained in this phase, a new policy for self-reliance and standardization in PWR technology started to emerge, and several important decisions were taken:

(1) S&L was selected to be the AE partner of the Korea Power Engineering Company (KOPEC), which is a subsidiary of KEPCO. While KEPCO was responsible for all project management, KOPEC was in charge of AE. In 1985, AE services were contracted for KNU 11 and 12. In 1986, after careful and detailed planning, a separate technology transfer agreement [19] was entered into by which S&L engineering tools, training and work were transferred to KOPEC engineers as part of an integrated team to design KNU 11 and 12. The tools consisted of S&L engineering standards, computer codes and software in all areas of engineering and engineering
support, including any future changes. The training programme consisted of formal classroom courses in the Republic of Korea, speciality training in Chicago, USA, and on the job training.

(2) In 1986, the move towards self-sufficiency in NSSS was made. KEPCO issued an international tender for KNU 11 and 12 [19], the criteria for acceptance being the most advanced PWR technology and the willingness to transfer such technology. To achieve self-reliance through various organizations, some tasks were assigned [18, 20], the most important of which were:

(a) The Korea Atomic Energy Research Institute (KAERI) was assigned the responsibility for the NSSS, initial core and fuel design. Hanjung, previously the Korea Heavy Industries and Construction Company, was assigned the responsibility for the design and manufacturing technology of heavy components. It has a large facility at Chang-Won, which is modelled on that of ABBCE at Chattanooga, USA. This facility is equipped to manufacture reactor components (including pressure vessels and steam generators, TG and other heavy equipment).

(b) The Korea Nuclear Fuel Company (KNFC) was assigned the task of fuel fabrication.

Accompanying this planning and organizational work, recruitment of the required workforce was undertaken. A new policy of self-reliance is in place and a programme under way. A new commitment has been made and the necessary organizational structure is in place. With the initiation of this culture, a new nuclear era began in 1987 in the Republic of Korea.

3.3. Implementation of the self-reliance programme


3.3.1. Phase 3

3.3.1.1. Architect–engineering [20]

(1) Management of technology transfer: The S&L/KOPEC technology transfer agreement was administered by a joint committee charged mainly with defining the procedures of technology transfer, monitoring the transfer of engineering standards and computer programs, overseeing the conduct of classroom and speciality courses, and adjusting the programme according to the trainee evaluation results.

(2) Training: Concerning formal training, 49 courses were conducted in the Republic of Korea, with early provision of text materials. These courses were given to groups
of 15–20 participants each. Also, 49 speciality courses were conducted at the S&L offices in Chicago for a carefully selected but limited number of experienced engineers with a view to their becoming specialists in certain topics. The courses provided one on one training (one or two engineers per course). The courses included assignments, examinations and evaluation of trainee performance.

(3) **Integrated team:** The design of KNU 11 and 12 was undertaken by an integrated team of engineers from S&L and KOPEC working side by side. This provided on the job training for the latter, as well as participation in the design. This was the culmination of AE training and the transfer of S&L design tools. During the preliminary design phase, S&L assumed a leading role and KOPEC played a supporting role; during the detailed design phase, KOPEC assumed the leading role and S&L acted mainly in an advisory capacity. Personnel participation for S&L and KOPEC was 60:40, respectively. The teams worked under one quality assurance programme, one project manual and one set of responsibility assignments.

Engineers trained in the design of Yonggwang-3 and 4 (KNU 11 and 12) took the lead in the preliminary, basic and detailed design of subsequent units. The number of S&L site engineers was reduced approximately by half in each succeeding job. The total number of on-site S&L engineers in the period 1987–1989 was 423 [22]. For the six units, the numbers were approximately 230, 130 and 63 for KNU 11 and 12, KNU 13 and 14, and KNU 17 and 18, respectively. These were supported by 98 engineers at headquarters. The degree of self-sufficiency in AE has increased gradually from 63% (1987) to 71% (1988), 77% (1989), 83% (1990), 87% (1991), 91% (1992), 93% (1993), 94.52% (1994) and 95.1% (1995).

Through this integrated approach of formal speciality and on the job training, as well as participation in design work, self-reliance was achieved. Another important aspect of this technology transfer system was the transfer of the work culture, environment and system of the AE office in Chicago to KOPEC in Seoul. Of great importance were the continual communication and accessibility of future developments in S&L tools, which are essential if the work of KOPEC is to progress.

3.3.1.2. Nuclear steam supply system [18, 19, 21]

In 1987, through an international tender emphasizing technology transfer, ABBCE was selected as a partner. The 1000 MW(e) PWR version of the ABBCE system 80 NSSS design was chosen, since it is based on the experience of the three standardized 1300 MW(e) units operating at Palo Verde, USA. Two units, KNU 11 and 12 (Yonggwang-3 and 4), were contracted. The contracts included technology transfer and licence agreements for the design and manufacture of an NSSS and its components. KEPCO assumed responsibility for project management and technology
transfer, and a Vice-President for Technology Development was appointed. The 1987 contracts were based on a long term partnership.

In 1991, these contracts were followed by a further contract for two units, KNU 13 and 14 (Ulchin-3 and 4), and in 1995 for two units, KNU 17 and 18 (Yonggwang-5 and 6). The scope of these contracts was modified to give a greater role and more responsibility to the Republic of Korea in view of the experience gained through technology transfer.

As in the KOPEC/S&L programme, the basic methods of technology transfer included classroom and on the job training, documentation and computer code transfer, and R&D programme participation and consultation. In the first 8 years, over 400 trainees received more than 2500 hours of classroom training and 5000 person-weeks of on the job instruction at the ABBCE facilities in the USA, covering all the disciplines of nuclear power technology. KAERI, KEPCO and their affiliates participated in plant design, construction and management. The milestones of technology transfer in nuclear design are shown in Table III.

In the 1991 contract, the design of Ulchin-3 and 4 (scheduled to be in operation in 1998 and 1999) was led by the team from the Republic of Korea, with ABBCE.

### TABLE III. MILESTONES AND METHODS OF TECHNOLOGY TRANSFER IN THE NUCLEAR SELF-RELIANCE PROGRAMME OF THE REPUBLIC OF KOREA

<table>
<thead>
<tr>
<th>Date</th>
<th>Task</th>
</tr>
</thead>
<tbody>
<tr>
<td>January 1987</td>
<td>First group of KAERI engineers begins 2 years of nuclear design training at ABBCE in the USA</td>
</tr>
<tr>
<td></td>
<td>Start of transfer of design documentation and computer codes</td>
</tr>
<tr>
<td>December 1989</td>
<td>Transfer of documentation and codes for Yonggwang-3 and 4 (KNU 11 and 12) is completed</td>
</tr>
<tr>
<td>March 1990</td>
<td>Establishment of a joint nuclear design centre at KAERI; ABBCE led the joint design team&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>October 1993</td>
<td>Nuclear design and licensing reports are finalized in the Republic of Korea for Yonggwang-3 and 4</td>
</tr>
<tr>
<td>September 1994</td>
<td>Operating licence and fuel loading completed for Yonggwang-3</td>
</tr>
<tr>
<td>March 1995</td>
<td>Yonggwang-3 achieves commercial operation on schedule</td>
</tr>
<tr>
<td>August 1995</td>
<td>Yonggwang-4 achieves 100% power ahead of schedule</td>
</tr>
</tbody>
</table>

<sup>a</sup> The team from the Republic of Korea was responsible for the design of Ulchin-3 and 4, which are the reference plants for the KNSPP.
providing mainly the design support services. Yonggwang-3 and 4 were completed in 1995, and self-reliance has reached about 95%, as planned. These two units have been used as the reference plants for Ulchin-3 and 4, which have been designated the first KNSPP. The design includes several advanced features that provide significant improvements in safety, operation and construction. This is the type of reactor offered to the Democratic Peoples Republic of Korea.

3.4. Observations

(1) The turnkey contracts used in phase 1 limited the opportunities for technology transfer.

(2) In KEPCO taking responsibility for the management and procurement of six units in the second phase, and ordering on a component basis, greater understanding has been achieved of the scope of the process, the international market, the local market and the potential for industrial participation. It also led to increased technology transfer and local participation, formulation of a new vision of nuclear self-sufficiency, definition of specific goals and the design of a self-reliance programme.

(3) By contracting a partner firm from the USA for AE services, comprehensive technology transfer, project management and the design of balance of plant have been attained, as well as the complete transfer of all the relevant documents and computer codes of the extensive training programme, leading to 95% self-reliance.

(4) A vendor from the USA willing to provide technology transfer was contracted as a partner under favourable political and market conditions. Follow-up was undertaken by the top management of KEPCO through the appointment of a Vice-President for Technology Development. A nuclear revolution has taken place in the Republic of Korea in that the nuclear industry has achieved its goal of 95% nuclear self-sufficiency and acquired experience in planning, design, engineering, manufacturing, construction and project management.

(5) Implementation on schedule (and even ahead of schedule) of a large and complex technology transfer programme by several organizations is the result of a highly developed nuclear culture, and excellent, rigorous and vigilant management. This culture is also reflected in the operational side of the power plants. Since 1984, the average annual capacity has been steadily maintained over the 70% level, and over the 80% level during the past 5 years, which is significantly higher than the world’s average [18].

(6) The CANDU PHWR programme is limited (see Table II). However, the next localized or domestic reactor is to be a 700 MW(e) PHWR fabricated by Hanjung [21]. PHWRs are simpler than PWRs in some respects, particularly their fuel cycle and some heavy components (the pressure vessel). The KHIC/AECL consortium, which is similar to KHIC/ABBCE, was set up to supply the NSSS for two CANDU
units. This was contracted in 1991. The Republic of Korea is the only country that has localized PWR and PHWR technologies.

(7) The nuclear power programme in the Republic of Korea was developed in an excellent project management school during the second phase. The Chinese nuclear power programme evolved in the reactor design and construction school that produced Qinshan 1 (300 MW(e) PWR); this school was the product of very early work in the design and construction of research reactors in R&D organizations and universities. The highly self-reliant Indian nuclear power programme was brought about by an excellent R&D school that emphasized technological development of the nuclear fuel cycle.

3.5. Guidelines for the promotion of technology transfer

From analysis of the PWR technology transfer experience gained in the Republic of Korea, as well as other experience accumulated in developing countries, an attempt was made to formulate guidelines that promote technology transfer. Essential to these guidelines are:

(1) Formulation as early as possible of a national policy and programme for self-reliance and technology transfer with clear objectives, in conjunction with a viable, uninterrupted nuclear power plant programme. The policy should establish the conditions and environment that are necessary to strengthen technology transfer.

(2) Development of technology transfer, the extent of which will increase as the size of the nuclear programme increases, albeit gradually.

(3) Development of a nuclear culture and excellent management for the entire programme, including careful and detailed planning, and the implementation and follow-up of the technology transfer activities by efficient top management. Planning activities include defining goals and formulating strategies with the support of a foreign partner and treating technology transfer as a dynamic, continuous process.

(4) Development of an appropriate workforce and infrastructure for a successful technology transfer programme; lack of a proper infrastructure will limit the extent of technology transfer, whereas an increase in the know-how potential through proper education and training will increase its efficiency.

(5) Intensification of R&D in relevant basic and applied research. An increase in co-operation between the nuclear industry, the R&D organizations and the universities will increase the efficiency and effectiveness of technology transfer.

(6) Entering into contractual agreements (with clearly defined technology transfer programmes) with willing partners such as power reactor vendors and AE firms is an essential requirement. The agreements could include formal, speciality and on-the-job training, as well as the transfer of basic documents, engineering standards and computer codes. This requires a conducive political environment, appropriate economic and marketing conditions, and a long term programme.
(7) Enhancement of co-operation with the IAEA in various aspects of planning, workforce development, on the job training, and safety and nuclear culture development should increase the efficiency of technology transfer. Co-operation with other nuclear countries, be they developing or developed, in areas such as regulatory technology, quality technology, risk analysis and R&D should also enhance technology transfer.

4. PROPOSED ACTION PLAN

On the basis of a national decision taken by a developing country without a nuclear power plant infrastructure to introduce one or more of the nuclear desalination options, an action plan is proposed in view of the importance of an organization culture and technology transfer.

4.1. Review of the existing legal and organizational structures

In the light of recent international developments, the necessary legal and organizational reforms should be introduced. It is also important that the independence of the regulatory body is ensured, and that commitment to the nuclear desalination programme, self-reliance and technology transfer is emphasized. It is essential that the relations between nuclear organizations are defined and that the importance of co-operation, especially with the relevant R&D organizations, is emphasized. All these activities can be realized with the support and co-operation of the IAEA. Participation of experts from developing countries with advanced nuclear capabilities is important at this stage.

4.2. Nuclear organization(s)

The following should be organized by the nuclear organization(s): the organizational structure; the vision statements; the cultural principles, and the overriding priority of the nuclear culture, and the safety, quality and performance subcultures; long range planning; the self-reliance and technology transfer policies, and (from the start) the degree of localization in the nuclear and desalination fields after conducting a national survey and assessment of the existing industrial and engineering capabilities; and the recruitment and training policy.

4.3. Recruitment, training and retraining

Recruitment should be based on excellent scientific and technical capabilities and the ability to work in a team.
Training and retraining should be based on Refs [3, 4, 23, 24]. The experience and facilities of the training school at the Bhābha Atomic Research Centre in India should be utilized in designing such training. The training should be supplemented by:

1. A nuclear culture, including the safety, quality (total quality management, quality assurance and quality control) and performance subcultures. The importance of organizational factors in improving safety and performance should be supplemented by success and failure case studies.
2. Team building and problem solving methods.
3. The lessons learned from problems and failures in the nuclear industry, particularly those related to deficiencies in culture.

Co-operation with the IAEA in designing and organizing such courses should be pursued.

4.4. Selection of partners

Normally, selection takes place after negotiations with the vendor(s) on the scope of the work, the scope and methods of technology transfer, the milestones, the monitoring parameters and the costs. It is important that, as early as possible, the required technology transfer and the degree of localization (nuclear and desalination) are defined and the joint R&D programme established. At the first stage, the following items should be strongly considered for technology transfer:

1. The project management and planning, the balanced plant design and the management of construction;
2. The nuclear design;
3. Probabilistic safety assessment level 2 for the plant;
4. The quality assurance technology, the codes and standards of the vendor, and the international codes and standards;
5. Certain parts of the fuel cycle, depending on the reactor type, with emphasis placed from the start on the waste management policy, the technology and the siting;
6. The regulatory policy and regulatory technology transfer.

The IAEA provides support for some aspects of the technology transfer programme.
4.5. Licensability

Safety assessment and review, and demonstration of licensability [1] should be based on:

(1) The licensability in the country of origin, provided the regulatory body of that country is assessed by the IAEA (through the International Regulatory Review Team) if this is required by the regulatory body of the importing country;
(2) Design review of the plant, to be reviewed by the IAEA;
(3) The presence of a demonstration plant.

This requires adoption of the relevant IAEA safety standards and codes, and the country relevant regulations of the vendor. Of particular note is IAEA Safety Series No. 110 [25], which contains 25 fundamental safety principles. One further principle for nuclear desalination has been added by Hammad [1], which states:

Principle 26: In an integrated nuclear desalination complex, the design and the performance of a coupling system — if needed — between the nuclear and the desalination plants shall ensure protection of the product water against radioactive contamination.

A safety assessment review could be undertaken in two stages, which might overlap. The first stage is to be undertaken in co-operation with the regulatory body of the vendor’s country using that country’s licensing requirements, criteria, codes, guides, practices, etc. Use of related licensing documents and assessments will be of great help at this early stage. The second stage is to be undertaken in co-operation with the IAEA, based on IAEA Safety Standards.

It should be emphasized that any assistance, advice or consultation does not relieve the national regulatory body of its licensing responsibility, based on a complete review. The regulatory body should be capable of undertaking the calculations and analyses judged necessary to verify the submitted information, and of providing firm bases for making the required safety assessment. This methodology involves the transfer of considerable know-how, documents and computer codes, and should be undertaken through the technology transfer agreement with the vendor country. Co-operation with the IAEA and the US Nuclear Regulatory Commission should be sought.

4.6. Public acceptance and the interaction between local communities and nuclear facilities

A successful nuclear power programme cannot be carried out without the understanding and support of society in general and local communities in particular.
In the case of nuclear desalination, which may involve the term nuclear water, public acceptance and symbiosis may be more difficult. From the beginning, formulation of a policy and programme, both for the short and the long term, should be afforded great attention. Satisfactory experience is available in several countries, including the Republic of Korea [18], and it should be considered when formulating such a policy and programme.

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The author is grateful to W.H. Köhler, Chairman of the Scientific Board of Directors of GTDC, for support. He is also grateful for the discussions held with KOPEC and Sargent and Lundy engineers.

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MARKET OPPORTUNITIES FOR DESALINATION USING NUCLEAR ENERGY

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Abstract

MARKET OPPORTUNITIES FOR DESALINATION USING NUCLEAR ENERGY.

Desalination technologies have become widely acceptable as a viable method for producing potable water from sea water. It is observed as a valuable adjunct to nuclear power generation provided coupling of the technologies is accomplished in a safe, efficient manner. An analysis is made of the potential areas of the world where desalination powered by nuclear energy is most likely. United Nations, IAEA and other literature were utilized to predict the power for desalination. At the end of 1995, the world capacity for desalination plants totalled 11 066 plants producing $20.3 \times 10^6 \text{ m}^3/d$. The new installed sea water total capacity is expected to grow exponentially at about 5.5%; the highest growth is expected to be in the Middle East and South Asia, followed by Western Europe, North America and Africa. The regions of greatest future need are the Middle East and Africa, therefore these are the most likely areas to place a nuclear desalination plant.

1. BACKGROUND

For many years, scientists have agreed that the energy source provided by nuclear reactors would be ideal for desalination processes, since the reactor produces copious volumes of heat. The heat source can be utilized directly to provide energy for evaporative processes, or converted to electric energy to drive reverse osmosis (RO). Lengthy discussions have been held to determine the most effective combinations of processes and reactors. Along the way, the perceived problems of coupling the technologies and avoiding cross-contamination have been generally resolved, but there has been no combination plant constructed to prove the accepted solutions to these problems.

The Options Identification Programme was initiated in 1996 [1] to identify and define the practical options for demonstration of desalination using nuclear energy. The programme was implemented by a Working Group of experts from interested Member States and IAEA staff through a series of periodic meetings and work assignments. The subject of determining the market for desalination using nuclear energy,
and the likely location for a demonstration plant, was undertaken by a Consultants Meeting that was convened in 1996. The findings of this report, with updated information, is the subject of this paper.

An assessment was made of the potential market for sea water desalination using energy produced by nuclear reactors. Starting with the current status of sea water desalination markets, the expected evolution of large plants (with a capacity greater than 10 000 m³/d) was projected.

2. CURRENT STATUS OF DESALINATION

The most complete current record of desalination plant construction is contained in International Desalination Association (IDA) Report No. 14 [2]. The report is prepared biennially, and includes all the commercial designs of desalination equipment: multi-stage flash (MSF), multi-effect distillation (MED), vapour compression (VC), RO, electrodialysis (ED), and a new category, membrane softening (MS). Applications for the processes range from sea water to waste water.

In examining the rationale for selecting potential markets for desalination using nuclear energy, consideration was made of the minimum size necessary for effective coupling to reactors. Although an earlier report [3] indicated that 25 000 m³/d may be considered small in view of the number of electricity generation plants where 1000 MW(e) is typical, for the purpose of this study 10 000 m³/d was chosen, since this is a practical modular unit with current RO technology. Evaporative process modular sizes currently range between 20 000 and 50 000 m³/d.

The current market demand for large plants with a capacity greater than 20 000 m³/d is concentrated in the modular size ranges outlined in Table I.

At the end of 1995, the total installed capacity of desalination equipment worldwide was more than $20 \times 10^6$ m³/d (Fig. 1). Of this, the largest volume in any country is in Saudi Arabia (Fig. 2). The top ten countries comprise over 75% of the total installed world capacity. The Middle East countries alone account for nearly half of the world’s total.

<table>
<thead>
<tr>
<th>Capacity (m³/d)</th>
<th>Market share (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 000–24 000</td>
<td>20.5</td>
</tr>
<tr>
<td>26 100–28 100</td>
<td>9.4</td>
</tr>
<tr>
<td>32 100–34 100</td>
<td>11.8</td>
</tr>
<tr>
<td>44 100–46 100</td>
<td>4.4</td>
</tr>
<tr>
<td>46 100–58 100</td>
<td>3.3</td>
</tr>
</tbody>
</table>
FIG. 1. Total installed desalination capacity.

FIG. 2. Desalination capacity by country.
A closer look at the installed capacity reveals interesting insights. Of the total capacity of plants greater than 100 m³/d, MSF makes up 47% and RO 36% (Fig. 3). An examination of plants with a capacity greater than 4000 m³/d, which is approaching the size that is more likely to be a candidate for combination with nuclear plants, 69% are MSF and 23% are RO (Fig. 4). Since it is likely that a large combined plant would be placed near to the ocean, the search for suitable sites can be further limited to those with access to sea water. The IDA inventory shows that the annual average increase in sea water desalting capacity is about 475 000 m³/d.
3. CURRENT STATUS OF DESALINATION USING NUCLEAR ENERGY

Although the number of desalination facilities using nuclear power plants is relatively low, some have been in operation since 1973 (Table II) [1]: four utilized MSF, three MED and three RO. The Kazakhstan plant is a combination of MED and MSF, and represents the largest installation (65 000 m³/d) of desalination at a nuclear facility. The rest of the installations are small, ranging from 1000 to 2600 m³/d.

4. STUDY METHODOLOGY

A simple method for analysing the potential for desalination using nuclear energy sources would be to project the overall growth rate as predicted in the IDA Inventory; however, it was felt that the large influence of the Arab states would make this type of analysis unrealistic, since it would not accurately reflect the anticipated growth rates of other countries. The Arab states clearly represent the largest growth potential for the industry. An examination of the water needs of key Middle East countries quickly establishes one of the principal reasons for needing desalination
TABLE III. COUNTRIES WHOSE WATER USE EXCEEDS 100% OF THE RENEWABLE SUPPLIES [4, 5]

<table>
<thead>
<tr>
<th>Country</th>
<th>Water withdrawals as per cent of renewable supplies</th>
<th>Years to double population at current rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Libyan Arab Jamahiriya</td>
<td>374</td>
<td>20.4</td>
</tr>
<tr>
<td>Qatar</td>
<td>174</td>
<td>33.0</td>
</tr>
<tr>
<td>United Arab Emirates</td>
<td>140</td>
<td>24.8</td>
</tr>
<tr>
<td>Yemen</td>
<td>135</td>
<td>21.7</td>
</tr>
<tr>
<td>Jordan</td>
<td>110</td>
<td>19.3</td>
</tr>
<tr>
<td>Israel</td>
<td>110</td>
<td>46.2</td>
</tr>
<tr>
<td>Saudi Arabia</td>
<td>&gt;100</td>
<td>21.7</td>
</tr>
<tr>
<td>Kuwait</td>
<td>&gt;100</td>
<td>23.1</td>
</tr>
<tr>
<td>Bahrain</td>
<td>&gt;100</td>
<td>28.9</td>
</tr>
</tbody>
</table>

(Table III) [4, 5]. All these countries already utilize varying degrees of desalination to augment their renewable supplies.

The methodology used for this assessment included analysis of individual countries that may have an interest in desalination technology, the required unit size and the type of desalination process used. A review was made (1973–1995) of individual countries with a sea water capacity that is greater than 10 000 m³/d. This target capacity was established as the probable minimum size necessary for combining an installation with nuclear energy, partly because of the likely size of the nuclear power plants. An earlier report [3] indicated that 25 000 m³/d may be considered small in view of the number of electricity generation plants where 1000 MW(e) are typical. The smallest commercial module is currently offered by RO (Table IV). It is believed that this modular increment will increase to 15 000 m³/d in the near future, and is primarily limited by a commercially available pump size. Use of multiples of this module size is common today.

TABLE IV. LIMITATIONS IN MODULAR CAPACITY

<table>
<thead>
<tr>
<th>Process</th>
<th>Present status</th>
<th>Near future limitations</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Capacity (m³/d)</td>
<td>Limitations</td>
</tr>
<tr>
<td>RO</td>
<td>10 000</td>
<td>Pump size</td>
</tr>
<tr>
<td>MED</td>
<td>20 000</td>
<td>Largest transportable size</td>
</tr>
<tr>
<td>MSF</td>
<td>50 000</td>
<td>Standardization</td>
</tr>
</tbody>
</table>
On the basis of surveys made by the World Resources Institute [6], an estimate of the future growth of sea water desalination was made, based on need, for each of the countries studied. The saturation limit (maximum total demand) for sea water desalination equipment was calculated, and the future total installed capacity and increments of sea water desalination for the years 2005, 2010 and 2015 were estimated using an exponential growth rate. This growth rate was established after examining the estimated capacity of projects known to the authors [7] for 1995–2000.

The future availability of energy and population growth rates were examined [8] to gain insight into the conditions in various target countries. Additionally, a key component to the study was assessment of those countries that are most likely to embrace nuclear power in the future. For this assessment, the opinion of the IAEA, as reflected in past meetings with Member States, was evaluated. Finally, the opinion of representatives at an IAEA Consultants Meeting [9] was considered.

The following assumptions and definitions were utilized in this study:

(1) Future population growth was calculated using the exponential growth rate based on the population base in 1991;
(2) The total municipal desalinated water demand (saturation limit) was based on the population, annual per capita and tourist demand, and the maximum percentage municipal supply of sea water desalination;
(3) The total net future desalting capacity reflected adjustments for the replacement market of sea water desalination plants up to 1990; 5% capacity compensation for availability; and 15% capacity compensation for pipe transition losses.

5. FUTURE MARKET

At the end of 1995, the world capacity for desalination plants totalled 11,066 desalting units producing a total of $20.3 \times 10^6$ m$^3$/d. During the 1994–1995 biennium, 997 units and $1.46 \times 10^6$ m$^3$/d were added to the capacity, representing a 5% increase in the number of units; however, the total incremental capacity was about 50% less than in the previous biennium. There are several reasons for this, the most important being that no large plants were contracted in the Arab states during this period. However, since then contract signings have indicated that continued growth can be anticipated. Of the total installed global capacity, 60.7% is for desalted sea water, 25.6% for brackish water, 5.3% for river water and 8.4% for other categories.
TABLE V. ANTICIPATED FUTURE SEA WATER DESALINATION MARKET

<table>
<thead>
<tr>
<th>Period</th>
<th>Increase in average annual capacity (m³/d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1996–2000</td>
<td>871 000</td>
</tr>
<tr>
<td>2001–2005</td>
<td>970 000</td>
</tr>
<tr>
<td>2006–2010</td>
<td>1 364 000</td>
</tr>
<tr>
<td>2011–2015</td>
<td>1 941 000</td>
</tr>
</tbody>
</table>

Assessment of the desalination need was based on population growth, historical records of installed capacity, known orders for new capacity over the next few years, and the experience and expertise of desalination specialists.

The capacity of newly installed sea water desalination during 5 year intervals is expected to grow exponentially at about 5.5% (Table V). The largest growth is expected to be in the Middle East and South Asia, followed by Western Europe, North America and Africa (Fig. 5). Further examination of those countries that are predicted to be affected most by water scarcity (Table VI) reveals that the regions with the greatest need for future desalinated water supply are the Middle East and Africa. These are the most likely areas to approach with regard to a combined desalination/nuclear power plant.

6. NEXT STEP

Having established that there is a reasonable market for desalination using nuclear energy, one must take a close look at the limiting factors in consideration of a suitable site. Once the need for both water and power is established for a specific country, other site factors become important. Owing to the copious quantity of water required for power plant cooling and desalination, a site close to an ocean is likely. In addition, the site must be located sufficiently far from any urban centre to satisfy safety concerns. One of the studies required early on in the evaluation was to determine whether the desalination plant should be on the same site as the power plant, or in closer proximity to the population centre. Of primary importance are the environmental considerations of the region.

Finally, it is unlikely that the combined plant will be successfully located in a country that is not ‘nuclear friendly’.

TABLE VI. WATER SCARCE COUNTRIES IN 1955, 1990 AND 2025 (ESTIMATED)

<table>
<thead>
<tr>
<th>1955</th>
<th>Added by 1990</th>
<th>Added by 2025 in UN growth projection</th>
<th>Added by 2025 in UN medium-high projections</th>
</tr>
</thead>
<tbody>
<tr>
<td>Malta</td>
<td>Qatar</td>
<td>Libyan Arab Jamahiriya</td>
<td>Cyprus</td>
</tr>
<tr>
<td>Djibouti</td>
<td>Saudi Arabia</td>
<td>Oman</td>
<td>Zimbabwe</td>
</tr>
<tr>
<td>Barbados</td>
<td>United Arab Emirates</td>
<td>Morocco</td>
<td>Tanzania</td>
</tr>
<tr>
<td>Singapore</td>
<td>Yemen</td>
<td>Egypt</td>
<td>Peru</td>
</tr>
<tr>
<td>Bahrain</td>
<td>Israel</td>
<td>Comoros</td>
<td></td>
</tr>
<tr>
<td>Kuwait</td>
<td>Tunisia</td>
<td>South Africa</td>
<td></td>
</tr>
<tr>
<td>Jordan</td>
<td>Cape Verde</td>
<td>Syrian Arab Republic</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Kenya</td>
<td>Islamic Republic of Iran</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Burundi</td>
<td>Ethiopia</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Algeria</td>
<td>Haiti</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Rwanda</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Malawi</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Somalia</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
For the IAEA programme, a thorough investigation was made of the available options for a demonstration plant. The next obvious step will be to build such a plant at a suitable site.

REFERENCES


THE ECONOMIC AND FINANCIAL ASPECTS OF NUCLEAR DESALINATION

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Vienna

Abstract

THE ECONOMIC AND FINANCIAL ASPECTS OF NUCLEAR DESALINATION.

The IAEA has studied the viability of sea water desalination using nuclear energy compared with fossil fuelled and renewable energy plants. The studies have shown that nuclear energy would be competitive with fossil energy for desalination in a range of situations. This applies in particular to countries that lack cheap indigenous energy resources, need large amounts of desalted water, and have the means and infrastructure to install medium or large sized nuclear power plants. Concerning financing, the availability of funds at reasonable terms is a key factor for the feasibility of every large power/desalination project, in particular for nuclear power. The relevant characteristics of commercial nuclear desalination projects that make arrangements for adequate financing difficult include high investment costs, long construction periods, a relatively high degree of uncertainty with respect to costs and scheduling, and potentially significant public opposition. These characteristics imply significant financial risks. It is thus essential that the uncertainties and risks of a nuclear desalination project be reduced. A helpful step towards realizing this goal would be the prior implementation of a demonstration project. Other relevant actions and policies to successfully implement a nuclear desalination project are summarized. The IAEA is ready to assist interested Member States, upon request, in building an adequate basis for a nuclear desalination programme as a prerequisite to sound economic assessments and in obtaining financing for a well defined project on reasonable terms.

1. ECONOMIC VIABILITY

The IAEA has studied the viability of using nuclear energy for sea water desalination by reviewing existing experience and by performing technical and economic assessments of relevant sea water desalination technologies. The sources of heat and/or electricity considered for the desalination processes included nuclear reactors, and fossil fired and renewable energy plants [1–4]. Potable water costs were calculated by means of the power credit method, based on the levelized electricity generation cost of the power plant. The studies have shown that nuclear energy would be competitive with fossil energy for desalination in a range of situations. This applies
in particular to countries that lack cheap indigenous energy resources, need large amounts of desalted water, and have the means and infrastructure to install medium or large sized nuclear power plants. The relevant factors for assessing the electricity and water costs, and thus the competitive situation of nuclear, fossil and renewable energy, include:

(1) Site conditions, including water and electricity demand, maximum unit size, sea water temperature and salinity, regulatory requirements and impact of local participation;
(2) Construction costs and construction schedule, in particular of the nuclear plant;
(3) The interest and discount rates;
(4) Plant availability and capacity factor;
(5) The fossil fuel prices during the economic plant life.

The economic analyses performed for these studies resulted in about the same levelized water production costs for both nuclear and fossil fuelled plants in a range of possible situations. The water production costs of reverse osmosis (RO) plants coupled contiguously to the power plant were estimated to be about US $0.1/m$^3$ lower than those of multi-effect distillation (MED) plants, and about US $0.4/m^3$ lower than those of multi-stage flash (MSF) plants.

In addition to their economic advantage, RO plants also have a higher operational flexibility than distillation plants. On the other hand, RO plants may require more extensive pretreatment of the sea water than assumed in IAEA studies, e.g. in the Arabian Gulf. Furthermore, good reliability and availability, as well as the long service life of distillation plants, have been well proven through their long and successful operating experience. In any case, decision makers will decide which desalination process is the most suitable for their particular country and situation.

In each specific situation, certain amounts of potable water and electricity to the grid will be required. Since different power plant types with the same electric output could supply different amounts of low pressure steam for a distillation process, it is interesting to analyse which power plant type would be most suitable in a given situation; this may also be characterized by the required ‘water to electricity ratio’.

Figures 1 and 2 show the results of an economic assessment of MED plants for comparing a medium sized nuclear plant with a combined cycle and a coal fired plant as the energy source, respectively. To characterize the MED plant for each co-production plant configuration, the gained output ratio (GOR) is given. The main input data are summarized in Tables I-III.

It can be seen from the figures that MED plants with a GOR of 8–14, corresponding to low temperature, horizontal tube multi-effect (LT-HTME) processes with maximum brine temperatures of 50–70°C, yield the lowest potable water production costs, independent of the energy source considered. LT-HTME plants
FIG. 1. Water production costs versus ratio of water to saleable electricity of MED plants coupled to a PWR (620 MW(e) base power plant capacity) or a combined cycle plant (612 MW(e) base power plant capacity) (ranges: oil/gas price = US $20–30/barrel; and PWR construction cost = 100–110% of the reference value).

operate at maximum brine temperatures of less than 70°C, allowing use of low cost materials such as aluminium heat transfer tubes, plastic pipes and epoxy painted steel shells. This enables use of a generous heat transfer surface, resulting in high thermodynamic efficiency of the distillation plant. Overall temperature differentials as low as 2–2.5°C per effect, including thermal driving forces, boiling point elevations and non-equilibrium losses, can be achieved with reasonable investment costs. For high temperature MED (HT-VTE) plants, higher cost thin walled titanium or high grade steel alloys have to be used as the tube bundle material in the top effects to prevent corrosion. To obtain a reasonable investment cost, the heat transfer area has to be limited, resulting in higher temperature differentials per effect, lower thermodynamic efficiency and higher energy costs than those for LT-HTME when coupled to dual
FIG. 2. Water production costs versus ratio of water to saleable electricity of MED plants coupled to a PWR (620 MW(e) base power plant capacity) or a coal fired plant (620 MW(e) base power plant capacity) (ranges: coal price = US $50–70/1; and PWR construction cost = 100–110% of the reference value).

purpose plants. Backup boilers were assumed where they could reduce the levelized water production costs, i.e. for HT-VTE but not for LT-HTME plants.

PWRs have a lower thermal efficiency than fossil fired plants, which is a disadvantage for electricity generation alone. However, through its low thermal efficiency and the absence of heat losses through combustion/exhaust gases to the atmosphere, the PWR power plant can provide much larger quantities of low temperature steam for distillation than the fossil energy plants considered. This means that, even for high water to electricity ratios of up to 50 m$^3$/MW(e)-h, the low cost LT-HTME process can well be applied for nuclear sea water desalination.

Another aspect favouring the PWR power plant as an energy source for distillation processes, especially for LT-HTME plants, is the low turbine efficiency
TABLE I. TECHNICAL AND ECONOMIC DATA OF SEA WATER DESALINATION PLANTS

**Technical data**

<table>
<thead>
<tr>
<th>Process</th>
<th>GOR</th>
<th>No. of effects/stages</th>
<th>Unit size (m³/d)</th>
<th>Typical range of base unit cost (US $/(m³/d))</th>
<th>Base unit cost assumed in assessment (US $/(m³/d))</th>
</tr>
</thead>
<tbody>
<tr>
<td>MED</td>
<td>11.5</td>
<td>14</td>
<td>24 000</td>
<td>900–1400</td>
<td>1300</td>
</tr>
<tr>
<td>MED</td>
<td>17</td>
<td>23</td>
<td>24 000</td>
<td>1000–1500</td>
<td>1430</td>
</tr>
<tr>
<td>MED</td>
<td>21</td>
<td>27</td>
<td>24 000</td>
<td>1100–1600</td>
<td>1520</td>
</tr>
<tr>
<td>RO</td>
<td>NA</td>
<td>1</td>
<td>24 000</td>
<td>800–1200</td>
<td>1000</td>
</tr>
</tbody>
</table>

**Operation and maintenance costs (US $/m³)**

For 24 000 m³/d desalination plants

<table>
<thead>
<tr>
<th></th>
<th>RO</th>
<th>MED</th>
</tr>
</thead>
<tbody>
<tr>
<td>Personnel</td>
<td>0.05–0.07</td>
<td>0.05–0.07</td>
</tr>
<tr>
<td>Maintenance</td>
<td>0.03–0.05</td>
<td>0.04–0.06</td>
</tr>
<tr>
<td>Chemicals</td>
<td>0.04–0.06</td>
<td>0.03–0.05</td>
</tr>
<tr>
<td>Membranes</td>
<td>0.05–0.08</td>
<td>NA</td>
</tr>
</tbody>
</table>

aN = not applicable.

b Depending on the number of employees and their salaries.
c Depending on the plant design and feedwater quality.

of its condensing turbines. As a result, the reduction in electricity generation per cubic metre of potable water produced is 0.7–1 kW(e)-h/m³ less than for both fossil energy sources coupled to MED plants of identical GOR. This will result in lower nuclear than fossil heat costs.

The results of the economic assessment for MED can be summarized as follows:

(a) Potable water production costs range from about US $0.65/m³ to about US $1.1/m³, depending mainly on the energy source, the discount rate, the fossil fuel price, the PWR investment cost and the water to electricity ratio;

(b) For most of the conditions considered, the potable water production costs of a MED process coupled to a PWR would be in the same range as the water costs from a MED process coupled to a coal plant;
### TABLE II. TECHNICAL PERFORMANCE AND COST DATA OF REFERENCE BASE POWER PLANTS

<table>
<thead>
<tr>
<th>Plant type</th>
<th>PWR</th>
<th>Combined cycle plant</th>
<th>Coal fired plant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel type</td>
<td>Nuclear</td>
<td>Oil/gas</td>
<td>Coal</td>
</tr>
<tr>
<td>Site net output (MW(e))</td>
<td>620</td>
<td>612</td>
<td>620</td>
</tr>
<tr>
<td>Net thermal efficiency (%)</td>
<td>32</td>
<td>51</td>
<td>40</td>
</tr>
<tr>
<td>Construction cost (US $/kW(e))&lt;sup&gt;a&lt;/sup&gt;</td>
<td>1840</td>
<td>660</td>
<td>1430</td>
</tr>
<tr>
<td>Operation and maintenance costs (mill/kW(e)-h)&lt;sup&gt;b&lt;/sup&gt;</td>
<td>8.8</td>
<td>5.5</td>
<td>3.5</td>
</tr>
<tr>
<td>Fuel cost (mill/kW(e)-h)&lt;sup&gt;b&lt;/sup&gt;</td>
<td>7.5</td>
<td>c</td>
<td>c</td>
</tr>
<tr>
<td>Decommissioning cost (mill/kW(e)-h)&lt;sup&gt;b&lt;/sup&gt;</td>
<td>1.0</td>
<td>d</td>
<td>d</td>
</tr>
<tr>
<td>Construction lead time (years)</td>
<td>5</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>Economic life (years)</td>
<td>30</td>
<td>30</td>
<td>30</td>
</tr>
</tbody>
</table>

<sup>a</sup> Including the owner's cost and contingency.

<sup>b</sup> mill (= US $10^{-3} = 0.1¢).

<sup>c</sup> Calculated from the fossil fuel prices assumed.

<sup>d</sup> Not considered.

### TABLE III. MAIN ECONOMIC PARAMETERS

<table>
<thead>
<tr>
<th>Reference values</th>
<th>Sensitivity values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference currency</td>
<td>US $ (Dec. 1996)</td>
</tr>
<tr>
<td>Operation reference date</td>
<td>1 January 2005</td>
</tr>
<tr>
<td>Economic life of energy co-production plants</td>
<td>30 years</td>
</tr>
<tr>
<td>Operating regime</td>
<td>Base load</td>
</tr>
<tr>
<td>Lifetime average load factor</td>
<td>80%</td>
</tr>
<tr>
<td>Power plants</td>
<td>91%&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>RO plants</td>
<td>75%&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>MED plants</td>
<td></td>
</tr>
<tr>
<td>Real interest and discount rates</td>
<td>8%</td>
</tr>
<tr>
<td>Levelized crude oil price&lt;sup&gt;c&lt;/sup&gt;</td>
<td>US $20/barrel</td>
</tr>
<tr>
<td>Levelized coal price&lt;sup&gt;c&lt;/sup&gt;</td>
<td>US $50/t</td>
</tr>
<tr>
<td>Potable water standard</td>
<td>World Health Organization</td>
</tr>
<tr>
<td>Nuclear plant construction cost</td>
<td>100%</td>
</tr>
</tbody>
</table>

<sup>a</sup> A 100% available electric grid was assumed as the back-up electricity source.

<sup>b</sup> Calculated by the combined availability of the power plant and the MED plant (no back-up heat source was assumed).

<sup>c</sup> Includes transportation cost.
(c) Water to electricity ratios smaller than 30 m$^3$/MW(e)-h, low levelized coal prices and high real discount rates favour the coal fired plant, whereas low real discount rates and high water to electricity ratios tend to favour the nuclear option;

(d) For low crude oil and gas prices, real discount rates of 8% or higher and low water to electricity ratios (<12 m$^3$/MW(e)-h), the combined cycle seems to be the economically best solution;

(e) However, for water to electricity ratios higher than 25 m$^3$/MW(e)-h, the combined cycle yields the highest potable water production costs from distillation processes.

It should be noted that the cost uncertainties of this general economic analysis are relatively large. This applies in particular to advanced nuclear plant designs for which no construction and operation experience exists. However, some of these advanced designs appear to be quite attractive, meeting the requirements of developing countries better than the large evolutionary nuclear power plants deployed in major industrialized countries, and may well be suitable energy sources for nuclear desalination.

2. ECONOMIC EVALUATION METHODOLOGY

Economic analyses were performed using the power credit method incorporated into the Co-generation/Desalination Economic Evaluation (CDEE) spreadsheet [5]. The CDEE methodology is suitable for economic evaluations and screening analyses of various desalination and energy source options. The spreadsheet includes simplified models of several types of nuclear/fossil power plant and nuclear/fossil heat source, and both distillation and membrane desalination plants. Cost and performance data are incorporated as default values, so that the spreadsheet can be quickly adapted to analyse a large variety of options with little new input data required. The spreadsheet is to be demonstrated at this Symposium.

The spreadsheet serves three objectives:

(1) Calculation of the levelized cost of electricity and desalted water as a function of the quantity, the site specific parameters, the energy source and the desalination technology;

(2) Side by side comparison of a large number of design alternatives on a consistent basis, with common assumptions;

(3) Quick identification of the lowest cost options for providing specified quantities of desalted water and/or power at a given location.

However, the user is cautioned that the spreadsheet is based on simplified models. In planning an actual project, the project costs should be assessed more
accurately on the basis of more substantive information, including project design and specific vendor data.

Potable water costs from co-generation plants are calculated in the spreadsheet applying the power credit method. This method is based on the concept that the electricity equivalent of the steam and/or electricity provided to the sea water desalination plant could have been sold to the grid, and that this loss in revenue from electricity sales should be charged to the water costs. The power credit is calculated by multiplying the reduction in electrical output by the levelized unit electricity generation cost of an equivalent single purpose power plant. Applying the power credit method, the potable water produced is credited with all the economic benefits of co-production. This method is often applied in situations with a well established electricity market, with potable water considered as a by-product. Other methods, including the water credit method, the caloric method and the exergetic method, allocate at least some benefits of co-production to electricity. The most equitable cost allocation method from the thermodynamic viewpoint is the exergetic method, described in Ref. [6].

3. FINANCING

Concerning financing, the availability of funds at reasonable terms is a key factor for the feasibility of every large power and/or desalination project, in particular for nuclear power. According to its statute, the IAEA cannot provide financing itself; however, the IAEA has co-operated with the World Bank and other banks in reviewing the main features and problems of financing nuclear projects, with special reference given to developing countries [7].

According to this review, the relevant characteristics of commercial nuclear desalination projects that make arrangements for adequate financing difficult include high investment costs, long construction periods, a relatively high degree of uncertainty with respect to costs and scheduling, and potentially significant public opposition. These characteristics imply significant financial risks.

The primary difficulty in financing a nuclear desalination project is the magnitude of the investment. The initial investment cost for a 600 MW(e) nuclear power plant ranges between about US $1300 and 1800 million. These costs will depend on the plant design, site characteristics, regulatory requirements and a number of other factors. Investment costs for a large desalination plant may range from about US $200 million for a 200 000 m$^3$/d RO plant to about US $850 million for a 50 000 m$^3$/d MED plant, which would result in about US $1500–2650 million for the complete power and desalination project.

The large capital requirements for a nuclear desalination plant may approach or even exceed the overall available credit limits identified by lenders for an individual developing country. Also, lenders may be reluctant to concentrate their financial risk
in a single project of this magnitude. Moreover, during the construction period, the owner is confronted with two problems that are more severe for nuclear than for non-nuclear desalination projects owing to the longer construction times:

1. The financial requirement to pay interest (debt servicing) during construction;
2. The initial lack of revenue from the project, since no electricity or water is being produced.

The construction schedules of the nuclear power plant and the desalination plant are usually arranged separately to minimize interface problems. The construction of the nuclear power plant will start first, because of its longer construction period and because a distillation plant needs steam and electricity from the nuclear power plant.

If alternative energy sources are available (such as electricity from the grid or heat from an auxiliary boiler), early construction of the desalination plant could allow potable water production that would satisfy both construction site requirements and consumers, thus allowing for revenues from the project prior to the completion of the nuclear plant. However, these revenues would be much smaller than the investment requirements to complete the project.

Regarding the uncertainty of the construction schedule, experience in various countries has shown that a nuclear power project can face severe obstacles, which may lead to construction times being much longer than expected. The relevant reasons included regulatory difficulties, legal or political intervention, and financial difficulties. Longer construction periods lead to large cost overruns, thus higher financing requirements and a possible renegotiation of financing arrangements, as well as an increase in the debt servicing payments.

In addition to these cost related considerations, public acceptance of nuclear energy has become an important issue. Public concern with regard to nuclear risks has had a direct and profound influence on the feasibility, schedule and cost of nuclear power projects worldwide.

It is thus essential that every effort be made by all the parties involved in the development of a nuclear desalination project to reduce the uncertainties and risks. It is important to have:

(a) Firm governmental commitment that is based on sound national policies and plans, and adequate international arrangements;
(b) Thorough technical, economic and financial analyses;
(c) Economic competitiveness, with equivalent alternative supply options;
(d) A plant design that is based on proven nuclear reactor and desalination technologies;
(e) Regulatory issues resolved before the start of construction;
(f) Efficient project management, with tight control of the quality, cost and schedule.
A helpful step towards realizing this goal would be the prior implementation of a demonstration project. The investment climate is also improved through a good record of consistent and fair dealing with lenders and investors by the government and the owner organization, by adequate risk sharing between the vendor, the owner and the financing institutions, and by setting the electricity and water tariffs at a level necessary for the financial strength of the utility. This is important since, in a period when many countries are facing difficulties in servicing their debt, commercial banks as well as the governmental organizations of exporting countries may be reluctant to lend these countries additional funds, especially to build a nuclear power plant that lending organizations view as a risky project.

Sources of foreign currency financing include bilateral arrangements through export credit agencies and suppliers’ credits, arrangements through commercial banks guaranteed by export credit guarantee agencies, multilateral development institutions (including the World Bank Group and regional development banks), and international capital markets.

Concerning bilateral arrangements, the Organization for Economic Co-operation and Development countries had concluded a ‘consensus’ on financing which foresaw a 1% higher interest rate for nuclear projects than for conventional energy projects. More recently, this interest rate differential was lowered to 0.75%. The consensus allows for 85% of the exported value to be covered by a main credit, with a complementary credit for the other 15% that can be used to finance either the capitalized interest during construction or the local part of the contract. The loan is made generally with a 7 year grace period (the construction period) and paid back over 15 years.

Multilateral development institutions provide financing for projects that would raise the standards of living in developing countries, including electricity and water projects. This financing is usually provided at terms which cannot be obtained from commercial banks or on the capital markets. Co-financing of nuclear projects was considered by some multilateral institutions, e.g. by the European Bank for Reconstruction and Development, but is not favoured by others.

The lending organizations display high prudence in the selection of borrowers. Only a country with acceptable credit ratings will qualify for bank loans and other credits for financing such a project. Sound economic policies and good debt management are essential for an acceptable credit rating.

As much as possible of the total project costs, but in any event the local portion of these costs, should be financed with domestic funds. Sound sources of local currency funding for investment in a public utility project would be funds of the project’s operating organization/utility, both from the equity and from the accumulated earnings set aside for such a planned investment, and the government budget. These sources could be supplemented by credits raised on the domestic capital market. A well functioning domestic capital market is particularly important for organizing local financing.
Adequate local financing must be arranged in good time and, in the case of loans, for a reasonable credit period. Realistic electricity and water tariffs that cover the full costs of generation, transmission and distribution are likely to be essential if plant owners are to achieve the sound financial strength needed to finance investments from their own resources and to be considered creditworthy by banks.

As foreign currency financing of local costs will increase the foreign debt burden and carry a significant foreign exchange risk, it is vital for successful project implementation to secure sufficient local financing. Some countries do not allow foreign currency sources to be used for the purpose of local cost payment for national economic and monetary reasons.

It has often proved difficult to raise enough money for local financing from local capital sources. The consequences of local financing constraints could be that a project may not be feasible or, if the project is started nevertheless, that costly delays occur during implementation.

4. BUILD–OWN–OPERATE (BOO) ARRANGEMENTS

The technical risks related to construction and operation could be reduced by prior implementation of a demonstration project and by involvement of companies with experience in construction and operation as plant owners/operators, e.g. in a BOO arrangement. BOO schemes have been applied at a number of conventional power projects, e.g. in Indonesia, Pakistan and Turkey. Such schemes can attract foreign capital, and reduce the requirements for government guaranteed debt. They could be applicable in situations where conventional financing is difficult; where foreign investors are interested in the construction business and in the local electricity and water market; and where the investors are likely to achieve an attractive capital return.

On the other hand, experience with the negotiation of BOO schemes for nuclear power projects has shown that the division of responsibilities and risks among the parties concerned is difficult, and that the contracts are complicated. While governments will ultimately bear some risk of public electricity and water supply, e.g. by covering the financial losses of the utilities and guaranteeing their debt, foreign partners in a BOO scheme will have to assume most of the risks themselves. The foreign partners will be responsible for all the technical, economic and financing aspects of plant construction and operation, including the construction schedule, the safety and reliability of the plant, and adequate insurance coverage. They will have to conclude long term power and water purchase agreements with local utilities to secure sales at agreed tariffs. These tariffs should be sufficiently high to offer foreign investors an attractive capital return, which will be related to their commercial risks, and will be higher than commercial interest rates.
An interesting option for a BOO project could be a floating facility installed at a coastal site. In the event of difficulties, e.g. non-payment of electricity and water, the barge or ship could be disconnected from the electricity and water grids and shipped off-shore. Such a redeployable asset would bear a smaller commercial risk than a land based facility. However, both the additional costs of a floating facility and the technicalities of disconnecting must be carefully assessed to judge the viability of this option.

The licensing of plant construction and operation, radioactive waste management, plant decommissioning and waste disposal are subject to the host country’s legislation and regulations, and commercial risks related to these areas are largely beyond the control of foreign companies. It has therefore been suggested that the host government should protect foreign investors against such risks. Concerning waste management and plant decommissioning, this could be done through local companies on an agreed tariff basis, or through a build–operate–transfer agreement, by which the plant and the remaining liabilities are transferred to a local company after a certain operating period.

5. CONCLUSIONS

For the conventional and alternative financing approaches, the following is essential for the host government and utility in order to successfully implement a nuclear desalination project:

(1) A clear commitment to the project, with necessary government support based on sound national policies and plans;
(2) Adequate international arrangements;
(3) A thorough financial analysis, together with an economic analysis for evaluating the feasibility of the project;
(4) Maintaining acceptable credit ratings in order to qualify for investments and debt financing at reasonable terms;
(5) Financing as much as possible of the local cost component of the project in local currency from sources within the host country itself; the importance and difficulties of such financing are often underestimated;
(6) Utilization of a full range of expertise to benefit from existing experience and to deal with the complex technical, financial and legal matters;
(7) Electricity and water tariffs at a level necessary for sound financial strength.

The IAEA is ready to assist interested Member States, upon request, in building an adequate basis for a nuclear desalination programme. This could include training of nuclear project staff, assistance in preparing or reviewing feasibility studies and tender documents, assistance to the regulatory authority, and other means of building or strengthening the nuclear infrastructure. This could contribute towards building a
firm basis for a nuclear desalination programme as a prerequisite to sound technical and economic assessments and to obtaining financing for a well defined project on reasonable terms.

REFERENCES


THE ECONOMICS OF NUCLEAR DESALINATION IN EGYPT

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Abstract

THE ECONOMICS OF NUCLEAR DESALINATION IN EGYPT.

A 2 year study on the utilization of nuclear energy for sea water desalination in several Egyptian sites has been in progress since December 1994. Within the framework of this study, three sites on the Mediterranean Sea coast have been identified as possible locations for the nuclear desalination plants, of which only El-Dabaa has been qualified as a nuclear site. Estimates of the desalination plant capacities needed in 2017 ranged from 87,000 to 172,000 m$^3$/d. The results are presented of a cost analysis made of the energy and water costs for the various combinations of energy source and desalination process proposed for the candidate sites. The reactors considered are advanced small and medium power reactors (SMPRs). Performance and cost analyses for water and power production were carried out using a computer cost program developed by the IAEA. The cost per cubic metre of desalted water ranged from US $0.8 to 1.9, depending on the plant size and the desalination process. The most economic desalination process is a contiguous reverse osmosis plant with preheated feedwater. Higher oil prices and/or lower interest rates tend to favour the nuclear option.

1. INTRODUCTION

Egypt is located in the extreme northeast of Africa and consists of $1 \times 10^6$ km$^2$ of land. As shown in Fig. 1, the country is generally organized into four major areas: (1) the Nile Valley and Delta; (2) the Western Desert; (3) the Eastern Desert; and (4) the Sinai Peninsula.

Analysis of the data on population development [1] indicates that, during the period 1882–1947, the average annual growth rate was about 1.6%. During the period 1947–1986, it was about 2.4%. Recent data from the Ministry of Population indicate that there has been a decline in the population growth rate since 1989; this trend is expected to continue in the future. The World Bank [2] has confirmed this fact, since it forecasts an average population growth rate of 1.7% for the period 1992–2000 and 1.3% for 2000–2025.

The comparison between the 1976 and 1986 census data indicates that the percentage urban population to total population remained constant at about 44%.
Despite the apparent halt in urbanization or concentration around the capital city, unequal distribution of population in Egypt still persists as a result of the previous high urbanization rates. To return to a balanced population distribution pattern, radical changes have to be made in the redistribution of population. This can only be achieved by developing new areas outside of the Nile Valley and Delta, which will require both electricity and water.

2. REPRESENTATIVE SITES

The cost of alternative energy supply options to be coupled to various desalination processes depends very much on the required desalination output. Therefore, in the context of the present study, the most important criterion for the selection of
representative sites for nuclear desalination was the existence of a potable water deficit that cannot be satisfied by existing natural resources.

Three sites on the Mediterranean Sea coast are proposed as possible locations for nuclear desalination plants in Egypt. They were selected for the following reasons:

1. The potable water needs of these sites differ, thus facilitating studies on the effect of desalination capacity on the unit cost of potable water;
2. These sites are representative of the Egyptian northern coast, extending from the Egyptian borders in the East to those in the West, thus facilitating interpolation to other locations on the Egyptian Mediterranean coast;
3. The El-Dabaa location has already qualified as a nuclear site through intensive studies carried out by the Nuclear Power Plants Authority since the late 1970s, and is the site selected for the first Egyptian nuclear power plant.

The town of El-Dabaa (Site I) is one of eight administrative centres constituting the Matrouh Governorate, which includes the Mediterranean coastal area from west of Alexandria to the border of the Libyan Arab Jamahiriya. Over the past few years, development of tourist facilities along the coast from Alexandria to Marsa Matrouh has undergone a dramatic increase. Although this has led to a large increase in the volume of business during the summer months, adverse effects have also emerged. The foremost of these problems is the shortage of water during the summer months. A possible solution would be the installation of a desalination plant at the El-Dabaa site to serve inclusively the area between Borg El-Arab and Marsa Matrouh.

During the period 1972–1992, the average annual growth rate of potable water consumption was 15%. To estimate the future potable water demands, the urban and rural specific water consumption in 1992 was assumed to increase at an average annual growth rate of 3 and 2%, respectively. Assuming plant availability of 80%, plant capacity has to be 20% higher than demand to ensure a constant supply. The projected development of the potable water supply, as shown in Fig. 2, indicates that the El-Dabaa area (Site I) would require a desalination plant of about 172 000 m³/d in 2017.

The other two sites were selected to the west and east of El-Dabaa to facilitate interpolation to other locations on the Egyptian Mediterranean coast. Site II is located to the east of El-Dabaa. The projected development of the potable water supply, as shown in Fig. 2, indicates that this site would require 108 400 m³/d of desalted water in 2017. Site III (Saloum) is also located in one of the eight administrative centres of the Matrouh Governorate to the west of El-Dabaa. The assumptions made to estimate the future potable water demands for the various population centres to be served by the plant, as well as the plant size, were the same as those used for El-Dabaa. Potable water demands will increase at an average annual growth rate of 6.5%, to reach 82 772 m³/d in 2017. The corresponding desalination plant capacity would be about 87 000 m³/d, as shown in Fig. 2.
3. DESALINATION PROCESSES

Previous work [3–5] has shown that reverse osmosis (RO), multi-stage flash (MSF) and multi-effect distillation (MED) are the most interesting large scale water production processes. All have been proved by experience and are commercially available. While RO requires electricity, MSF and MED use mainly thermal energy and to a lesser extent electric energy. RO has the lowest energy consumption and the largest development potential [6], particularly when the RO feedwater is preheated in the power plant condenser.

The MSF process is the most widely used desalination process, especially in Middle East countries, where oil is plentiful. Inherently, however, the MED process has lower energy consumption, lower investment costs, and appears to be less sensitive to corrosion, scaling and fouling than the MSF process [4, 5]. In addition, its operational flexibility in partial load is higher.

On the basis of the above factors, MSF has been excluded from the economic assessment, since it has no inherent advantages over MED. In the present analysis, MED and RO were selected as the preferable technologies for cost comparison.

4. ENERGY SOURCES

The energy costs were found to be 35–58% of the total desalted water costs [3]. Therefore, it is essential that the correct source of primary energy for sea water desalination be selected, and that scanning of a wide range of energy sources be made. However, because the focus in this study is on nuclear energy, investigation of other energy sources is confined to providing a gauge to the economic competitiveness of nuclear energy.
TABLE I. REACTOR SCREENING CRITERIA [6]

<table>
<thead>
<tr>
<th>Category</th>
<th>Point</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Design status</strong></td>
<td></td>
</tr>
<tr>
<td>Conceptual or basic design</td>
<td>0</td>
</tr>
<tr>
<td>Detailed design</td>
<td>1</td>
</tr>
<tr>
<td>In operation or under construction</td>
<td>2</td>
</tr>
<tr>
<td><strong>Licensing status</strong></td>
<td></td>
</tr>
<tr>
<td>Not submitted for licensing</td>
<td>0</td>
</tr>
<tr>
<td>Licensed or in the process of licensing</td>
<td>1</td>
</tr>
</tbody>
</table>

The reactors considered for the present study are advanced small and medium power reactors (SMPRs), whose technical and economic data were provided by vendors in the course of an IAEA study [4]. To provide initial screening of these nuclear reactors, the set of criteria utilized in a recent IAEA study [6], and shown in Table I, was used as a filter to eliminate reactors of only conceptual or basic design status, or of a design that has not yet been submitted for licensing. In a second stage of the selection process, the above criteria and the following considerations were applied:

(1) In general, BWRs are regarded as being less attractive than PWRs for integration with desalination processes, since the primary reactor coolant reaches the condenser;
(2) LMRs do not seem to offer economically competitive short or medium term conditions on the nuclear power market;
(3) The prospects of high temperature GCRs appear promising in the longer term, but there seem to be no major ongoing design efforts leading to a reasonable expectation of short term commercial availability;
(4) The projected size of the Egyptian grid allows the introduction of any of the commercially available large nuclear reactors.

Consideration of the above factors resulted in the following list of reactors which could be considered for nuclear desalination and which appear to offer the best prospects for near term commercial deployment in Egypt:

(a) Large sized PWRs (900–1000 MW(e)) Various designs
(b) A medium sized PWR (400–800 MW(e)) AP-600 (United States of America)
(c) PHWRs (400–800 MW(e)) CANDU-3 (Canada)
    CANDU-6 (Canada)
(d) A small sized PWR (25–300 MW(e)) NP-300 (France)
However, because economic data for large sized PWRs are not available at present, the economic evaluation only considered the following nuclear options: AP-600, CANDU-3, CANDU-6 and NP-300. Some of these reactors have already been considered for electricity generation in Egypt in the course of another study [7]. The fossil options were steam and combined cycles. All operate in the co-generation mode (electricity and heat), which was found to be more economic than heat only options [4, 5].

5. COUPLING ASPECTS

There is no impediment to the use of nuclear reactors for the supply of energy to desalination plants in an integrated facility in which both the reactor and the desalination plant are located on a common site (nuclear desalination). The safety, regulatory and environmental concerns in nuclear desalination are mainly those related to the nuclear power plants, with due consideration given to the coupling process.

TABLE II. MAIN COUPLING CHARACTERISTICS OF THE MED AND RO PLANTS

<table>
<thead>
<tr>
<th>Source</th>
<th>MED</th>
<th>RO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water cooled reactors</td>
<td>The intermediate loop produces steam in a two stage flash tank. The steam produced in each stage is mixed and fed into the MED plant.</td>
<td>Power is taken directly from the power plant. There is common sea water intake and the RO feedwater is taken from the power plant condenser and, hence, is preheated.</td>
</tr>
<tr>
<td>Fossil combined cycle</td>
<td>Low pressure steam from the bottom steam turbine exhaust is fed directly into the MED plant.</td>
<td>Power is taken directly from the power plant. There is common sea water intake and the RO feedwater is taken from the power plant condenser and, hence, is preheated.</td>
</tr>
<tr>
<td>Fossil steam turbine</td>
<td>Low pressure steam from the steam turbine exhaust is fed directly into the MED plant.</td>
<td>Power is taken directly from the power plant. There is common sea water intake and the RO feedwater is taken from the power plant condenser and, hence, is preheated.</td>
</tr>
</tbody>
</table>
It is essential that the possibility of radioactive traces penetrating the desalination system be eliminated. Thus, at least two barriers between the primary coolant and the saline water are required, in addition to pressure reversal. When coupling a PWR to MSF, the steam generator would be the first barrier, with the brine heater, acting as the steam condenser, serving as the second barrier [3].

To achieve pressure reversal, the brine heater should be maintained at a higher pressure than the heating fluid, so that the direction of leakage would be from the desalination system, not into it [3]. However, for MED, which unlike MSF does not have a brine heater, thermal coupling has to be implemented by an isolation loop, using either high quality water in a closed loop or saline water recirculation in an open loop. Table II summarizes the main coupling characteristics of the selected energy sources and desalination processes.

6. ECONOMIC ANALYSIS OF THE DESALINATION OPTIONS

To estimate the cost of power and water for the nuclear and fossil desalination options, the IAEA Co-generation/Desalination Economic Evaluation (CDEE) spreadsheet [8] was used. This is an improved version of that applied in previous studies [4, 5]. The methodology used in the CDEE to perform comparative economic evaluations is that of the lifetime levelized unit cost of the potable water produced, expressed in US $/m³. The details of this methodology have been described in several IAEA publications [4, 7].

Apart from minor changes, the cost comparison in the present study was very similar to that carried out in Refs [4, 5]. Assumptions included an 8% real interest rate and a US $15.5/barrel crude oil price, with 2% real escalation. The economic assessment was performed using cost data for the nuclear energy sources provided by vendors in 1991 for an IAEA study [4], and cost experience data for desalination and fossil fired plants available on the international market [4–6], restated in 1996 US dollars. The operation reference date was assumed to be 1 January 2017 to tie in with the projected water demands for the same year.

The main economic and performance parameters adopted are summarized in Table III. Because the construction costs were based on the experience gained in industrialized countries, a 10% increase in the base construction cost was included to allow for the added costs of installing such plants in Egypt, as applied in previous feasibility studies [5, 7].

The water costs were obtained by dividing the sum of the annual costs (for levelized capital costs, the expenses of various energies, operation and maintenance, current expenses such as insurance and taxes, and a decommissioning allowance) by the average annual production of water. The resulting levelized water costs (in US $/m³) at the desalination plant outlet at the various sites are summarized in
TABLE III. MAIN ECONOMIC AND PERFORMANCE PARAMETERS

<table>
<thead>
<tr>
<th>Reference currency</th>
<th>US $ (January 1996)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operation reference date</td>
<td>1 January 2017</td>
</tr>
<tr>
<td>Economic life</td>
<td>30 years</td>
</tr>
<tr>
<td>Operating regime</td>
<td>Base load</td>
</tr>
<tr>
<td>Lifetime average load factor</td>
<td></td>
</tr>
<tr>
<td>Nuclear power plants</td>
<td>80%</td>
</tr>
<tr>
<td>Desalination plants</td>
<td>91%</td>
</tr>
<tr>
<td>Backup heat boiler for MED plants</td>
<td>90%</td>
</tr>
<tr>
<td>Real escalation rate of nuclear fuel</td>
<td>0%</td>
</tr>
<tr>
<td>Real escalation rate of fossil fuel</td>
<td>2%</td>
</tr>
<tr>
<td>Real interest and discount rates</td>
<td>8% (sensitivity values: 5 and 10%)</td>
</tr>
<tr>
<td>Crude oil price</td>
<td>US $15.5/barrel (sensitivity: US $20.5/barrel)</td>
</tr>
<tr>
<td>Product water standard</td>
<td>World Health Organization</td>
</tr>
</tbody>
</table>

TABLE IV. LEVELIZED WATER COSTS

<table>
<thead>
<tr>
<th>Energy source</th>
<th>Power (MW(e))</th>
<th>Site I (172 000 m³/d)</th>
<th>Site II (108 000 m³/d)</th>
<th>Site III (87 000 m³/d)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>MED</td>
<td>RO</td>
<td>MED</td>
</tr>
<tr>
<td>Nuclear</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NP-300</td>
<td>300</td>
<td>1.140</td>
<td>0.840</td>
<td>1.172</td>
</tr>
<tr>
<td>CANDU-3</td>
<td>450</td>
<td>1.113</td>
<td>0.779</td>
<td>1.203</td>
</tr>
<tr>
<td>AP-600</td>
<td>600</td>
<td><strong>1.026</strong></td>
<td>0.765</td>
<td><strong>1.070</strong></td>
</tr>
<tr>
<td>CANDU-6</td>
<td>660</td>
<td>1.087</td>
<td><strong>0.750</strong></td>
<td>1.133</td>
</tr>
<tr>
<td>Fossil</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Combined cycle</td>
<td>350</td>
<td><strong>0.900</strong></td>
<td>0.748</td>
<td><strong>0.918</strong></td>
</tr>
<tr>
<td>Steam turbine</td>
<td>600</td>
<td>1.042</td>
<td>0.795</td>
<td>1.055</td>
</tr>
</tbody>
</table>

a Numerals in bold type are the most economic nuclear and fossil options coupled to MED and RO.
Table IV. It is clear from the table that, under the assumptions made for the various combinations at each site, the most economic nuclear and fossil options are CANDU-6/RO and combined cycle/RO, respectively.

However, the uncertainties of using advanced SMPRs for sea water desalination are quite large [5], e.g. the construction costs, and the reliability and availability of the nuclear reactors and the desalination plants. Therefore, a limited sensitivity analysis was performed on the interest rates and oil prices for the most economic nuclear and fossil options; the results are given in Figs 3 and 4, respectively.
The sensitivity analysis of the interest rate (Fig. 3) indicates that, while the base case (8% interest rate) would give practically identical results for both the nuclear and fossil options, an interest rate of 5% would make the nuclear option more economic. For a 10% interest rate, the fossil option is cheaper. An increase in oil prices to US $20.5/barrel, including transportation costs, and with the same 2% per year escalation rate, would render the nuclear option more economic (Fig. 4).

7. CONCLUSIONS

The results of the economic evaluation confirmed those obtained during an IAEA generic study [4] and a North African regional study [5], where the levelized water costs for both the nuclear and fossil options were in the same range. Higher oil prices and/or lower interest rates favour the nuclear option. The most economic desalination process is contiguous RO with preheating.

REFERENCES

A NUCLEAR DESALINATION DEMONSTRATION OPPORTUNITY IN THE REPUBLIC OF KOREA

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Abstract

A NUCLEAR DESALINATION DEMONSTRATION OPPORTUNITY IN THE REPUBLIC OF KOREA.

The International Atomic Energy Agency has been studying the technical and economic feasibility of nuclear desalination for the past several years. A recent study has identified the most practical options for near term demonstration of nuclear desalination. An opportunity exists for such a demonstration at the Wolsong site in the Republic of Korea. As in other parts of the country, drought conditions and increasing levels of pollution have led to water shortages at the site and in the surrounding community. Canada has introduced the concept of integrating reverse osmosis desalination with the CANDU reactor to use the waste heat from the plant to improve the efficiency of the desalination process. Predesign feasibility studies and conceptual design work on the system have been essentially completed. At this stage, the technology is ready for demonstration and deployment in commercial production facilities. The Republic of Korea and Canada have enjoyed a co-operative relationship in developing the CANDU programme in the Republic of Korea. The essential elements (the need for water, a well developed technological concept, an appropriate location, etc.) are present to provide an opportunity for continued co-operation in demonstrating nuclear desalination at Wolsong. Such a demonstration, carried out in the near term and at a relatively modest cost, would provide data for use in the validation of RO system technical and economic modelling and for direct comparison between the actual and the predicted performance characteristics. With international participation and the support and co-operation of the IAEA, the programme could also provide data that may be of value to the Republic of Korea and other nations considering nuclear desalination as a potential solution to their water supply problems.

1. INTRODUCTION

The International Atomic Energy Agency, along with its Member States, has been studying the technical and economic feasibility of nuclear desalination for the past several years [1–3]. Interest among Member States has increased dramatically,
and the IAEA has, over the past 2 years, been carrying out a study to identify the most practical options for near term demonstration of nuclear desalination [4]. The results of this study indicate that among these options is the coupling of a reverse osmosis (RO) desalination system using preheated feedwater to a currently operating or newly constructed medium sized reactor.

Canada has actively supported the work of the IAEA in nuclear desalination, and with the completion of the options identification study [4] strongly believes that it is now time to move forward with demonstration of nuclear desalination. The purpose of this paper is to describe one such possible demonstration project.

2. CANADIAN NUCLEAR DESALINATION TECHNOLOGY (CANDESAL)

Canada has introduced the concept of integrating RO desalination with the CANDU reactor in such a way that it uses waste heat from the reactor to improve the efficiency of the RO desalination process. The CANDESAL system, although simple in concept, can result in significant improvements in water production efficiency, while having an essentially zero impact on the design, operation or safety of the nuclear reactor.

2.1. Reactor type

The CANDESAL development activities have been based on using the highly successful and well proven CANDU reactor as an energy source for desalination. The currently available CANDU 6 and other newer CANDU models have been evaluated in detail and found to be well suited to nuclear desalination application. The integration of reactor and desalination technologies allows the use of a standardized reactor design, thereby eliminating the need for reactor design changes to accommodate the desalination application and retaining the maximum efficiency of electrical generation from the nuclear power plant.

2.2. Desalination system

Reverse osmosis has been selected as the desalination technology for the Canadian system. It is recognized as being the most energy efficient process currently available. It also has the advantage of offering the most potential for additional technological advances that could lead to further improvements in water production efficiency and reduced costs.
2.3. Integrated plant concept

Proper design integration and optimization of the performance characteristics are essential to achieving the objectives of improved efficiency and reduced costs. In addition to the electrical coupling required for RO systems, the Canadian approach to system integration uses the reactor condenser cooling water discharge stream as preheated feedwater to the RO system. This provides a significant improvement in RO system efficiency, thereby reducing both the capital cost and the unit water production cost. Figure 1 provides an illustration of the increase in potable water production efficiency that can be achieved as a result of increasing the feedwater temperature. Further improvements are achieved by using advanced feedwater pretreatment, energy recovery systems and sophisticated RO system design optimization techniques that are similar to those used in the nuclear industry. Increases in the water production efficiency of the order of 10–15% and potential savings in the unit water production cost of the order of 8–10% are considered achievable, depending on the degree of preheated feedwater. Water production can vary over a range of a few tens of thousands of cubic metres per day to several hundred thousand cubic metres per day, depending on the user requirements and on the particular CANDU reactor being utilized. Up to 25% of the reactor’s electric power production can be economically used for water production, with the balance being distributed to the grid.

FIG. 1. Increase in potable water production efficiency as a result of preheated feedwater.
2.4. Status

Predesign feasibility studies and conceptual design work on the CANDESAL system have been essentially completed. A design approach based on system integration and design optimization has been developed. Numerous studies have been carried out to assess the benefits of the design innovations introduced. These include studies to establish the specific performance characteristics, to quantify the degree of performance improvement and to assess the economics of the system. Preliminary design and detailed engineering will be carried out on a project specific basis. A wide range of water production capabilities has been evaluated to determine optimum integration of the reactor and the desalination system for the large scale, efficient, economic production of potable water. At this stage, the technology is considered ready for deployment in commercial production facilities.

The technological risk in moving ahead with a full scale production facility is considered negligible, and demonstration is not required to confirm the viability of the concept. Rather, a demonstration project is considered to be highly desirable in order to validate the performance and economic models to experimentally quantify the degree of efficiency and economic improvement, to gain hands on operational experience, and to contribute to the overall confidence in and acceptability of nuclear desalination.

3. AN OPPORTUNITY IN THE REPUBLIC OF KOREA

3.1. Selection of a demonstration site

One of the primary difficulties in advancing towards a nuclear desalination demonstration project is selection of a site where such a demonstration could take place. It is desirable that the demonstration be done at a reasonable cost, in a country with an active nuclear power programme, and where a need for water exists so that the demonstration has value in terms of both the data obtained and the water produced.

The Wolsong site in the Republic of Korea is just such a location and CANDU 6 reactors are already in operation and under construction there. The general availability of clean water resources in the Republic of Korea has been reduced significantly over the past few years by drought resulting from weather anomalies and worsening levels of pollution [5]. More specifically, the Wolsong site has begun to experience significant fresh water supply shortages. At times, the situation has been so bad that staff living on the Wolsong town site and working in the site construction offices were without an adequate fresh water supply for
significant periods. There is concern that the shortage of fresh water may become sufficiently severe that it will adversely affect reactor construction schedules. Several sources of additional water supply are being explored; however, to date it does not appear that sea water desalination has been considered as one of the alternatives for an additional fresh water supply.

3.2. Demonstration of nuclear desalination

The Republic of Korea and Canada have enjoyed a very strong and positive co-operation relationship in developing the CANDU programme in the Republic of Korea. The essential elements (the need for water, a well developed technological concept, an appropriate location, etc.) are present to provide an opportunity for continued co-operation in demonstrating nuclear desalination at Wolsong. Such a demonstration could be carried out in the near term, and at a relatively modest cost.

A demonstration project at the Wolsong site would provide data for use in the validation of RO system technical and economic modelling and for direct comparison between the actual and the predicted performance characteristics. In particular, the economic benefits of RO system preheated feedwater could be validated under actual operating conditions, and the potential for interaction effects between the reactor and the desalination units could be studied.

With international participation and the support and co-operation of the IAEA, a demonstration at Wolsong could be structured in such a way that it could provide data having the broadest possible applicability to other nations considering nuclear desalination as a potential solution to their own water supply problems. Such data could be particularly valuable as input to the decision making process that must be gone through in order to select the most appropriate desalination technology for a nuclear desalination programme.

4. PROPOSED DEMONSTRATION

4.1. First phase

As noted in Ref. [3], many issues must be considered in the implementation of a nuclear desalination demonstration programme. It is, therefore, prudent to proceed in a phased manner.

In the case of Wolsong, there is, as noted in Section 3.1, a need for additional fresh water production on-site and in the nearby community. An appropriate first phase would thus be the design and construction of an RO sea water desalination unit for initial operation as a stand alone unit, drawing electric power for its operation
from the Wolsong 1 nuclear generating station. The water production capacity would be determined on the basis of both the fresh water requirement and the need for a unit of sufficient size to serve as a suitable demonstration. Because RO systems are readily modularized, installation of a unit of about 1000 m$^3$/d would provide an effective starting point. The addition of subsequent modules to increase the capacity to 3000–5000 m$^3$/d, or larger if appropriate, could then follow.

Initial implementation as a stand alone system would allow a very short design and construction period. This would provide a near term solution to the water shortage problem at the Wolsong site, as well as an immediate return on the capital investment in the unit.

### 4.2. Nuclear phase

Following successful implementation of the stand alone system, the ‘nuclear phase’ of the demonstration programme could begin. The RO unit could be ‘coupled’ to Wolsong 1 by simply drawing its feedwater from the condenser cooling water discharge stream.

While it is a relatively straightforward matter to design and install the necessary coupling between the reactor and desalination systems, to do so would require the approval of the licensing authority. Although the potential for interaction between systems is minimal in the case of RO, the potential for an adverse operational or safety impact must be examined. This provides an opportunity, as well as a requirement, to address the design, safety, operational and regulatory issues associated with nuclear desalination.

The time frame to examine these issues and to obtain the necessary regulatory approval remains to be determined. Nevertheless, the required activities are well defined, and it is reasonable to expect that they could be carried out over a period of about 1 year. Hence, the issues that will eventually have to be dealt with in a commercial nuclear desalination programme could be addressed at an early stage, on a real project, through the vehicle of the proposed nuclear desalination demonstration project.

### 5. CONCLUSIONS

The above mentioned countries have enjoyed a strong co-operative relationship in developing the CANDU programme in the Republic of Korea, and both nations have active, ongoing programmes in nuclear desalination. As a result, a unique opportunity exists at the Wolsong site to implement a nuclear desalination demonstration programme. Such a demonstration could be put in place in the near term and at a relatively modest cost, and could be carried out under conditions that
would be fully consistent with the goals and objectives of the IAEA. With IAEA endorsement and technical support, the demonstration could be carried out in such a manner as to obtain data of value to a wide range of nations considering nuclear desalination. The project would therefore draw the interest and attention of the international community, as well as provide a mechanism for the Republic of Korea and Canada to deal with a variety of issues that could not otherwise be addressed until much later.

REFERENCES


IMPLEMENTATION OF NUCLEAR DESALINATION IN SAUDI ARABIA

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Riyadh, Saudi Arabia

Abstract

IMPLEMENTATION OF NUCLEAR DESALINATION IN SAUDI ARABIA.

Most of the Saudi desalination plants are of the multi-stage flash (MSF) type. These plants are often constructed as a dual purpose installation, producing power and water. MSF plants are considered to be energy intensive, where the energy cost is a major controlling parameter in the overall cost of desalination. Oil price fluctuations affect the cost of desalted water significantly. On the other hand, nuclear power offers price stability in the long term. Nuclear powered desalination provides long term availability of indigenous fuel, as well as long term fuel price stability. It has a minimum environmental impact if compared with other conventional desalination processes. The operational expenses of nuclear desalination are far lower than those of conventional plants. Implementation of nuclear desalination in Saudi Arabia is essential where large water requirements exist. The CANDU PHWR is the appropriate type of nuclear reactor for Saudi Arabia. A hybrid reverse osmosis/MSF CANDU PHWR is the candidate system for applying dual purpose nuclear desalination plants in Saudi Arabia.

1. INTRODUCTION

Saudi Arabia is a large arid country without any rivers. The average rainfall is less than 101.6 mm (4 in) and surface water resources are scarce. Hydrological investigations have pointed to large resources of underground water of two types: replenishible and non-replenishible. Replenishible groundwater, on average 10 years old and found mainly in the central part of the country, has a volume of more than $200 \times 10^6 \text{m}^3$. A proven reserve of $338 \times 10^9 \text{m}^3$ of non-renewable subsurface water is estimated that may have been formed some 20 000 years ago.

Water consumption in Saudi Arabia has increased rapidly over the past few years, of which agriculture accounts for more than 80%. The projected water demand in Saudi Arabia is $6523 \times 10^6 \text{m}^3/d$ in the year 2000 [1]. Table I shows the
projected water balance in Saudi Arabia. A simple water demand model can be given as [2]:

$$D_t + ae^{bt}$$

where $D_t$ is the water demand in $10^6$ m$^3$/d at year $t$, $t$ is the time in years ($t = 0$ in the year 1399 Anno Hegirae (1978)), and $a$ and $b$ are regression coefficients. The coefficient $a$ indicates the initial demand and $b$ the growth rate. The values of $a$ and $b$ are as follows:

<table>
<thead>
<tr>
<th>Sector</th>
<th>$a$ ($10^6$ m$^3$/d)</th>
<th>$b$ ($a^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urban and industrial</td>
<td>500.0</td>
<td>0.0744</td>
</tr>
<tr>
<td>Rural and livestock</td>
<td>25.8</td>
<td>0.0177</td>
</tr>
<tr>
<td>Agriculture</td>
<td>1683.3</td>
<td>0.0300</td>
</tr>
<tr>
<td>Surplus (deficit)</td>
<td>2916.4</td>
<td>-0.0453</td>
</tr>
<tr>
<td>Total</td>
<td>4715.9</td>
<td>0.0162</td>
</tr>
</tbody>
</table>

The negative value of $b$ in the surplus forecasting model means that surplus water decreases with time, indicating the need for better water resources management [2].

**TABLE I. PROJECTED WATER BALANCE IN SAUDI ARABIA ($10^6$ m$^3$/d)**

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Water resources</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Non-renewable</td>
<td>3450</td>
<td>3450</td>
<td>3450</td>
<td>3450</td>
</tr>
<tr>
<td>Renewable</td>
<td>1145</td>
<td>1145</td>
<td>1145</td>
<td>1145</td>
</tr>
<tr>
<td>Desalination</td>
<td>63</td>
<td>605</td>
<td>794</td>
<td>1199</td>
</tr>
<tr>
<td>Urban waste</td>
<td>—</td>
<td>140</td>
<td>335</td>
<td>730</td>
</tr>
<tr>
<td><strong>Total resources</strong></td>
<td>4658</td>
<td>5340</td>
<td>5724</td>
<td>6523</td>
</tr>
<tr>
<td><strong>Water utilization</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Urban and industry</td>
<td>502</td>
<td>828</td>
<td>1211</td>
<td>2279</td>
</tr>
<tr>
<td>Rural and livestock</td>
<td>27</td>
<td>28</td>
<td>31</td>
<td>38</td>
</tr>
<tr>
<td>Irrigated agriculture</td>
<td>1832</td>
<td>1873</td>
<td>2345</td>
<td>3220</td>
</tr>
<tr>
<td>Surplus</td>
<td>2247</td>
<td>2611</td>
<td>2137</td>
<td>986</td>
</tr>
<tr>
<td><strong>Total resources</strong></td>
<td>4658</td>
<td>5340</td>
<td>5724</td>
<td>6523</td>
</tr>
<tr>
<td><strong>Total utilization</strong></td>
<td>4658</td>
<td>5340</td>
<td>5724</td>
<td>6523</td>
</tr>
</tbody>
</table>
The best way of obtaining fresh water in Saudi Arabia is to make efficient use of the sea and groundwater resources. Unfortunately, these sources are highly saline and cannot be used directly without desalination. It was planned to supply fresh water from sea water desalination with groundwater as backup. However, the groundwater resources are limited and also need to be desalted. Nearly 50% of the desalination

<table>
<thead>
<tr>
<th>TABLE II. MAJOR DESALINATION PLANTS IN SAUDI ARABIA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plant</td>
</tr>
<tr>
<td>-------------</td>
</tr>
<tr>
<td>Hagl II</td>
</tr>
<tr>
<td>Duba III</td>
</tr>
<tr>
<td>Al-Wajh II</td>
</tr>
<tr>
<td>Al-Wajh extension 1</td>
</tr>
<tr>
<td>Al-Wajh extension 2</td>
</tr>
<tr>
<td>Um-Lujj II</td>
</tr>
<tr>
<td>Rabig I</td>
</tr>
<tr>
<td>Aziziah I</td>
</tr>
<tr>
<td>Al-Birk</td>
</tr>
<tr>
<td>Farasan I</td>
</tr>
<tr>
<td>Farasan extension I</td>
</tr>
<tr>
<td>Jeddah II</td>
</tr>
<tr>
<td>Jeddah III</td>
</tr>
<tr>
<td>Jeddah IV</td>
</tr>
<tr>
<td>Jeddah RO 1</td>
</tr>
<tr>
<td>Medinah–Yanbu I</td>
</tr>
<tr>
<td>Shoaibah I</td>
</tr>
<tr>
<td>Assir I</td>
</tr>
<tr>
<td>Al-Khafji II</td>
</tr>
<tr>
<td>Al-Khobar II</td>
</tr>
<tr>
<td>Al-Jubail I</td>
</tr>
<tr>
<td>Al-Jubail II</td>
</tr>
<tr>
<td>Medinah–Yanbu II</td>
</tr>
<tr>
<td>Jeddah RO 2</td>
</tr>
<tr>
<td>Al-Jubail RO</td>
</tr>
<tr>
<td>Al-Khobar III</td>
</tr>
<tr>
<td>Shoaibah II</td>
</tr>
</tbody>
</table>

^a^ 1 gal(US)/d = 3.785 \times 10^{-3} m³.
plants in operation worldwide are located in Saudi Arabia [3]. A large number of multi-stage flash (MSF) plants are used for sea water desalination in the country. Reverse osmosis (RO) is used mainly for the treatment of brackish water. A growing trend is towards applying RO in the desalting of sea water because of the high energy consumption of MSF, the country's economy and the advancements made in membrane technology. Table II shows the desalination facilities in Saudi Arabia.

The RO and MSF plants use fossil fuel, whereas MSF utilizes the steam in the brine heater as a primary source of energy. RO is derived mainly by electricity, which pumps the feedwater against the membranes. Steam and electricity can be produced easily by nuclear reactors, which can be coupled to desalination plants (either MSF or RO). This integrated plant will be capable of producing power and water at a reasonable cost, and the maintenance and operating costs will drop significantly.

2. ENERGY REQUIREMENTS FOR THE DESALINATION PROCESSES

In MSF, sea water is boiled at progressively lowered temperatures in a sequence of decreasing pressure chambers. It is heated in the brine heater to its saturation temperature, and steam is used to provide the necessary energy. When sea water is introduced to the first MSF evaporator stage, which is under a sufficiently low pressure, it flashes, producing water vapour that condenses to give pure distillate. A pressure reduction at each stage is the key to repeated flashing. About 3–9 kg (6–20 lb) of product water are produced by 1055 kJ (1000 Btu) of input energy. The heat of consumption of MSF, $Q_h$ (kJ/s), is given by the following relation [4]:

$$Q_h = \frac{M_d \times 2326 \times 1.04}{PR}$$

where $M_d$ is the distillate flow (kg/s), $PR$ is the performance ratio (kg of distillate/2326 kJ of heat input), and 1.04 is to allow for the steam consumed by the ejectors. For large MSF plants, about 3.7 kW·h/m$^3$ of electric energy is consumed.

The RO plant is operated on the opposite principle of osmosis. Sea water is subjected to a pressure that is higher than the osmotic pressure. Desalted water is then forced to permeate through the semi-permeable membrane. For typical sea water of about 35 000 ppm total dissolved salts (TDS), the minimum energy needed to separate 3.785 m$^3$ (1000 gallons (US)) is 3 kW·h. The typical energy consumption of RO with 30% water conversion is about 9.7 kW·h/m$^3$. When using an energy recovery turbine of 80% efficiency, the electric energy consumption is reduced to 6.5 kW·h/m$^3$ [4].
The energy cost is a controlling parameter in the desalination cost. The energy requirements (performance ratio) of most of the common desalination processes are given in Table III. It should be noted that low energy requirements do not necessarily indicate the least cost desalination method. Selecting a desalination process requires an extensive cost analysis of other system parameters such as the capital cost, and the operation and maintenance costs.

**TABLE III. TYPICAL ENERGY CONSUMPTION OF THE DESALINATION PROCESSES**

<table>
<thead>
<tr>
<th>Process</th>
<th>Feature</th>
<th>Production rate (lb/m²)</th>
<th>Performance factor (lb/10³ Btu)</th>
<th>Pumping energy (kJ/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar pond</td>
<td>Single effect</td>
<td>4.0</td>
<td>0.95</td>
<td>2443</td>
</tr>
<tr>
<td>MSF</td>
<td>90°C</td>
<td>9.5</td>
<td>8.0</td>
<td>290</td>
</tr>
<tr>
<td>MSF</td>
<td>120°C</td>
<td>14.0</td>
<td>12.0</td>
<td>193</td>
</tr>
<tr>
<td>Multi-effect evaporation (MEE)</td>
<td>71°C</td>
<td>8.0</td>
<td>8.0</td>
<td>290</td>
</tr>
<tr>
<td>MEE</td>
<td>120°C</td>
<td>13.0</td>
<td>15.0</td>
<td>155</td>
</tr>
<tr>
<td>Vapour compression</td>
<td>65 kW-h/kgal</td>
<td>50.0</td>
<td>38.0</td>
<td>61</td>
</tr>
<tr>
<td>Freezing</td>
<td>50 kW-h/kgal</td>
<td>—</td>
<td>49.0</td>
<td>47</td>
</tr>
<tr>
<td>RO</td>
<td>Sea water feed</td>
<td>100.0</td>
<td>54.0</td>
<td>43</td>
</tr>
<tr>
<td></td>
<td>(45 kW-h/kgal)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RO</td>
<td>5000 ppm feed</td>
<td>75.0</td>
<td>200.0</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>(12 kW·h/kgal)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electrodiagnosis</td>
<td>5000 ppm feed</td>
<td>30.0</td>
<td>200.0</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>(12 kW·h/kgal)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

a 1 lb = 0.4536 kg.
b 1 Btu = 1.055 × 10³ J.

Most of the sea water MSF plants are constructed as dual purpose installations that produce power and water. The fuel consumption of a dual purpose plant is much lower than that of the two separate power or desalination plants. For example, a 189 250 m³/d (50 × 10⁶ gal(US)/d) and 500 MW dual purpose plant consumes about 1700 MW of thermal power. A power plant of the same capacity (500 MW) consumes about 1500 MW of thermal power. A desalting plant with a capacity of 189 250 m³/d consumes about 700 MW of thermal power. Therefore, a total of 2200 MW is required for the two separate plants compared with only 1700 MW for a dual purpose plant.
In a dual purpose MSF plant, energy is often supplied to the desalination plant by one of the following sources: backpressure steam turbine exhaust; extraction from a passout steam turbine; exhaust heat recovery from a gas turbine; or exhaust heat recovery from a diesel generator.

Darwish [5] proposed two schemes for combining a steam power plant and an RO system. In the first scheme, a large capacity pump from the steam turbine is used to supply the RO modules with the feed at the required high pressure, up to 70 bar. The consumed power is 12.3 MW for a 37 850 m³/d (10 × 10⁶ gal/d) RO plant with feedwater of 43 000 TDS pumping 1750 L/s at an average pressure of 56 bar (812 psi) for 25% recovery [5]. The proposed scheme produces 233 MW and 30 280 m³/d (8 × 10⁶ gal/d) of desalted water.

In the second scheme, a steam power plant is combined with a hybrid MSF and RO desalting system. This scheme produces 212.5 MW and 48 500 m³/d (12.8 × 10⁶ gal/d) from the RO plant and 17 030 m³/day (4.5 × 10⁶ gal/d) from the MSF plant [5].

3. SELECTION OF THE NUCLEAR DESALINATION SYSTEM

The installed power capacity in Saudi Arabia has increased from 418 MW in 1970 to 21 901 MW in 1994, representing an average annual growth rate of 19.2% [6]. The electric energy sold has increased from 1.7 × 10⁹ kW-h in 1970 to 82.2 × 10⁹ kW-h in 1994, with an average annual growth rate of 19.1% [6]. The energy demand in the year 2000 is estimated to be 227.3 × 10⁹ kW-h [7]. Nuclear power generation in Saudi Arabia is considered a favourable option to meet the fast growing energy demands in the country [7]. Adoption of nuclear reactors for producing power to satisfy the energy demands and to provide a useable source of energy in the desalination plants would be a fruitful option.

Nuclear reactors are used mainly for producing heat or power. In nuclear heating reactors (NHRs), heat can be extracted at various temperature levels in the form of hot gas or steam. The low pressure and temperature steam may be used to supply the necessary energy for MSF, or any other distillation units. Electricity can be generated from the nuclear power reactor (NPR) for the high pressure pumps of the RO desalination plants. Developing the most appropriate plant configuration for the nuclear reactor (NHR or NPR) and the desalination process (distillation or membrane) is indeed the most crucial factor that will determine the feasibility of nuclear desalination.

The choice of a suitable nuclear reactor and desalination process depends on several factors. In the event of coupling between the NHR and the distillation process, it will be necessary for the two plants to be on the same site in order to cut down the cost of transporting heat over long distances and to avoid unnecessary
losses. For coupling NPR and RO, no special arrangements are required other than an electrical connection between the two plants.

In Aktau, Kazakhstan, the BN-350 liquid metal cooled fast breeder reactor (LMFBR) is coupled to a multi-effect distillation (MED) facility. This plant produces 120 000 m$^3$/d (31.7 x 10$^6$ gal/d) of desalted water and 150 MW of electricity. Steam from the BN-350 unit (4.5 MPa and 723 K) is directed to the backpressure turbines (P-50-45) and to the condensing turbine (K-100-45). Steam from the fossil fuel boiler (9.0 MPa and 808 K) enters the turbine (PT-60-90/13). Steam from the turbines (P-50-45 and PT-60-90/13) is directed towards the desalination unit via a double pipe system [8].

Coupling MSF and RO to the nuclear steam supply system (NSSS) will yield some economic and technical advantages. A comparison between NSSS–MSF and NSSS–RO desalination plants is given in Table IV [9]. In Kalpakkam on the east coast of India, a hybrid RO–MSF nuclear desalination plant is being considered [10]. This will include an MSF plant producing 3800 m$^3$/d (1 x 10$^6$ gal/d) and RO units producing 1500 m$^3$/d (0.4 x 10$^6$ gal/d). The desalination facilities will be coupled to a 2 x 170 MW(e) nuclear power station. An MSF plant requires about 21 t/h of steam at around 3.5 bar and 400 kg/h of steam for the ejectors at 7 bar. Steam will be tapped at 3.5 bar from a suitable point in the turbine for heating the brine in the MSF plant.

Hussein [11] conducted a computer code study based on Saaty’s mathematical pairwise comparison technique to find the most suitable reactor for water desalination and power generation in Saudi Arabia. He found that the Canadian deuterium uranium heavy water reactor (CANDU HWR) is the most suitable type of reactor for desalination and power generation. Producing heavy water in Saudi Arabia is TABLE IV. COMPARISON BETWEEN NSSS–MSF AND NSSS–RO DESALINATION PLANTS [9]

<table>
<thead>
<tr>
<th>Item</th>
<th>NSSS–MSF</th>
<th>NSSS–RO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Availability</td>
<td>0.9</td>
<td>0.89</td>
</tr>
<tr>
<td>Product salinity (kg/m$^3$)</td>
<td>0–1</td>
<td>0.5–1.5</td>
</tr>
<tr>
<td>Capital cost</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Operation interface</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Energy consumption</td>
<td>Steam and power</td>
<td>Power only</td>
</tr>
<tr>
<td>Safety consideration</td>
<td>Radiation contamination</td>
<td>Nuclear plant only</td>
</tr>
<tr>
<td>Load regulation</td>
<td>Flexible</td>
<td>No load regulation</td>
</tr>
<tr>
<td>Coupling</td>
<td>Requires extensive care</td>
<td>Direct coupling</td>
</tr>
<tr>
<td>Thermal pollution</td>
<td>High</td>
<td>Medium</td>
</tr>
<tr>
<td>Workforce</td>
<td>Highly qualified</td>
<td>Qualified in nuclear</td>
</tr>
<tr>
<td>Plant site</td>
<td>On the same site</td>
<td>RO near to the city</td>
</tr>
<tr>
<td>Transportation cost</td>
<td>Required</td>
<td>Not required</td>
</tr>
</tbody>
</table>
basically simpler than enriching uranium. Commercial heavy water plants have been built that are smaller than would be possible for uranium enrichment plants.

Abulfaraj et al. [12] also concluded that the CANDU PHWR reactor is attractive and appropriate for Saudi Arabia on the basis of a technical and economic comparison of major commercial nuclear power reactor systems. The CANDU PHWR has marginal economic advantages compared with other reactor types, but it has certain important features that make it appropriate for Saudi Arabia. As fuel, it uses natural uranium, which is found in the country and can be relatively easily supplied from the international market. Several developing countries have operated and built CANDU PHWRs indigenously [12].

The CANDU HWR was developed by the Atomic Energy of Canada Ltd. Natural uranium dioxide is used in the reactor vessel, with pressurized heavy water as the coolant and cool heavy water as the moderator. The CANDU PHWR is well established, with 32 units operating or under construction around the world and more than 300 reactor-years of operation [13]. There are three versions of CANDU reactors: CANDU 3, with a gross output of 500 MW(e); CANDU 6, with 700 MW(e); and CANDU 9, with 1000 MW(e). CANDU 80 is the latest CANDU design, with an output range of 300 MW(th) and 100 MW(e). It is ideally suited to applications utilizing electricity and co-generation, such as desalination.

The electric and thermal power produced from CANDU 80 may be utilized for desalination plants of the RO, MSF or MED type. This makes such an option more favourable for Saudi Arabia in order to meet the increasing power and water demands. Nuclear dual purpose plants for power and desalination using a PWR have been examined by Drude and Rohl [14]. The possible coupling schemes of heat and power are the pure backpressure cycle, the extraction scheme, and the combination of backpressure and the condensing turbine cycle.

4. CONCLUSIONS

The long experience gained by Saudi Arabia in the desalination field, together with the exceptionally large desalting capacities, has enabled the country to introduce nuclear powered desalination systems. Use of nuclear desalination is practically essential in Saudi Arabia, where massive quantities of desalinated water exist.

There is no technical impediment to the use of nuclear reactors for the supply of either heat or electricity, or both, to a desalination plant. However, the cost effectiveness of nuclear desalination is a site dependent matter. The type of desalination process and the size and type of the nuclear reactor have to be determined on the basis of the specific site data. However, the CANDU PHWR is the appropriate type of nuclear reactor for Saudi Arabia. A hybrid RO–MSF CANDU PHWR is the candidate system for applying dual purpose nuclear desalination plants in the country.
REFERENCES


THE SEA WATER DESALINATION NEEDS OF TUNISIA AFTER THE YEAR 2010

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Centre national des sciences et technologies nucléaires,
Tunis, Tunisia

Abstract
THE SEA WATER DESALINATION NEEDS OF TUNISIA AFTER THE YEAR 2010.
The supply of drinking water for north and central Tunisia is guaranteed from surface water resources in the north and other subsurface resources. These resources will satisfy the water demand in this region until the year 2010. In the south of Tunisia, the water supply comes from local subsurface resources, including the lake water of the chotts. Maximum exploitation of these lakes, whose average salinity exceeds 2 g/L, has already been reached. Therefore, non-conventional resources such as desalination have become unavoidable if the water quality is to be improved and the resources are to be maximized. The needs of this region will reach 60 000 m³/d by the year 2010. This deficit can only be met by the desalination of sea water. At present, about 45 000 m³/d of water is desalinated using the reverse osmosis process and electric energy.

1. WATER RESOURCES

Rainfall in Tunisia varies between 200 and 1000 mm. The potential water resources amount to $4.4 \times 10^9$ m³, of which 60% are surface waters. Of these resources, 68% have already been tapped. It is expected that by the year 2010 all these water resources will have been exploited. Only 50% of these resources have a salinity of less than 1.5 g/L, while 30% have more than 4 g/L. It is worth noting that in 1994, $110 \times 10^6$ m³ of waste water were treated, of which only 23% were used for irrigation.

2. WATER DEMAND

The water demand in 1994 reached $2.2 \times 10^9$ m³, 80% of which were used for irrigation and the rest as potable water. For the latter, the average domestic consumption is less than 100 L/d, whereas the average tourist consumption is 550 L/d. The increase in potable water was about 4% during the period 1992–1996. Water consumption as a function of use (Fig. 1) is as follows: 67% for domestic
consumption; 15% for collective consumption (administration, commerce, etc.); 12% for industrial consumption; and 6% for tourist consumption.

3. DEMAND–RESOURCE BALANCE IN THE SOUTH OF TUNISIA

3.1. Introduction

Potable water in north and central Tunisia is supplied from surface waters in the north and from groundwater resources. These resources will meet the demand until the year 2010. In the south of the country, notably in the regions of Gabès, Medenine and Tataouine, water is supplied from local groundwater resources, e.g. from Chott El Fejij, Gabès south, Zeuss–Koutine and El Ababsa. These water resources, with an average salinity of more than 2 g/L, have already reached their maximum exploitable capacity. Therefore, non-conventional resources such as desalination have become unavoidable if the water quality is to be improved and the resources are to be maximized.

3.2. Water demand

The south of Tunisia is defined as the counties of Medenine and Tataouine, and the regions of greater Gabès and Mareth. In 1995, these areas had 700 000 inhabitants; this is expected to reach 1 050 000 in the year 2010. Details of the water demand (1990–2010) are given in Table I.
TABLE I. WATER DEMAND

<table>
<thead>
<tr>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Population (10^3)</td>
<td>603.5</td>
<td>694.1</td>
<td>797.6</td>
<td>914.3</td>
<td>1048.1</td>
</tr>
<tr>
<td>Specific consumption (L/d)</td>
<td>67</td>
<td>70</td>
<td>73</td>
<td>76</td>
<td>79</td>
</tr>
<tr>
<td>Total consumption (m^3/d)</td>
<td>40.435</td>
<td>48.588</td>
<td>58.226</td>
<td>69.487</td>
<td>82.802</td>
</tr>
<tr>
<td>Distribution losses (%)</td>
<td>28.0</td>
<td>27.2</td>
<td>26.3</td>
<td>25.4</td>
<td>24.6</td>
</tr>
<tr>
<td>Requirements (with losses) (m^3/d)</td>
<td>56.159</td>
<td>66.741</td>
<td>79.004</td>
<td>93.146</td>
<td>109.817</td>
</tr>
<tr>
<td>Requirements (with losses) (L/s) (peak)</td>
<td>910</td>
<td>1081</td>
<td>1280</td>
<td>1509</td>
<td>1779</td>
</tr>
<tr>
<td>Tourist requirements (L/s) (peak)</td>
<td>241</td>
<td>293</td>
<td>353</td>
<td>421</td>
<td>474</td>
</tr>
<tr>
<td>Total for Gabès (L/s) (peak)</td>
<td>512</td>
<td>598</td>
<td>719</td>
<td>861</td>
<td></td>
</tr>
<tr>
<td>Total for Medenine and Tataouine (L/s) (peak)</td>
<td>862</td>
<td>1035</td>
<td>1211</td>
<td>1392</td>
<td></td>
</tr>
<tr>
<td>Total requirements (L/s) (peak)</td>
<td>1151</td>
<td>1374</td>
<td>1633</td>
<td>1930</td>
<td>2253</td>
</tr>
</tbody>
</table>

3.3. Water resources

3.3.1. Gabès region (Table II)

This region is supplied mainly from the wells at Chott El Fejij, which is located 40 km from Gabès, and also from local water resources in Mnara and Boulbaba. The salinity of these resources, which are estimated to be 850 L/s during daily peaks, is 3.2 and 2.8 g/L for Chott El Fejij and Mnara and Boulbaba, respectively.

A 22 500 m^3/d reverse osmosis desalination station (three lines) has been in service since January 1996, supplying the Gabès region with potable water; the salinity does not exceed 1.5 g/L. The conversion rate for this station is 65%, therefore the total available resources are 710 L/s, of which 450 L/s are waters with 3 g/L of salinity and 260 L/s with 0.5 g/L. In 1998, a fourth line will be put into service, which will increase the station capacity to 30 000 m^3/d. The available resources will be 663 L/s, of which 347 L/s will be desalinated water (Table III).

TABLE II. WATER RESOURCES (L/s) IN THE SOUTH OF TUNISIA

<table>
<thead>
<tr>
<th></th>
<th>1995</th>
<th>1998</th>
<th>1999</th>
<th>2010</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gabès</td>
<td>710</td>
<td>663</td>
<td>663</td>
<td>663</td>
</tr>
<tr>
<td>Medenine</td>
<td>815</td>
<td>815</td>
<td>1093</td>
<td>1093</td>
</tr>
<tr>
<td>Tataouine</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>1525</td>
<td>1478</td>
<td>1756</td>
<td>1756</td>
</tr>
</tbody>
</table>
### TABLE III. DEMAND–RESOURCE BALANCE IN THE SOUTH OF TUNISIA

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Demand (L/s)</td>
<td>512</td>
<td>562</td>
<td>598</td>
<td>861</td>
</tr>
<tr>
<td>Resources (L/s)</td>
<td>710</td>
<td>663</td>
<td>663</td>
<td>663</td>
</tr>
<tr>
<td>Balance (L/s)</td>
<td>+198</td>
<td>+101</td>
<td>+65</td>
<td>-198</td>
</tr>
<tr>
<td>(m³/d)</td>
<td></td>
<td></td>
<td></td>
<td>17 100</td>
</tr>
</tbody>
</table>

### TABLE IV. DEMAND–RESOURCE BALANCE IN THE MEDENINE AND TATAOUINE COUNTIES

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Demand (L/s)</td>
<td>862</td>
<td>962</td>
<td>1035</td>
<td>1392</td>
</tr>
<tr>
<td>Resources (L/s)</td>
<td>815</td>
<td>1093</td>
<td>1093</td>
<td>1093</td>
</tr>
<tr>
<td>Balance (L/s)</td>
<td>+47</td>
<td>+131</td>
<td>+58</td>
<td>-299</td>
</tr>
<tr>
<td>(m³/d)</td>
<td></td>
<td></td>
<td></td>
<td>25 800</td>
</tr>
</tbody>
</table>

#### 3.3.2. Medenine and Tataouine counties

Potable water is transported to this region via a supply system called ‘adduction du sud Tunisien’. This system ensures the transport of groundwater from Zeuss-Koutin, south of Gabès and El Ababsa to various towns in the two counties. Local wells at Ghomrassene, Tataouine and Ben Guerdane also reinforce these resources. The overall capacity is evaluated at 815 L/s during daily peaks (including the wells at El Maouna) (Table IV). The overall salinity of these resources is relatively high, and can reach 2.5 g/L, especially during peak periods.

To increase the resources and to improve the water quality, two reverse osmosis desalination stations, each with a capacity of 12 000 m³/d, are to be constructed in Jerba and Jarzis; startup is scheduled for 1998. They will desalinate brackish water, with 6 g/L drawn from the Miopliocene reserve. Therefore, the water resources of this region will increase to 1093 L/s during peak periods.
PANEL 2
Panel 2

WHY ARE THERE NOT MORE DESALINATION PLANTS USING NUCLEAR ENERGY?

Chairperson: D.H. Furukawa (United States of America)

Members: B.M. Misra (India)
J.D. Birkett (United States of America)
Chang Sun Kang (Republic of Korea)
F.H. Hammad (Global Technology Development Center)
E.D. Muralev (Kazakhstan)

Although many nuclear power generation plants utilize desalination to produce high quality water for use within the plant, few have been specifically built to couple nuclear energy generation and desalination. The two fields are well developed. In 1995, there were 437 nuclear plants generating 17% of the world’s electricity; at the end of 1995, more than 11,000 desalination plants were in operation, producing $20.3 \times 10^6 \text{m}^3/d$. It is well known that desalination processes are energy dependent. Why, then, have not more plants been built to take advantage of the low cost energy production from nuclear plants? The panel explored several possible reasons for the paucity of nuclear desalination plants.

One of the premises put forward was that perhaps not all the elements required to justify such a plant have been recognized: a deficiency in electric power; a shortage of fresh water; the availability of large quantities of saline water; the absence or scarcity of cheap organic fuel; and the availability of competent labour.

The six leading producers of nuclear generated electricity all have a relative abundance of renewable fresh water. Thus, it appears that there was not an overpowering need to build a combined plant in these areas, although one included a semi-arid zone that needed development and now houses a nuclear desalination plant.

It was proposed that perhaps the lack of coupled plants is caused by modern educational compartmentalism. There is an alarming trend towards specialization. It is essential that not only the harmony of professionalism and humanism is achieved, but also the balance between specialists and generalists for systematic management in each stage of the planning, organization, implementation and measure of the project. Modern educational systems should be able to cope with this situation and rigid compartmentalism should be prevented.
It has long been contended that technical factors such as coupling and transient behaviour have been at fault. Indeed, these aspects are important and have been extensively studied. There is no difficulty in ensuring the steady operation of desalination plants between 70 and 105% of their full rated capacity with slow changes in load. However, it is difficult to ensure steady desalination plant operation with a sudden, large reduction in the steam flow rate; these plants have a limited degree of flexibility.

In very arid areas where the water needs are high, large urban demands for electricity in the summer (primarily air-conditioning) are followed by much lower demands in the winter. The turn down ability required of power plants is not easily achieved with nuclear energy. Design precautions have been developed to avoid the possibility of contamination in the heat recipient system.

Throughout the Symposium and during the panel discussion, the question of public acceptance of nuclear desalination was raised. This is a critical issue and has no doubt contributed to the lack of such plants today; it will also heavily influence future implementation. Although most of the participants at this Symposium believe that safety and public health can be dealt with more adequately through technical design, operation and regulatory means, the rest of the world may be segmented into three groups: group A, which fervently opposes anything of a nuclear nature; group B, which has no set point of view, but might be slightly critical of anything new; and group C, which feels comfortable with nuclear facilities as they exist today and, presumably, would feel similarly inclined towards nuclear desalination.

By and large, group A will never be convinced of nuclear safety, no matter what arguments are presented and demonstrated. They will continue to proselytize groups B and C with their views. Group B will be vulnerable to persuasion by group A, unless presented with strong counterarguments. Group C, those currently disposed towards nuclear, could be lost to groups B or A if they become disillusioned with the experts.

Thus, those interested in promoting nuclear desalination must: (1) contain group A; however, we, as individuals, must be wary of direct public debate, as this plays into the strengths of activists and away from the skills of technologists; and (2) solidify the positions of groups B and C through appropriate education and public relations and, especially, continued safe operation of existing nuclear facilities.

A very conservative approach must be taken in the design and cost estimation of new plants. Successful operation may go unnoticed, but any shortcomings will be publicized and never forgotten. The whole idea of coupling desalination to nuclear energy may appear to group A as one more opportunity to put the public at risk.

To say that 'perception is reality' is to say that we must be guided by delusions. However, it is true that perception may be as important as reality, or even more important. The only answer is through education.
HIGHLIGHTS
HIGHLIGHTS
OF THE SYMPOSIUM

1. INTRODUCTION

Potable water is a basic requirement of human life and for the development of civilization. For coastal areas with an insufficient supply of natural fresh water, sea water desalination offers a realistic alternative for the supply of additional potable water resources. There is an increasing level of interest among Member States of the IAEA in the use of nuclear power as an energy source for sea water desalination. Interest in this subject has led to a number of meetings, extensive technical and economic evaluations, and several publications on this particular application of nuclear technology.

To focus attention on the current status and future opportunities for nuclear desalination, the IAEA sponsored a Symposium on Desalination of Seawater with Nuclear Energy, which was organized in co-operation with the Korea Atomic Energy Research Institute (KAERI), the Global Technology Development Center (GTDC) and the International Desalination Association (IDA), and held in Taejon, Republic of Korea, from 26 to 30 May 1997.

The purpose of the Symposium was to provide an international forum for the exchange of information and ideas regarding all aspects of the desalination of sea water using nuclear power as the energy source. This included technical sessions, which addressed the current status of national programmes and activities, operating experience, technical aspects and future opportunities, as well as two panel discussions, which covered various societal and institutional issues that have an impact on the implementation of nuclear desalination.

A brief summary is given of the highlights of the Symposium. It is not intended that the papers presented by the many experts from around the world who participated in the Symposium are summarized. Rather, it is hoped that these highlights will serve to provide an overall perspective on the Symposium and its role in stimulating further interest in the commercial deployment of nuclear desalination. The highlights are presented in the order in which the sessions and panel discussions took place.

2. OPENING SESSION

The Symposium was opened by Seung Yun Kim, President of KAERI, Hans Blix, Director General of the IAEA, and Sook Il Kwun, Minister of Science and Technology, Government of the Republic of Korea, Republic of Korea.
In their remarks, the importance of electric and non-electric applications of nuclear technology was stressed, both in the Republic of Korea and globally. It was noted that nuclear power is now a mature technology, but much of the focus in the past has been on its use for the generation of electricity. It is now time to focus on new and advanced applications of the technology. The expanding demand for sea water desalination presents a potential market for the introduction and commercial deployment of nuclear desalination. The belief was expressed that in the future nuclear desalination will be a major source of potable water, and an effective solution to the acute problem of potable water shortages in many parts of the world.

The public attitude to nuclear energy was identified as an issue, but growing global concern over the environmental consequences of burning fossil fuels was said to be a factor that should speak firmly for expanded future use of nuclear power. As the public’s concern over global warming grows, the urge to find realistic substitutes will increase, with nuclear energy as the strongest candidate. The public demands a higher level of safety for nuclear power than for other energy sources. This is being met through vehicles such as the IAEA Convention on Nuclear Safety. It was noted that a global nuclear safety culture is developing, and that nuclear desalination can be an important step towards expanding the peaceful (and socially acceptable) uses of nuclear power throughout the world.

Finally, the speakers extended their best wishes for a successful Symposium, expressed their gratitude to the participants, and noted that the Symposium should be useful in showing that nuclear energy can play a very important role in the production of potable water through desalination.

3. SESSION 1: OVERVIEWS

This set the stage for the sessions to follow by providing overviews of the international organizations involved in dealing with various aspects of the growing concern over the ever increasing problem of limited fresh water resources. Representatives from the World Health Organization (WHO), the IDA, the IAEA and the European Commission presented papers.

The lack of adequate and safe water supplies was said to be a socioeconomic issue of the first order. About one-fourth of humanity is currently living in a low income, high water stress situation. It is estimated that by the year 2025 as much as two-thirds of the world's population may be living in moderate to high water stress situations. With increasing water stress and scarcity, drastic changes must be introduced. Improved strategies have to make use of rigorously enforced demand management, better water resource management, waste water reuse and, finally, desalination of sea water and brackish groundwaters.
It was noted that it is now technically and economically practical to generate large volumes of water of suitable purity through the desalination of sea water. Desalination is already in use in 120 countries around the world, and by the end of 1995 over 11,000 desalination units, with a capacity in excess of 20 million m$^3$/d of desalinated water, had been either installed or contracted. About half of this capacity is based on the multi-stage flash (MSF) principle and about one-third on reverse osmosis (RO), with the remaining one-sixth being multi-effect distillation (MED) and vapour compression (VC). Use of RO is increasing, with MED and VC also expected to play an important role in the future. One of the more promising concepts is the hybrid, which combines power-distillation and membrane technologies, because it offers the potential for taking advantage of the best features of each technology. One of the impacts of the advances being made in desalination technology is a reduction in the water production costs. As a general rule, large scale desalination plants will have to produce water at a cost that does not exceed US $1/m$^3$ in order to remain competitive.

The Middle East countries, particularly the Gulf States, are the largest users of desalination, with nearly 50% of the installed capacity located in this area. In Europe, Spain is the largest producer of desalinated water, followed closely by Italy and Germany. The relative proportion of membrane technologies and VC is much larger in Europe than in the Middle East, while in Japan almost all desalination is done using membrane technologies.

Operational experience with the various technologies has shown that good feedwater intake design and adequate feedwater pretreatment are critical to successful operation. Long term success and high availability are also greatly dependent on plant operation and operating personnel. Institutional issues have an impact, since various institutions and governmental bodies may be involved in sea water desalination and/or energy supply. In some cases, good co-operation and understanding among the various bodies has led to satisfactory results, whereas in other cases the degree of co-operation needs improvement.

In response to the increasing interest being shown by its Member States, the IAEA has been evaluating the application of nuclear power as an energy source for sea water desalination. Technical and economic feasibility have been studied, as well as coupling of desalination processes to nuclear reactors. Studies by the IAEA and its Member States have led to the conclusion that small and medium sized reactors are suitable for nuclear desalination. Methodologies have been developed to enable site specific technical optimization and economic evaluation. A 2 year Options Identification Programme was carried out that led to the identification of three practical options for the near term demonstration of nuclear desalination. The infrastructure requirements for nuclear desalination are recognized as being similar to those for nuclear power. A demonstration project could be a very effective and practical framework within which a nuclear infrastructure could be developed. The work done within
this framework has shown what can be achieved through co-operative approaches. To further facilitate the sharing of knowledge and experience, the IAEA is establishing an International Nuclear Desalination Advisory Group with the participation of interested Member States that are operating, developing, designing or showing interest in the deployment of nuclear desalination plants.

In summary, the importance of desalination as a solution to the increasing problem of global water scarcities was recognized and acknowledged, and the application of nuclear energy to sea water desalination was seen to be a realistic option. The challenge ahead is to demonstrate its use by proceeding with effective development and practical application.

4. SESSION 2: NATIONAL PROGRAMMES AND ACTIVITIES

Descriptions were given of the national programmes and/or activities in several IAEA Member States with an interest in nuclear desalination. Representatives from China, India, the Republic of Korea and the Russian Federation presented papers from the perspective of countries involved in the development of nuclear desalination technology. Representatives from Algeria, Egypt, Indonesia and Morocco presented papers from the point of view of countries interested in nuclear desalination as a solution to their own potable water supply problems.

In the papers presented by those countries involved in the development of nuclear desalination it was made clear that all are experiencing, or expect to experience within the next few decades, serious water shortages in at least some regions of their country. Hence, in most cases domestic needs are the primary motivation for the development programmes, although potential export of the technology and its application in other countries are also considerations. The following programmes were described:

(1) China is proceeding with the development of a nuclear desalination capability based on their HR-200 heating reactor and MED desalination technology. A small scale pilot facility using a 5 MW(th) reactor, with a desalination capacity of $3500 \text{ m}^3/\text{d}$, has been proposed. A full scale demonstration project based on the 200 MW(th) HR-200, with a capacity of $150 000 \text{ m}^3/\text{d}$, is in the prefeasibility study stage. As noted in later discussions, China has also entered into a bilateral co-operative agreement with Morocco for the prefeasibility study of a demonstration project in Morocco based on a 10 MW(th) heating reactor.

(2) India has been involved in desalination research for 15–20 years. Over the past few years, a number of pilot plants have been operated at the Bhabha Atomic Research Centre. Using the operational experience gained from these plants, a
6300 m$^3$/d hybrid MSF–RO desalination demonstration plant is being designed for coupling to an operating PHWR. The hybrid design is being pursued, since it is considered to be economic to build and operate under the conditions that exist in the country.

(3) The Republic of Korea has announced a nuclear desalination R&D programme based on MSF desalination technology. This programme focuses on the design of a new 100 MW(e) integral reactor with enhanced safety features. KAERI is responsible for programme management and reactor design/development. The intent is to have the basic design completed by the year 2001, with construction of a demonstration facility by about the year 2006 for the co-generation of water and electricity.

(4) The Russian Federation has been involved in activities related to nuclear desalination since the early 1960s, when an energy and desalination complex was constructed to supply heat, power and water to the mining industry and municipal consumers in the City of Shevchenko (now Aktau, Kazakhstan). All small and medium sized reactors currently under development in the Russian Federation have been evaluated as potential energy sources for nuclear desalination. A priority of the current programme is the development of a small floating nuclear desalination complex based on the KLT-40 reactor design. A bilateral co-operative agreement has been put in place to couple the Russian reactor with Canadian RO desalination technology for a barge mounted floating system.

The remaining papers in this session were presented primarily from the perspective of potential users of nuclear desalination technology. Nevertheless, each of these countries has an active or developing nuclear programme, and a long term interest in the eventual operation of nuclear power plants and/or nuclear facilities for the co-generation of power and water. The following requirements for nuclear desalination were described:

(a) It was stated that the sea water desalination potential in Algeria (a production capacity that cannot be met economically through dams, aquifers, springs and other conventional resources) is of the order of 600 000 m$^3$/d. For this reason, sea water desalination is being seriously considered by decision makers. Oran, the second largest town in Algeria, is likely to be the first location where the domestic water requirements will be supplied primarily by desalination, and a planning project is under way for a 150 000 m$^3$/d plant. The Oran project is based on MSF desalination technology. This process was chosen because of some adverse experience with RO in Algeria at the time the project was initiated (1994), and because of the opportunity it offers for local participation and manufacturing.

(b) Desalination plants have been in use in Egypt for the past 25 years. Current studies aimed at estimating the future water supply and demand, based on the present
trend of desalination having a 10% share of the water supply, indicate that by the year 2017 there will be approximately 350 000 m$^3$/d of desalinated water available. However, the continuing decline in per capita availability of water resources leads to the projection that the desalinated water requirements could be as high as 1.9 million m$^3$/d by that time. This level of demand is large enough to support desalination facilities with production capacities in excess of 100 000 m$^3$/d. A recent study carried out by North African countries indicated that in this size range desalination facilities coupled to nuclear reactors could be competitive with fossil fired plants.

(c) As much as one-third of Indonesia is located in a low wetness level zone and experiences serious water shortages in the dry season. In addition, use of deep water wells has resulted in sea water intrusion into the water supplies. Owing to industrial and population growth, the need for additional potable water supplies is increasing. The electrical requirements are also increasing, with a demand of about 28.8 GW projected for the year 2005. To meet these needs, use of dual purpose nuclear plants producing both electricity and energy for sea water desalination is seen as a good option. Economic studies published by the IAEA indicate that the cost of water produced by nuclear desalination can be competitive with that supplied by the local water authority, PDAM JAYA.

(d) The available water resources in Morocco are declining as a result of severe drought cycles, and natural supplies are not well distributed (either throughout the year or with respect to the population). Recognizing the potential for serious shortages, Morocco is planning to carry out a study on the Tan–Tan site, which could produce 8000 m$^3$/d of desalinated water by the year 2000. Within the framework of co-operative agreements between Morocco and China, and with the assistance of the IAEA, a prefeasibility study has been launched to evaluate a MED desalination plant coupled to a 10 MW(th) heating reactor. The expected duration of the study is 18 months.

5. PANEL 1: THE CHALLENGES OF INTERNATIONAL CO-OPERATION

The first panel of the Symposium was convened to address the challenges and opportunities afforded by international co-operation. A distinguished panel of experts from agencies and organizations, whose role it is to promote international co-operation, shared their views and experience. Representatives from the IAEA, the IDA, the Middle East Desalination Research Center, the Arab Atomic Energy Agency, the United Nations Industrial and Development Organization (UNIDO) and the Republic of Korea served on the panel.

One of the major themes expressed by the panellists, and echoed by the participants in the ensuing discussion, was that international co-operation can optimize the use of resources. In return, the benefits are shared by all. Pooling of resources
encompasses both personnel and funds. However, the issue that must be addressed is how best this can be effectively and efficiently achieved, and with the necessary speed.

International co-operation can take place at many levels, including at the task, programme and project levels. The necessary agreements required to implement such co-operation may include bilateral and multilateral agreements among governments, and between governmental and non-governmental organizations (NGOs).

United Nations organizations can provide an umbrella for international co-operation. With its responsibility for the application of nuclear energy, the IAEA plays a leading role in nuclear desalination. Nevertheless, other UN organizations, such as UNIDO, can assist countries to enhance their level of industrial development.

NGOs can also play a significant role in creating opportunities for international co-operation, and in promoting co-operation and R&D, technology transfer, information exchange and technical training. They provide a mechanism for overcoming some of the barriers to effective international co-operation, since they can often make decisions more quickly and, in some cases, may offer the opportunity for creative, non-traditional approaches that cannot be achieved in somewhat more traditional governmental institutions.

Regional co-operation among neighbouring countries is another important mechanism for pooling resources and sharing experience. Co-operation between regional and international organizations can assist in establishing effective and efficient international co-operation. In particular, interaction between regional users and international suppliers can be beneficial.

Finally, it was noted that the question of public acceptance is an important consideration in international co-operation. Gaining public acceptance is one of our most important tasks, and to do so we must understand public attitudes and the social impact of our projects. International co-operation can promote the sharing of experience and the establishment of effective information that leads to better communications with the public and the media, drawing on techniques that have proved effective elsewhere.

The session closed with lively discussion from the floor. Suggestions for areas of future co-operation included developing tools to improve comparison of options and decision making on projects; increasing the level of South–South co-operation; improving educational activities to enhance the level of public acceptance; sharing databases and other technical information; developing safety regulations; and improving the workforce.

There is a strong belief in and support for nuclear desalination. Demonstration and implementation of nuclear desalination projects face many real challenges. International and regional co-operation provide a means of sharing information and
resources such that these obstacles can be overcome and the dream of nuclear desalination realized.

6. SESSION 3: TECHNICAL ASPECTS

Having established an overall perspective through the overviews and discussion of the national programmes and activities, the focus of the Symposium was shifted towards addressing more specific technical issues related to nuclear desalination. Owing to the large number of contributions, the session was divided into two parts.

6.1. Part 1

Eight papers covered the specific technical aspects of desalination plants, the nuclear power plants that are being considered for their energy supply, and the coupling of these two technologies to an integrated nuclear desalination facility. Representatives from the IAEA, the United States of America, the Russian Federation, the Republic of Korea, Argentina and Egypt presented papers.

The IAEA, in co-operation with and in support of its Member States, has carried out many evaluations of the technical and economic feasibility of nuclear desalination. These have included most recently an Options Identification Programme, whose main objective was to identify suitable practical options for demonstrating nuclear desalination that could facilitate commercial deployment of the technology. The options identified included RO and MED technologies coupled to medium and small water reactors, respectively, as their source of energy.

The nuclear safety and regulatory aspects pertinent to nuclear desalination were also discussed. Nuclear power plants used for desalination are similar to those used for energy generation or district heating, and present essentially the same challenges to safety, with due consideration given to the additional aspect of coupling to a desalination plant. One of the primary challenges is that very often countries needing water have only a limited infrastructure in place to deal with nuclear technology. Upgrading national infrastructures, developing competent staff, strengthening the regulatory regime and establishing a positive safety culture will all be essential requirements for ensuring safety.

One of the interesting questions related to the economics of nuclear desalination is how to allocate the relative costs of water and electric energy production. An exergetic technique was described that allocates costs to each product on the basis of the thermodynamic value of the relative energy flows required to produce the product. This was described as an appropriate cost allocation methodology, since it...
allocates the economic benefit obtained by integrating the two single purpose facilities into one integrated plant in an equitable way.

The principal desalination technologies considered for nuclear desalination are based on concepts that generally appear simple and straightforward in their application. In practice, however, the choice of technology, the plant design and the reliability of operation are often affected by factors that might at first glance seem trivial. These include the challenge of removing as much as 50 kg of solids from each cubic metre of water processed, of dealing with undesirable minor constituents such as inorganics and non-condensable gases, and of maintaining the reliability of power supply to the desalination plant. These issues can be successfully addressed, but they must be considered in the early design and planning stages.

Three reactor designs under development for desalination application were described. One, the Russian Federation's RUTA-TE, is a 70 MW(th) swimming pool reactor. The other two, Argentina's Carem 25 project and the Republic of Korea's 330 MW(th) SMART, are advanced integral PWRs. The design features, particularly those unique to the specific design, were described. For each design, special attention was given to the incorporation of design features intended to provide enhanced levels of safety and operational reliability. This focus on enhanced safety reflects current standards in reactor design, the need for improved levels of public acceptance and, in many cases, the requirement for siting near populated centres or in developing countries where a sophisticated nuclear safety infrastructure is not currently available. In all three cases, the designs are being developed with the capability of co-producing water and electricity. These small reactor designs are considered to be particularly well suited to remote locations, and to the solution of water supply problems in locations where large water and electricity production capacities are not required. It was noted that use of these reactors for desalination represents a particularly important non-electric application of nuclear technology.

In addition to the more traditional methods of energy transfer between the reactor and the desalination unit often described in discussions of coupling, an interesting approach to energy transfer using heat pipes was proposed. Heat pipes are considered to be more efficient and easier to maintain, and to offer better fault detection than conventional heat exchangers. They also have the advantage of providing a double separation boundary for enhanced safety. Studies are under way in Egypt to evaluate the use of heat pipes in coupling a 500 kW gas turbine to a 200 m³/d MED-TVC desalination unit.

6.2. Part 2

Eight papers covered a wide variety of topics related to the technical aspects of desalination and ranged from broad discussion of several nuclear desalination projects under consideration to a more detailed description of specific desalination
processes. Representatives of the Russian Federation, China, Indonesia, Algeria, India, Kuwait, Japan and the Ukraine presented papers.

Three nuclear desalination projects were described, illustrating various applications and a variety of choices for both the nuclear and desalination technologies chosen. The projects are each in the early stages of development and preliminary design. A floating nuclear desalination facility is being developed in the Russian Federation. Two concepts are being evaluated. In one, a single floating barge contains two KLT-40 PWRs coupled to a MED desalination unit; in the other, a power barge containing the two reactors is coupled to a desalination barge containing a Canadian designed RO desalination system. In China, a land based system is being developed using an NHR-200 nuclear heating reactor coupled to a MED desalination plant. Two different interface designs are being considered that allow water production only, and combined water and electricity production. In Indonesia, nuclear desalination is being developed to supply water to meet the needs of the Natuna project petrochemical complex. For this project, a high temperature gas cooled reactor is being evaluated, with the intention of coupling it to a hybrid MED-RO desalination system.

As noted earlier in the Symposium, MSF and RO are at present the two most commonly used desalination processes. In Algeria, a comparative study has been carried out to evaluate the relative merits of these two technologies, given a consistent set of design parameters. The study was based on two 60 000 m$^3$/d desalination plants, and resulted in a set of comparison criteria that could be used as a basis for making decisions regarding appropriate selection of desalination technology to satisfy a given set of site specific design and performance requirements.

A number of less commonly used desalination technologies are also being evaluated for nuclear desalination projects. In general, the motivation for studying such technologies is improved performance and operating characteristics, as well as increased efficiency and better economics. In India, a study of low temperature vacuum evaporation has been carried out, and details of a pilot plant demonstration based on this technology are being developed. In Kuwait, thermal vapour compression (TVC) is being considered as an attractive alternative. A mathematical model has been developed to analyse the TVC process and to allow comparisons of its characteristics with more traditional technologies.

In Japan, RO desalination plants have been in use at two nuclear power plants to provide boiler feedwater. The performance specifications were described, and it was noted that excellent operating experience has been shown over the past 4–5 years, with performance improvements resulting in reduced membrane replacements as operation progressed. The Ukraine has 14 nuclear power units in operation, with considerable scientific and design bases in desalination. They have not yet, however, made use of desalination in conjunction with nuclear plants. It is hoped that input from this Symposium will help stimulate the development of nuclear desalination in this country.
Seven papers described operating experience with a variety of desalination facilities using various desalination technologies and energy sources. Representatives from Kazakhstan, Japan, Israel, Morocco and the IDA presented papers.

As expected, most of the world's experience with the operation of sea water desalination plants has been with those using conventional fossil energy sources. Nevertheless, some limited experience has been accumulated on the use of nuclear power plants for desalination. The first nuclear desalination took place as early as the 1960s in what is now the town of Aktau, Kazakhstan. An energy complex consisting of a BN-350 sodium cooled reactor operating in parallel with several fossil fired boilers provides steam to ten MED desalination units with a total installed capacity of 120 000 m$^3$/d. The operating experience gained at Aktau has been good, and has shown that reactor and fossil units can be operated in a combined facility with very high reliability. Furthermore, the radiological characteristics of the product water from the nuclear desalination unit are no different to those of the fossil units.

Other experience accumulated on desalination in conjunction with the operation of nuclear facilities was reported by Japan. Several of the nuclear power plants in this country are equipped with sea water desalination facilities in order to secure fresh water as boiler feedwater and for domestic needs. Initially, MSF was the desalination process used, but more recently MED and RO have been applied to desalination because of their higher efficiency; capacities range from 1000 to 2600 m$^3$/d. RO units were put in service at new construction sites using electricity from adjacent nuclear plants to provide site water during construction. No serious operating anomalies have been experienced at any of these sea water desalination facilities, and there has been no leakage of radioactive materials into the product water.

A demonstration plant was operated in Ashdod, Israel, to demonstrate the feasibility of coupling a large MED unit to a nuclear power plant. The last two turbine blade stages were removed in an existing 50 MW fossil plant to simulate the backpressure conditions in a nuclear power plant. Successful operation of the plant yielded meaningful and encouraging results.

The remaining operating experience described during this session was with desalination units drawing their energy supply from conventional sources. The Laayoune plant in Morocco, designed for 7000 m$^3$/d using RO, has operated successfully since its commissioning in 1995. The plant production capacity continues to exceed design values, and the product water purity remains far below the design specifications. RO systems have also been operated at the Diablo Canyon nuclear power plant to supply system make-up water and at the Bayswater/Liddell cooling water treatment facility to remove dissolved salts from the cooling water return. These systems have operated successfully for more than 10 years.
primary lessons learned in the operation of these facilities is that successful operation is a direct result of good design, particularly with respect to the feedwater pretreatment system. By far the largest pool of operating experience comes from plants operated by the Saline Water Conversion Corporation (SWCC) in Saudi Arabia. SWCC operates more than 25 plants in 13 locations, generating about 2.8 million m$^3$/d of potable water. MSF and RO are the primary technologies currently in use, although MED is becoming a strong candidate in this region. Continuing technological development as operating experience grows is leading to advances in RO, with longer membrane lives and higher recoveries, as well as in MED and MSF, where the advances are generally in the area of operating efficiencies and higher gain output ratios.

With favourable operating characteristics exhibited by all the desalination technologies, one of the most important questions to be addressed is how a decision can be made on the appropriate technology for application in any given project. The criteria for selection can include diverse elements such as water demand, power demand, base load versus peak load, annual demand cycle, fuel cost and type, train size, sea water feed characteristics and product water specifications. The power to water ratio was introduced as a design characteristic that could be useful in making such decisions. This ratio gives an indication of the power plant size that is needed to be able to supply sufficient energy to operate the desalination plant under consideration. It should be noted that, since not all the energy produced by a plant can be used for water production, this is not a measure of energy consumption but rather a measure of power plant size. The relevance of this parameter in making a decision depends on the relative values of the two commodities, and on their relative importance.

8. SESSION 5: OPPORTUNITIES FOR DESALINATION SYSTEMS USING NUCLEAR ENERGY

Having reviewed the current status of nuclear desalination from both the programmatic and the technological perspective, the focus of the Symposium shifted towards examining the transition from ‘an interesting subject for study’ to commercial deployment of the technology. Seven papers covered a broad range of topics related to the future of nuclear desalination. Representatives from the GTDC, the USA, the IAEA, Egypt, Canada, Saudi Arabia and Tunisia presented papers.

The introduction and development of a sustainable nuclear desalination project requires a well developed nuclear programme with an infrastructure capable of supporting the safe, reliable and economic production of potable water using nuclear energy. In many of the countries where water shortages are most severe, the introduction of nuclear desalination requires the application of nuclear technology. Considerable technology transfer and technical co-operation are required on an
international and a bilateral basis to achieve this goal. Factors that tend to promote effective technology transfer include a national policy of self-reliance; establishment of appropriate ‘cultures’ (safety culture as well as others); proper infrastructures; suitable education and training; strong R&D programmes; and effective partnership projects. Achievement of this level of technology transfer is a challenging task that requires a strong national will and the determination to maximize local participation so that the national capability to manage a nuclear desalination programme is enhanced. The Republic of Korea was pointed out as a significant example of a highly successful technology transfer programme.

An assessment was made of the market opportunities for commercial deployment of nuclear desalination. The methodology used for the assessment included analysis of those countries that may have an interest in the technology and a review of the required unit sizes, of the types of desalination process used and of currently installed capacities in excess of 10 000 m$^3$/d. The historical growth rate of installed capacities combined with known orders for a new capacity and the judgement of experts in the field served as the basis for projecting the required capacities to the years 2005, 2010 and 2015. As a result of this assessment it was concluded that there is indeed a potential market for nuclear desalination. The annual average requirement for a new installed capacity is expected to reach 1 941 000 m$^3$/d by the year 2015. The two market niches that are most likely to be suitable for nuclear desalination include units in the 80 000–100 000 and 200 000–500 000 m$^3$/d ranges.

The economic and financial aspects of nuclear desalination were discussed. IAEA studies have shown that nuclear energy would be competitive with fossil energy for desalination in a variety of situations. This applies, in particular, to countries that lack cheap indigenous energy resources, that need large amounts of desalinated water, and that have the means and infrastructure to install medium or large sized power plants. The availability of financing at reasonable terms is one of the key factors in establishing the feasibility of a project. The characteristics that make arrangements for the adequate financing of nuclear desalination difficult are essentially those associated with nuclear power, namely, high investment costs, long construction periods, and a relatively high uncertainty with respect to costs and schedule. A variety of alternative financing schemes are available, and these can serve as a mechanism to attract capital in situations where conventional financing is difficult. For conventional and alternative financing, the essential factors for successful implementation of a commercial nuclear desalination programme include a clear commitment to the project, with appropriate levels of government support; a thorough financial analysis, together with an economic analysis establishing the feasibility of the project; acceptable credit ratings to qualify for investments and debt financing; financing as much as possible of the local content in local currency; and electricity and water tariffs that are determined at a level that is essential for sound financial strength.
In addition to the IAEA's overall economic evaluation, a more specific study was carried out for several sites in North Africa. In conjunction with this study, three sites on the Mediterranean Sea coast in Egypt were evaluated. It is projected that the requirements for desalination at the El-Dabaa site, the only nuclear qualified site of the three, will reach 172 000 m$^3$/d by the year 2017. Performance and cost analyses were carried out using the IAEA economic evaluation spreadsheet. The results of the evaluation indicated that the levelized costs of water production for both fossil and nuclear fuels were comparable. Production costs ranged from US $0.8 to 1.9, depending on the plant size and the desalination process. Under the site specific conditions taken for this study it was found that nuclear desalination using RO with preheated feedwater provided the best economics. Higher fuel costs and/or lower interest rates tend to improve the competitiveness of the nuclear option.

A demonstration project could serve as one of the steps towards commercial deployment of nuclear desalination, reducing the level of uncertainty on the part of those decision makers who are required to make a commitment to a major project. As noted in a previous presentation, the IAEA has identified suitable candidates for a near term demonstration project, one of which was RO desalination with preheated feedwater used in conjunction with a medium sized reactor already in operation. One of the difficulties in moving forward with a demonstration project is selection of a site where such a plant could be put in place at a reasonable cost, in a country with an active nuclear programme, and where a need for water exists so that the demonstration has value both in terms of the data obtained and the water produced. It was noted that the Wolsong site in the Republic of Korea is just such a location. The strong cooperative relationship between Canada and the Republic of Korea in developing the CANDU programme in the latter country would serve as a basis for continued bilateral co-operation, with international participation, in carrying out a demonstration of nuclear desalination that was fully consistent with the goals and objectives of the IAEA.

Any discussion of the opportunity for commercial deployment of nuclear desalination must take into consideration Saudi Arabia, where the MSF process alone accounts for more than one-third of the world's desalination capacity. Even with their vast reserves of oil, nuclear desalination has gained interest in Saudi Arabia. Desalination is an energy intensive process, and oil price fluctuations affect the cost of desalinated water significantly. Nuclear power offers long term price stability and has minimal environmental impact compared with other desalination alternatives.

Tunisia was described as another country in which the need for desalination has become inescapable as a source of potable water. In the southern part of the country, the population is expected to increase by about 50%, and the demand for water is expected to double, by the year 2010. While natural water resources are available, the salinity of much of the available water supply exceeds WHO standards for drinking water. Salinity of the order of 1.5 g/L is typical for a large portion of the available
water supply, with levels reaching as high as 4 g/L in some cases. Hence, in this region the quality of the available resources is one of the major driving forces for desalination.

9. PANEL 2: WHY ARE THERE NOT MORE DESALINATION PLANTS USING NUCLEAR ENERGY?

The final session of the Symposium consisted of a panel discussion aimed at addressing the issue of how to stimulate further commercial deployment of nuclear desalination by examining the reasons why there are not more nuclear desalination facilities currently in operation. The Chairperson noted that the potential for nuclear desalination is a very real possibility. There has been much study, and many programmes are under way. Are the reasons, then, related to cost, to lack of public acceptance, to technical difficulties in coupling, to mismanagement, to sociopolitical problems, or to other causes entirely? Representatives of India, the USA, the Republic of Korea, the GTDC and Kazakhstan shared their views and experience before opening the topic to the floor.

Technical factors such as transient behaviour were presented as being the areas that need to be addressed. It was noted that the site and size requirements of nuclear plants have probably been the major impediments. Coupling issues for dual purpose plants have been extensively studied for fossil plants, and so should not be a serious impediment to nuclear desalination. Transient behaviour can create some disequilibrium, but solutions do exist; those for fossil plants should be equally applicable to nuclear plants. Finally, radioactive monitoring of product water is essential. Carryover of radioactive materials into the potable water is a question that must be addressed; it cannot simply be overlooked.

Public acceptance was identified as being an issue that will continue to be a major impediment. Perceptions of the level of competence will need to be considered. Working against the effort to gain high levels of acceptance is the fact that successful operation goes largely unnoticed, while any shortcomings are raised and never forgotten. Education was identified as being the key to achieving any significant level of public acceptance. It should be focused on those groups that are generally comfortable with nuclear technology, or who have no set point of view but are open to reason. If open lines of communication are not maintained, these groups could be lost. It is essential that a symbiosis be maintained between the local community and the ‘nuclear community’ if nuclear desalination is to develop without the stigma of ‘radiated water’.

Modern educational compartmentalism was identified as being of major concern. Rigid compartmentalism stifles creativity and prevents a multidisciplinary approach being taken towards problem solving. Nuclear desalination is a large
multidisciplinary technology and should enjoy the benefits of multidisciplinary thinking. The educational system must prevent rigid compartmentalism.

A view was expressed that the greatest impediment has been the fact that countries with nuclear technology do not have a significant need for desalination, while those with the greatest water needs do not have nuclear technology. Some countries have developed desalination, but these have generally had an abundant supply of fossil fuels. Thus, where developing countries with nuclear technology have a need for potable water production, nuclear desalination is likely to proceed.

The session closed with lively discussion from the floor. The issue of cost was discussed. It was noted that water deficiency means no water. This is a real need, and must be faced from the perspective of having no water available. Size was identified as an important factor. Many locations with serious water shortages are not large enough to support the current generation of nuclear power plants. One of the difficulties noted was that in most countries the government authorities responsible for water resources and electric supplies differ, creating an institutional impediment to the development of a technology that deals with the two together. Finally, it was observed that we must re-examine our own thinking. To advance technology, we need to develop strategies for moving forward as a group. We need to take a broad approach to the issues involved, rather than to act as individuals pursuing their own agendas.

10. CLOSING SESSION

The Symposium was officially closed with remarks from the Scientific Secretary. He noted that we had reviewed desalination plant operating experience, received reports on national and international programmes, considered a variety of technical issues, and discussed forecasts and the challenges that lie ahead. No technical impediments to nuclear desalination had been observed. What now remains is to show that nuclear desalination is economically and socially acceptable. It may not be easy, but it may not be as difficult as perceived if we go forward together.

The future is bright. Our mission now is to carry this message to others. The intense press coverage on the first day of the Symposium gave a clear indication of the level of interest being shown in nuclear desalination. The Symposium had been a success because of the positive participation of all involved, and should serve as a good starting point for advancing towards the future. Also, it had hopefully renewed the close co-operation between those in the nuclear field and those in the desalination field.
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