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Floating nuclear energy plants for seawater desalination

Proceedings of a Technical Committee meeting held in Obninsk, Russian Federation, 29–31 May 1995

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FOREWORD

Potable water is a basic requirement of human life. For coastal areas with insufficient supply of natural fresh water, seawater desalination offers a realistic alternative for the supply of additional potable water resources. In this regard, there is an increase of interest among Member States in the potential for deployment of nuclear reactors as energy sources for seawater desalination. The interest in this subject has led to a number of meetings, extensive technical and economic evaluation, and several publications on this particular application of reactor technology.

Floating nuclear desalination facilities are one of the alternatives being considered. They may offer a particularly suitable choice for remote locations and small island or coastal communities where the necessary manpower and infrastructure to support desalination plants are not available.

In the interest of focusing specific attention on the technology of floating nuclear desalination, the IAEA sponsored a Technical Committee Meeting on Floating Nuclear Plants for Seawater Desalination from 29 to 31 May 1995 in Obninsk, Russian Federation. This publication documents the papers and presentations given by experts from several countries at that meeting. It is hoped that the information contained in this report will be a valuable resource for those interested in nuclear desalination, and that it will stimulate further interest in the potential for floating nuclear desalination facilities.

The generous support by Member States of the IAEA activity in nuclear desalination and the valuable contributions by experts at the Obninsk meeting are highly appreciated.

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SUMMARY

1. INTRODUCTION

At the 1989 session of the IAEA General Conference, renewed interest in the potential of nuclear reactors for seawater desalination was expressed by some Member States, and in the resolution the General Conference requested the Director General to assess the technical and economic potential of nuclear reactors for seawater desalination in the light of the relevant experience gained during the previous decade. Since then, the IAEA has organized a number of meetings and published several technical documents, related to the subject area.

In response to the 1993 General Conference resolution, the IAEA distributed letters to all Members States requesting them to provided information about their interest in possible demonstration facilities for seawater desalination using nuclear energy. Several positive replies have been received with varying levels of interest, from indication of interest to provision of funds. In addition, a working programme was developed by an Advisory Group Meeting, describing the essential ingredients needed to move ahead with the implementation of a demonstration programme, including as a first step , the performance of an options identification programme.

The results of the survey and the working programme were reported to the General Conference which adopted a Resolution, requesting the Director General to undertake similar consultation for implementation of the main recommendations of the Advisory Group on demonstration facilities.

The purpose of the options identification programme was to reduce the very broad range of possibilities to a much more limited set of practical demonstration projects. this limited set of options should be well defined with an applicability much broader than the specific country and site at which they could be carried out, and which could practically be developed on a time scale commensurate with the needs of that specific option being identified. It was estimated that the options identification programme can be carried out over a period of about two years. During the first Consultancy Meeting on the programme, several activities which the IAEA should undertake were recommended. Among these recommendations the review of floating nuclear desalination facilities for seawater desalination was included.

Therefore, the IAEA convened a Technical Committee Meeting (TCM) on "Floating Nuclear Plants for Seawater Desalination" from 29 to 31 May 1995. The TCM was hosted by the Institute of Physics and Power Engineering (IPPE) and was held in Obninsk, Russian Federation.

The object of the TCM was to provide a forum to review and discuss the technology, design, economics and experience of floating seawater desalination plants using nuclear energy, including plants on anchored ships or anchored barges, or with permanent foundation; to investigate the feasibility of coupling various small nuclear reactors with desalination processes in a floating system; to identify safety criteria and to assess the comparative advantages and disadvantages between land based plants and floating plants.

2. CONCEPTUAL DESIGNS FOR FLOATING DESALINATION FACILITIES

Various concepts for floating desalination facilities, including nuclear and non-nuclear floating ships, were presented.

2.1. APWS-80 design

Based on their experience with ice-breakers and marine nuclear propulsion plants, Russia has developed several conceptual designs of floating nuclear desalination plants.

Two variants of floating nuclear desalination plant, based on the KLT 40 type reactor, have been considered. They are: APWS 80 with two reactors, and APWS-40 with one reactor.

The KLT-40 is a pressurized water reactor. The rated thermal power is 80 MW. It has been modified for each new ship generation based on accumulated experience. Safety of the KLT-40 type reactor has been verified. The KLT-40, already used in nuclear powered ice-breakers, has a repair free life span of 110 000 hours.

The APWS-80 floating nuclear seawater desalination plant is designed for electricity production and for seawater desalination by distillation, using four distillation plants with film type horizontal-tube evaporators. It can produce 15 MW electricity and 80 000 m^3 desalted water per day. The APWS-80 is a special non-self propelled ship, basically a barge, with dimensions of 160 m in length and 44 m in width. Approximately US $300 million and 5 years would be required for construction of a prototype APWS-80 nuclear floating desalination station.

In parallel with the APWS-80 development, a floating complex for the production of electricity and seawater desalination using reverse osmosis, which is more economical, was developed. The complex includes two floating barges: a nuclear power station barge with two KLT-40 type reactors and a reverse osmosis desalination plant barge. The floating nuclear power station barge has the dimensions of 120 m in length and 28 in width. The maximum desalinated water production capacity of the complex could be as high as 310 000 m^3 per day with the reverse osmosis process.

CANDESAL (Canada) has developed a new approach for integrating reverse osmosis (RO) desalination systems with nuclear reactors as an energy source. Using waste heat from the electrical generation process to preheat the RO feedwater improves the efficiency of the RO process. By also using advanced feedwater pre-treatment and sophisticated system design integration and optimization techniques, an overall improvement in efficiencies, cost and environmental impact is achieved.

CANDESAL has studied the coupling of its reverse osmosis technology with the Russian APWS-80 floating nuclear desalination plant. The study shows that the energy consumed for the CANDESAL optimized APWS-80 design configuration is 4.22 $kW \cdot h/m^3$ compare to the base APWS-80 design value of 4.9 $kW \cdot h/m^3$.

2.2. ABV design

A floating nuclear desalination complex based on the ABV type reactor plant is currently being developed in Russia. The complex consists of a 12 MW(e) floating nuclear power station (FNPS) barge and a desalination barge for reverse osmosis seawater desalination.

For the FNPS there are two 6 MW(e) ABV type reactors and two reserve 2.8 MW diesel generators to provide electrical power during refueling. The ABV type reactor is a small pressurized water reactor producing 38 MW thermal power. It is based on the proven design and technologies of both the ground-based and marine propulsion KLT-40 plants. The reactor has a traditional two-circuit layout using an integral type reactor vessel with natural convection of primary coolant. The integral design and natural convention of the primary coolant allows considerable reduction in primary circuit volume, simplifies power supply and plant control and decreases power consumption for the station itself.

The desalination barge comprises a water intake system, water pre-treatment system, high pressure pump house, reverse osmosis units, and the systems for cleaning and regeneration of the desalination units. It could produce fresh water at a rate of 40 000 m^3/d. The desalination barge has dimensions of 72 m in length, 24 m in width and 3.9 m in draught.

Approximate specific operating costs amount to US \$0.86/m^3. If the reactor thermal power is increased to 60 MW, which allows production of more than 65 000 m^3/d of fresh water, then the specific operating costs could be reduced to US \$0.53 per m^3/d. Currently, preparations for construction of a pilot FNPS at St. Petersburg are under way.

2.3. Cruise-M design

Russia has unique experience in the development and use of lead-bismuth coolant in marine reactors. A conceptual design for a floating nuclear desalination plant, Cruise-M, in which the nuclear steam producing unit is based on a fast reactor with lead-bismuth coolant, has been developed. The Cruise-M floating nuclear desalination plant, with two nuclear power units, could produce 25 MW(e) electricity and 80 000 m^3 of water per day.

The lead-bismuth coolant, which has been developed in Russia for nuclear powered submarines, has a high boiling point (1670°C) that eliminates the possibility of coolant boiling in the highest power fuel sub-assemblies, even in the beyond design basis accidents. The void coefficient of reactivity for lead-bismuth coolant is negative. The low chemical activity of lead-bismuth eliminates the possibility of fires and explosions in the event of loss of a coolant accident. All of these characteristics provide a high degree of safety. Several nuclear power installations with lead-bismuth coolant have been constructed, and their total operating time is approximately 80 reactor-years.

The floating nuclear power plant has dimensions of 49.5 m in length, 16 m in width and the average draught is 12 m.

2.4. Small floating desalination plant design

A conceptual design of a small floating seawater desalination plant using a nuclear heating reactor coupled with the multi-effect distillation (MED) process has been developed in China. It coupled two proven technologies, the nuclear heating reactor (NHR-10) and a low temperature MED process. This floating plant could provide 4000 m^3/d of fresh water and 750 kW of electricity.

The NHR-10 is a pressurized water reactor, with an integral pressure vessel and primary circuit design in producing 10 MW thermal power. It is based on experience with a 5 MW thermal district heating reactor, which has been operated for the winter seasons since 1989. The reactor is cooled by light water with natural circulation, and the primary system is self-pressurized. The suitability of natural circulation for marine conditions needed to be analyzed and investigated. The preliminary results show that under a rocking or inclining angle within $\pm 30^\circ$ and with low frequency rocking conditions, the behavior of natural circulation would not be significantly influenced. A specially designed hydraulic control driving system is adopted in NHR-10. It is enclosed in the pressure vessel without penetration of the pressure vessel head and eliminates the control rod ejection accident. A series of experiments was performed, and they verified that the hydraulic control driving system can be operated normally and safely under rocking condition.

Steam from the steam generator flows to a turbine with back pressure of 0.00386 MPa. Saturated steam with a temperature of $75^\circ C$ from the last stage of the turbine is supplied to the first effect of the MED process. The MED plant has two units, and each has a water production capacity of 2000 m^3 per day.

The floating nuclear desalination plant is mounted on a ship or on a barge. The dimensions of the ship are 80 m in length, 16 m in width, 6 m in draught and the total displacement is 5000 tons.

2.5. Conventional floating desalination complex Geyser-1 in Russia

The Geyser-1 complex is a conventional floating desalination barge conceptual design using the reverse osmosis process for seawater desalination. The complex potable water output is 40 000 m^3 per day.

Five ADG-5000 conventional diesel generators, each with a rated power of 5000 kW(e), supply the electricity needed for the reverse osmosis desalination plant. The fuel storage in the on-board tanks guarantees 15 days of operation. The reverse osmosis desalination plant is grouped in four independent assemblies, of nine desalination units per assembly. Each desalination unit, comprising 150 tubular membrane filtration elements, is arranged within the confines of an international class sea container having dimensions of 6 m $\times$ 2.5 m $\times$ 2.6 m.

The dimensions of the Geyser-1 barge are 96.4 meter in length, 24 meter in width, and the displacement is about 7000 tons.

The cost of the complex would be around US $22 million. The specific fresh water production cost was estimated to be around US $0.7-0.78/ m^3.

2.6. Onboard floating desalination platform

A small desalination unit (1 m^3/d of potable water), using the low temperature vacuum evaporation (LTVE) process, suitable for a floating platform has been designed, fabricated and operated in India. Based on the performance data from this unit, a 30 m^3/d LTVE desalination plant for floating structures was designed, operated and tested for endurance.

It utilizes waste heat (60-65°C) for potable water production. Feedwater enters the heater tubes and part of it evaporates by the time it comes out at the top of the vertical tube bundle. The vacuum evaporation of seawater takes place at 40°C to 50°C. The vapour enters the horizontal tube bundle at the top of the vertical shell and condenses on the condenser tubes. The tubes are cooled by seawater flowing inside. The product water is pumped out. Due to low boiling temperature and brine density, scale formation is eliminated.

A technical/economic study has been carried out to examine the feasibility of coupling a LTVE floating desalination platform to a 500 MW(e) PHWR nuclear power plant for utilizing the waste heat from the moderator. The heavy water is cooled from 80°C to 55°C in a process water heat exchanger. The process water is heated from 32°C to 55°C, heating the seawater from 32°C to 42°C for the LTVE process. It can produce 900 m^3/d high quality potable water in coastal regions.

3. EXPERIENCE AND OPERATION OF FLOATING DESALINATION FACILITIES

Russia has experience with water desalination plants on nuclear powered icebreakers and on nuclear powered freight carrier. Two kinds of distillate plants have been used: M4C-l on nuclear powered icebreakers and M3C on the nuclear powered freight carrier. The M4C-1 plant can produce 120 m^3 potable water per day and the M3C can produce 60 m^3 potable water per day.

The effect of ship's roll and heel will influence the thermal process in the plant's horizontal heat-exchangers due to the exclusion of part of the tubes from active heat exchange. This is solved through an appropriate arrangement of the horizontal tube bundles, and design measures ensure a complete condensate removal from the apparatus even when inclined to either side. Reliable operation is ensured under the following conditions: static fluctuations to either side up to 15° without time restriction; dynamic inclinations (rolling) at an amplitude of 45° and period of 7-14 seconds.

At the present time 10 plants of the M4C l type are operating on nuclear icebreakers of the "Arktika" class, and 6 plants of the M3C type are operating on nuclear icebreakers of the "Taimyr" class and the nuclear powered freight-carrier "Sevmorput". In total there are more than 50 plants of M4C l and M3C are operating on different types of ship.

The 40 years of experience in developing and operating desalination plants in Russia has shown that multistage distillation desalinating systems with horizontal tube film evaporators could be the most suitable equipment for floating nuclear desalination complexes. This is in part because they are characterized by the absence of large moving water masses with a free surface, which would be sensitive to the ship's oscillating motions during operation.

4. EXAMPLE OF POTENTIAL MARKETS

The advantage of floating nuclear desalination plants is the possibility of building and testing them in the shipyards of the supplier country and handing them over on turnkey basis. They can be recommended as power/water desalination complexes for water shortage countries and regions such as North Africa, the Near East and some regions in the Indian Ocean.

The prospect of floating desalination facilities using nuclear energy in Indonesia was discussed. Indonesia is located in the west tropical zone, and has an abundance of water resources. Unfortunately water resources are not always available at the right time and locations. In some areas the price of one liter of bottled water is higher than the price of one liter of petrol. Geographically, the arid regions cover many islands which are separated by a large distance. Therefore floating desalination facilities are considered to be suitable for those areas.

5. CONCLUSIONS

(a) The participants at the Technical Committee Meeting represented countries which have an interest in floating nuclear desalination plants both from the standpoint of potential users of that technology and the designers and suppliers of the technology. A broad range of background information, expertise and experience was presented in the field of nuclear power and desalination technology. The papers presented, along with the ensuing discussion, indicated that a growing need for potable water production exists, some of which could be met by floating nuclear desalination units.

(b) The design and safety considerations of a nuclear desalination unit on board a floating platform are different from those of a land based nuclear desalination unit. The limitations due to marine environment including conditions of sea and wind, space availability, weight limitations, weight of the desalination unit and technical considerations including pump cavitation and vibration, must be considered in the design stage.

(c) As cost effective solutions to existing needs for potable water emerge, a demonstration project might be appropriate to prove the system performance, system capabilities, system cost effectiveness and other factors . Such a demonstration is consistent with the IAEA's current work in the framework of the Options Identification Programme leading towards the definition of suitable demonstration facilities or locations.

FLOATING NUCLEAR POWER STATION OF APWS-80 TYPE FOR ELECTRICITY GENERATION AND FRESH WATER PRODUCTION

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Abstract

To solve the problem of seawater desalination and electric energy generation, the designing organizations of Russia have developed two variants of floating nuclear desalination plant. The KLT-40 type reactor, with maximum 160 MW thermal power, is used as the power source for such plant. Depending on the customer requirement one or two power unit could be installed in the floating desalination plant. There are APWS-80 with two reactors, producing 80 000 m³ desalinated water per day and APWS-40 with one reactor, producing 40 000 m³ desalinated water per day. The advantages of floating desalination plants are the possibility to build and test them at the ship-build plant of the supplier country and to hand them over on turnkey base.

1. INTRODUCTION

For seawater desalination and electricity generation Russian design organizations have developed and can supply to Customers floating nuclear power/desalination stations based on the KLT-40 type reactor plant (Fig. 1). These plants meet international safety requirements for marine nuclear power plants (NPPs) and the requirements of Russian regulatory codes for NPPs including IAEA recommendations.

Main Reactor Plant Data

Thermal power, MW	up to 160
Steam capacity, t/h	up to 260
Steam temperature, °C	up to 300
Steam pressure, MPa	up to 4

The KLT-40 reactor has been successfully operated for many years in Russian nuclear ships and has been modified for each new ship generation based on accumulated experience.

The KLT-40 reactor plant was the winner among plants of the same power level at a competition "Small Nuclear Power Stations-91" held by the Russian Federation Nuclear Society.

Depending on customer requirements, the power/desalination station may be a one-reactor (APWS-40 type) or a two-reactor (APWS-80 type) design, hence the reactor thermal power is within 80 - 160 MW. Advantages of floating power/desalination complexes are:

- convenient maintenance by a floating base at a mooring site and decommissioning by tugging to the Supplier's country;
- commercial production and long-term confirmation of service life characteristics of the KLT-40-type reactor plants and desalination units;

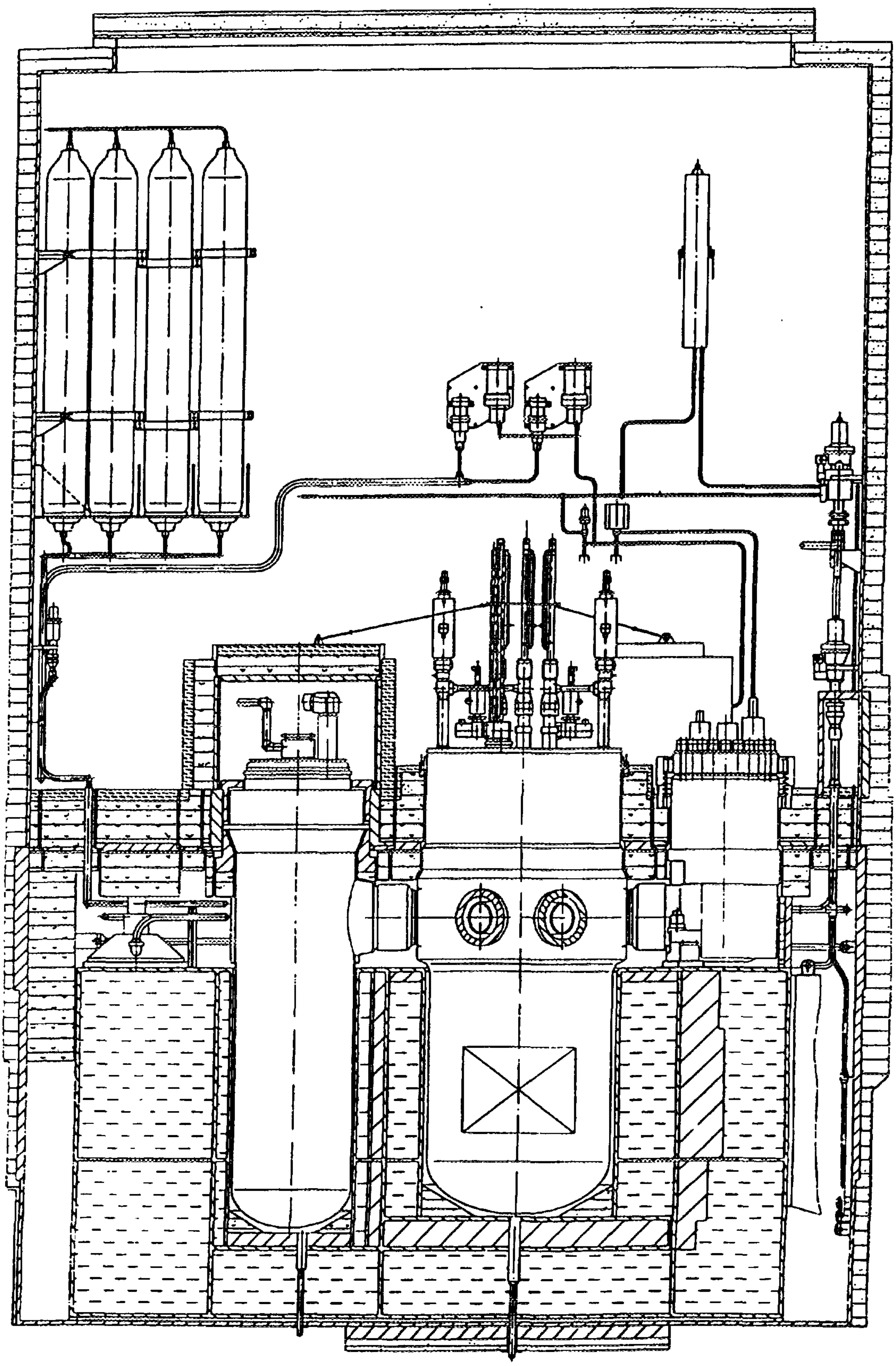


Fig. 1a. KLT-40 reactor plant.

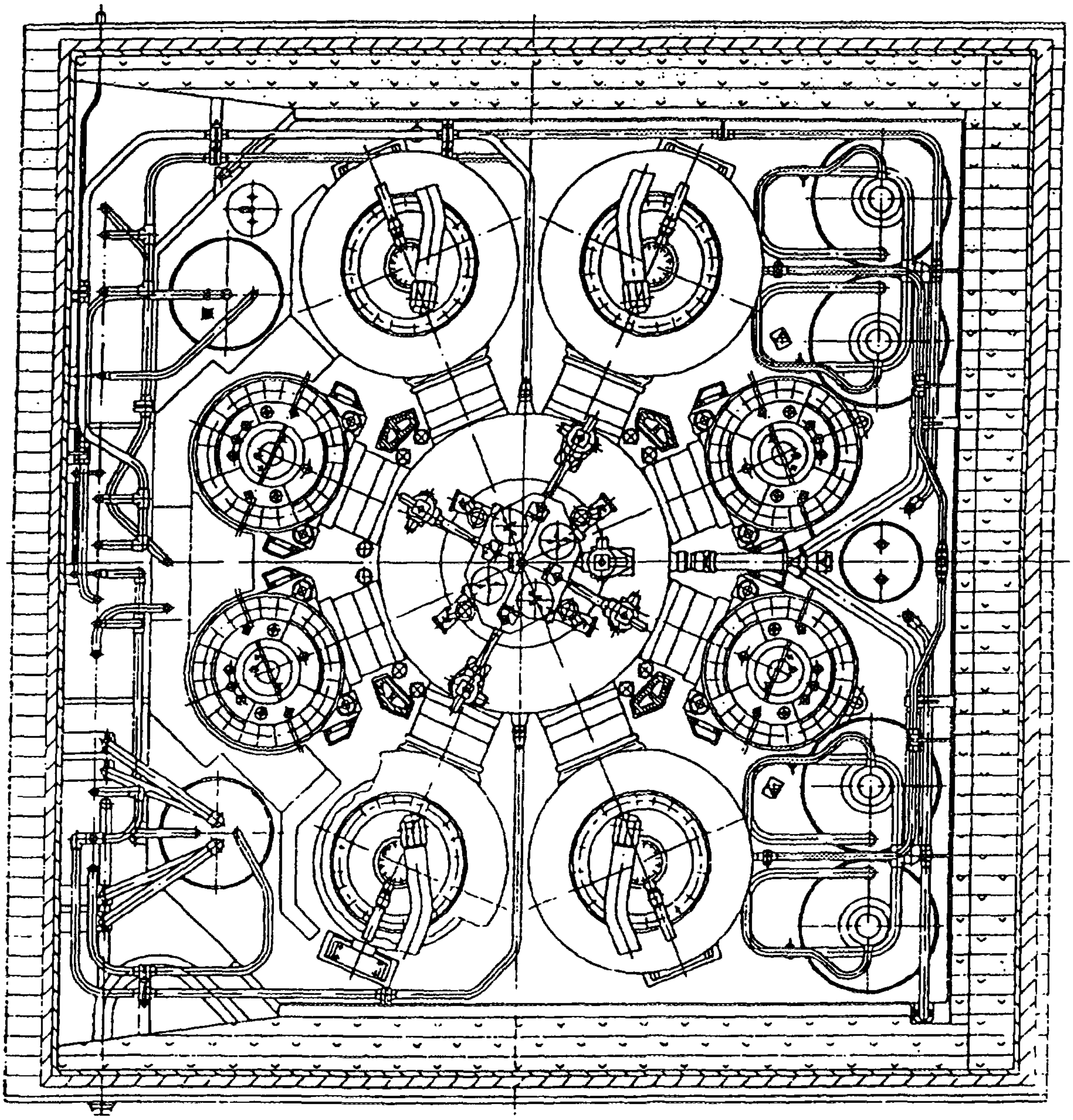


Fig. 1b. KLT-40 reactor plant.

- possibility of installation in different coastal regions of the world;
- high fabrication quality at a shipyard and "turn-key" delivery to the Customer in a short period of time.

For any of the options, the supply of electrical energy to users within the plant is provided by the shipboard electric power station.

2. CHOICE OF EQUIPMENT AND SCHEME FOR REACTOR AND DESALINATION PLANT COUPLING

Analysis of schemes for coupling of reactor with desalination plants is performed so as to achieve the specified thermal power of the reactor with maximum efficiency and minimum probability of radioactive contamination in the desalinated water. Therefore turbo-generators with condensing and back pressure turbines were considered for the electrical plant, and distillation or reverse osmosis plants for the desalination plant. Electricity generated was used for the station's own needs, for seawater desalination or for sale. Thermal power was supplied to distillation type desalination plants either by intermediate steam extraction from the turbine or by removal of heat from a back pressure turbine condenser.

It seems that the most preferable from the above mentioned point of view is a design using a condensing turbine with high cycle efficiency and a reverse osmosis desalination plant with low specific consumption of electric energy. It is evident that this scheme completely excludes radioactive contamination of desalinated water. However, at present reverse osmosis is hardly the most economic method due to limited lifetime of the filter elements, high costs for service and treatment of fresh water.

Desalination stations of the APWS-80 type using distillation plants with back pressure turbines are of practical interest. Heat for the distillation plant is supplied through an intermediate circuit, with water pressure exceeding the pressure in the adjacent circuit from the reactor side in order to prevent ingress of radioactive contamination in the event of heat exchanger leakage.

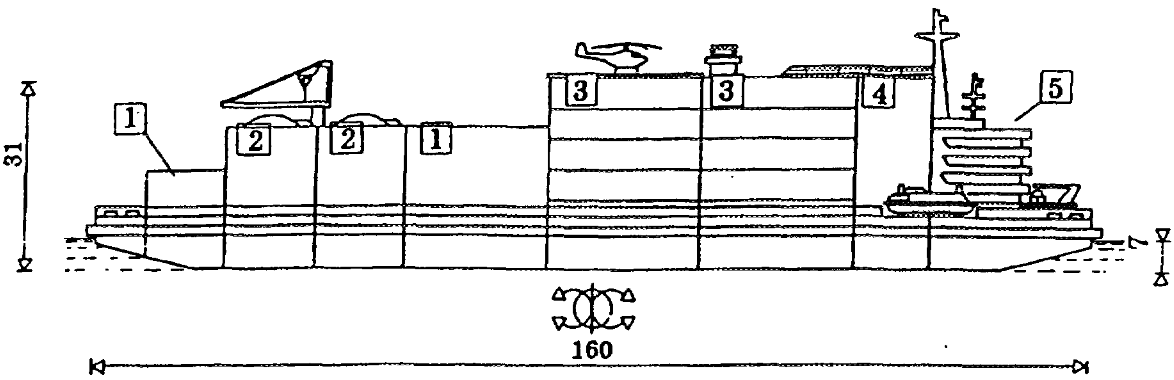
3. APWS-80 FLOATING NUCLEAR POWER STATION FOR PRODUCTION OF ELECTRICITY AND SEAWATER DESALINATION BY DISTILLATION

The APWS-80 floating nuclear seawater desalination plant is a special non-self-propelled ship with two-reactor power plants designed for production of electricity and seawater desalination. It is intended for use in a protected water area, together with a complex of external servicing structures. The main ship layout and the principle flow diagram of the station are shown in Figs 2 and 3. The station's main technical data are as follows:

Station Main Technical Data

Width, m	160
Breadth, m	44
Draught, m	7
Desalinated water capacity, m^3/d	80 000
Electric power (gross), MW(e)	~25
Electric power consumed by station, MW(e)	~ 10

The reactor operates at a reduced power of approximately 80 MW(th). If each reactor were to be operated at its full power of 160 MW(th), desalinated water capacity and electric power generation would be doubled.



1 - engine compartment

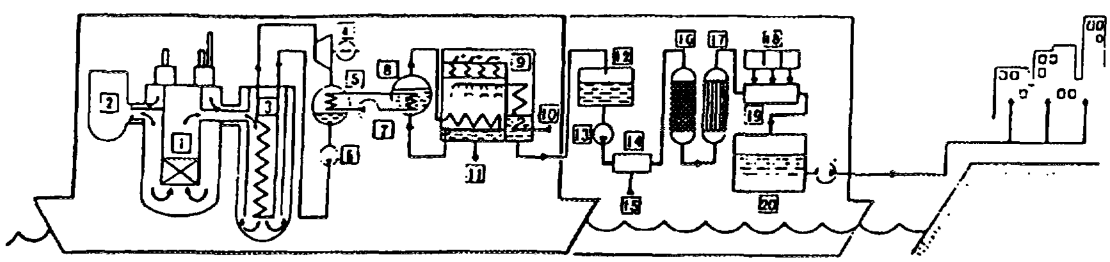
2 - central power compartment

3 - desalination plant

4 - potable water preparating plant

5 - living compartment

Fig. 2. Ship layout.



1 - reactor
2 - primary circuit circulator
3 - steam generator
4 - turbo-generator
5 - condenser
6 - secondary circuit electric pump
7 - intermediate circuit electric pump
8 - steam generator
9 - distillation desalinaton plant
10 - sea water
11 - evaporated sea water
12 - intake tank for distillation
13 - electric pump of potable water preparation plant
14 - mixer
15 - H_2CO_3 solution
16 - water enrichment facility
17 - running water ssorbent containing filter
18 - plant for fluorine, chlorine water treatment and stabilization
19 - mixer
20 - potable water tank

Fig. 3. Principal flow diagram of the station.

Besides the reactor plant, the station includes the desalination plant, a drinkable water production plant, and ship general systems. As the desalination plant, four distillation plants with film-type horizontal-tube evaporators are used in APWS-80. Many years of experience exist using analogous plants for an industrial complex in Aktau (Kazakhstan).

Excess electricity can be used either for the production of additional desalinated water using reverse osmosis or for sale. The cost of desalinated water can be materially reduced by compensating part of the production costs out of the profits from sale of electric energy.

Construction of desalination plants using distillation plants with film-type horizontal evaporators seems to be the most practical at this time. The use of back pressure turbines as the source of thermal energy results in some excess electric energy in relation to the power consumed for the station's own needs.

In order to reduce the probability of radioactive contamination of the desalinated water, two intermediate circuits are provided in the station design. One of these is pressurized to a higher pressure than the reactor side circuit.

4. NUCLEAR FLOATING COMPLEX (STATION) FOR PRODUCTION OF ELECTRICITY AND FOR WATER DESALINATION USING REVERSE OSMOSIS

As previously stated, the most economical approach is seawater desalination using reverse osmosis. Therefore, in parallel with the APWS-80 development, a floating complex for the production of electricity and seawater desalination using reverse osmosis was developed. It is proposed that this system use high thermal efficiency condensing turbines in conjunction with the desalination units.

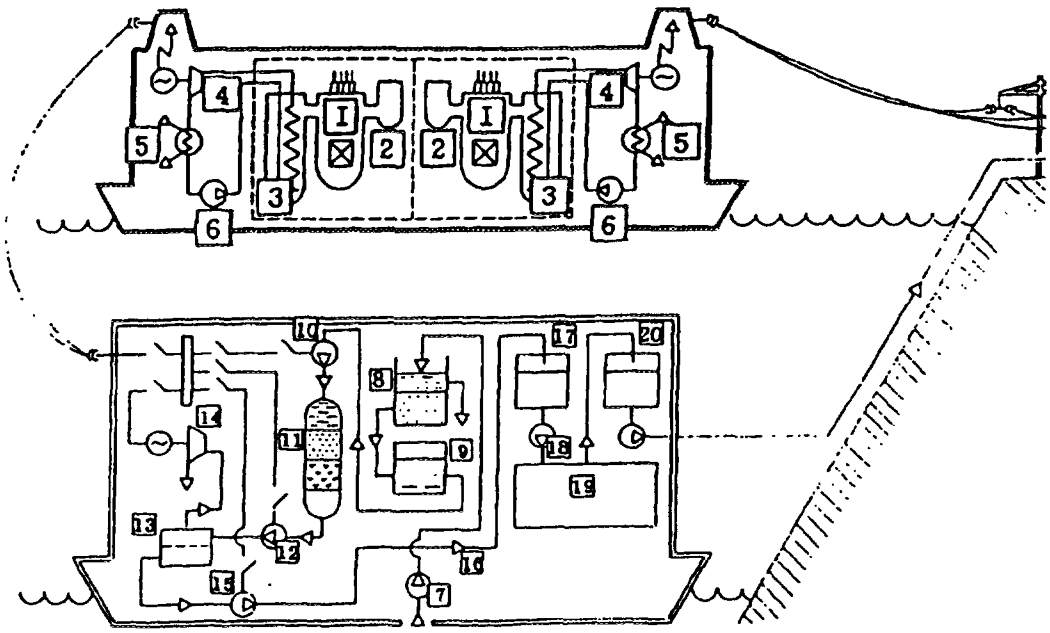
The complex includes two floating structures: a floating nuclear power station (FNPS) and a ship for seawater desalination using reverse osmosis (Figs 4 and 5). The floating nuclear power station is a special non-self-propelled ship for the production of electricity. It is designed for use in a protected aquatorium, or harbour. The station includes:

- Two nuclear steam supply systems of the KLT-40 type;
- A steam turbine plant;
- An electrical generating plant;
- Servicing facilities and ship's general systems.

Main FNPS Technical Data

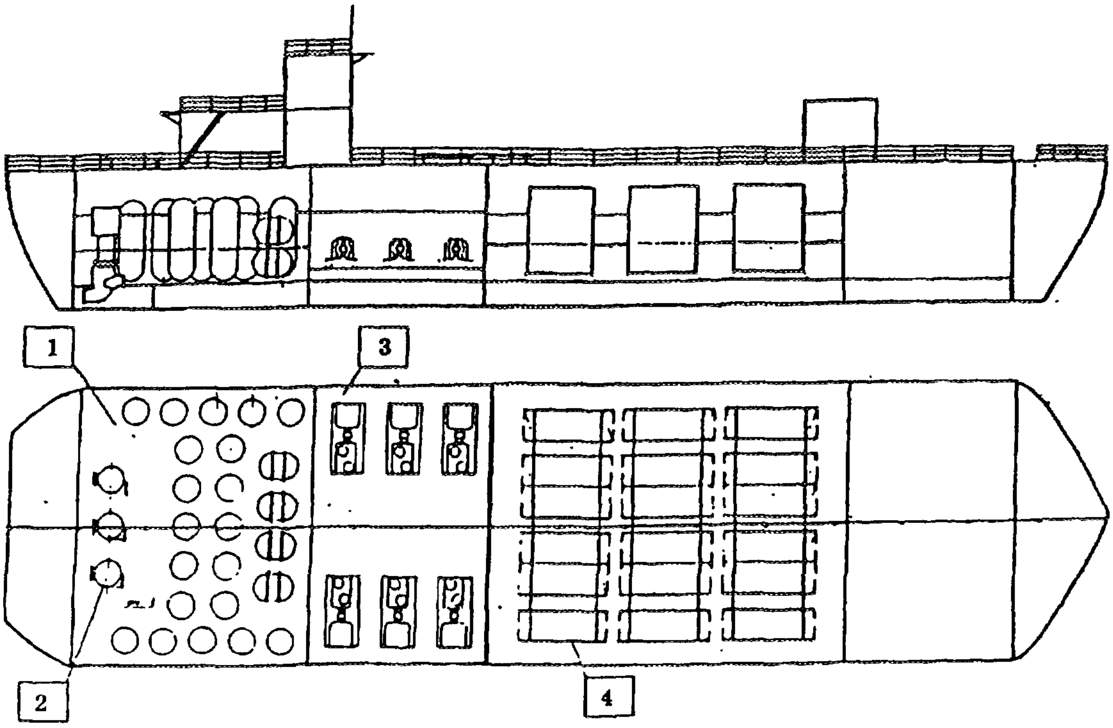
Length, m	120
Width, m	28
Draught, m	3.5 - 4 5
Electric power (gross), MW	~ 70
Electric power consumed by FNPS, MW	~ 5
Reactor power, MW(th)	160

The rapid maneuvering characteristics of the ship's reactor plant allow it to closely follow power demand, and thereby to ensure highly economical operation.



1 - reactor
2 - primary circuit circulating pump
3 - steam generator
4 - turbogenerator
5 - condenser
6 - secondary circuit electric pump
7 - sea water
8 - gravity filter
9 - clarified water tank
10 - booster pump
11 - twin-layer pressure filter
12 - high pressure filter
13 - reverse osmosis module
14 - hydroturbine
15 - fresh water pump
16 - filtrate
17 - filtrate intake tank
18 - electric pump of potable water preparation system
19 - potable water preparation unit
20 - potable water storage tank

Fig. 4. Principal flow diagram of the complex.



1 - room for sea water pre-treatment system

2 - booster pump

3 - desalinating system pump room

4 - desalinating modules

Fig. 5. Desalination plant layout.

The design and industrial enterprises of Russia are working on the development of a floating nuclear cogeneration plan for the country's northern regions. This can serve as a prototype for the FNPS desalination complex.

The electric energy generated by the FNPS is partially transmitted to the ship for seawater desalination and its excess is used for supply to coastal users.

This arrangement, which separates power generation and desalinated water production, has certain advantages over an arrangement in which they are combined on one floating structure. It simplifies a solution to the problem of preserving a high efficiency of desalinated water production from the complex when the reactors are shutdown by supplying the desalination plant with electric energy from the external grid. The scheme seems to be sufficiently flexible since it allows the optimal ratio for production of the required amounts of water and electric energy.

The ship for reverse osmosis desalination is a non-self-propelled structure housing systems and equipment providing for the supply of seawater, its pretreatment, desalination, supply of desalinated water to users, and cleaning of the desalination units (Fig. 5). With the objective of optimizing the of technical and economic characteristics of the complex, some variations with different desalinated water output were considered.

Desalinated water capacity, thousand m^3/day	0	20	40	80	318
Electric power required for desalination plant, MW (at specific consumption 4.9 kW·h/m^3)	0	4.1	8.2	16.4	65
Excess electric power of complex, MW	65	60.9	56.8	48.6	0

The desalinated water production plant can also be arranged on shore in the vicinity of the FNPS. The advantage of having the desalination plant arrangement on a ship is that there is the possibility of plant manufacture and testing at a shipyard in the Supplier country.

At present new technologies are being developed for seawater desalination using reverse osmosis. For example, in the Canadian CANDESAL desalination program the use of reverse osmosis technology is accompanied by preheating of the seawater in the turbine condenser. Preheating allows considerable reduction in the specific power consumption for desalination and in the cost of desalinated water.

In this connection it seems beneficial to develop a joint Canada-Russian project for floating nuclear power/desalination complex, with the FNPS based on the KLT-40 shipboard reactor plant and the new application of reverse osmosis seawater desalination.

5. CONSTRUCTION SCHEDULE

Approximately 300 million US dollars is required for construction of the prototype APWS-80 nuclear floating desalination station. The sum indicated may be returned to the countries financing the station creation after selling of the desalinated water and electricity produced. Specialists of these countries may have an opportunity to train at the prototype station.

A staged approach to the construction and operation of the prototype APWS-80 floating desalination station is envisaged, including:

- Search for a Customer;
- Development (in conformity with requirements of the Customer), construction and "turnkey" commissioning of the plant (4-5 years);
- Surveying the site and construction of external servicing structures around the mooring site (2-3 years);
- Shipping the facility to the mooring site (0.5 year);
- Its operation and maintenance;
- Facility decommissioning after the end of its service life.

Activity on design and construction of the station can begin immediately after contract signing.

Construction Schedule For APVS-80 Prototype Floating Station

	Name of a phase	1-st year	2-nd year	3-rd year	4-th year	5-th year
1.	Reception of the request for proposal	. . .	. . .	. . .	. . .	. . .
2.	Precontract design					
3.	Conclusion of a contract					
4.	Detailed design					
5.	Licensing					
6.	Documentation ordered					
7.	Working drawings					
8.	Operational documentation					
9.	Fabrication of KLT-40 RP equipment					
10	Building berth period with fabrication and delivery of the rest equipment					
11.	Completion of the construction					
12.	Tests and delivery					

6. CONCLUSION

As to level of safety and environmental impact, the floating nuclear desalination plant meets modern international codes and requirements, and can be recommended as a power/water desalination complex for the countries of North Africa, the Near East, and some regions of the Indian Ocean.

The principal engineering features of the station and its subsystems have been proven during many year of operation for both the reactor and desalination parts of the station. This allows a minim period of construction (4-5 years) and acceptable cost of desalinated water.

A floating nuclear cogeneration plant constructed in Russia can become a prototype power source for floating desalination complexes elsewhere. It can validate their viability, expedite their design/development and reduce their construction time.

It seems that participation of other country's designers and potential Customers in the development of floating nuclear desalination stations of the APWS-80 type is worthwhile.

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THE WATER DESALINATION COMPLEX BASED ON ABV-TYPE REACTOR PLANT

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Abstract

A floating nuclear desalination complex with two barges, one for ABV type reactor plant, with twin reactor 2 × 6 MW(e), and one for reverse osmosis desalination plant, was described. The principal specifications of the ABV type reactor plant and desalination barge were given. The ABV type reactor has a traditional two-circuit layout using an integral type reactor vessel with all mode natural convection of primary coolant. The desalted water cost was estimated to be around US $0.86 per cubic meter. R&D work has been performed and preparations for commercial production are under way.

1. GENERAL CHARACTERISTIC OF THE COMPLEX

The floating nuclear desalination complex is intended for desalination of seawater with total dissolved solids (TDS) content up to 41 g/l. The desalinated product water has a salt content of 500 mg/l (consistent with international standards for desalinated water). Nominal capacity of the complex is 40 000 m^3/day.

The complex comprises two barges:

- The 12 MW(e) "Volnolom"-type floating nuclear power station (FNPS) with an ABV reactor plant (RP);
- The desalination barge for seawater desalination by reverse osmosis.

This arrangement of the complex allows:

- Providing a possibility for separate application - the FNPS may be used for electricity and heat supply to industrial enterprises and villages in remote regions, and the desalination barge might be included, where economically expedient, in complexes with conventional power sources;
- Softening the requirements for the rigging of building enterprises and for dimensions and depths of the installation site due to reduction of the ship dimensions and displacement;
- Involving ship-building enterprises not specialized in nuclear ship building for fabrication of the desalination barge.

These factors provide an opportunity to increase the economic efficiency of the complex, including increasing the serial production volume.

Crew number:

– FNPS	54 men
– Desalination barge	21 men

The institutions responsible for development of the complex are CPB "Baltsudproect", St. Petersburg, the designer-general of the complex and OKB Mechanical Engineering, N. Novgorod, the designer-general of the reactor plant.

The complex should be installed with consideration of a particular site for its arrangement. Installation is possible either within naturally protected areas (fjords, bays, lagoons), or using man-made protective structures. Depths in the complex installation area should be not less than 5.4 m at the time of the ebb. The plant supporting system insures normal operation of the equipment under conditions of up to sea state 3 and wind velocity up to 40 m/s. The complex is installed on "mooring posts" using PMK-type wharves and "dead anchors".

Plant installation in areas where wind velocity does not exceed 25 m/s is possible with application of either standard anchors or using conventional mooring to a floating wharf. Final selection of the supporting scheme should be made according to the specific conditions of its arrangement. All ship-building components of the complex, strength characteristics, stability and floodability are consistent with the Russian Register Rules for sea-going ships.

2. "VOLNOLOM" FNPS WITH ABV REACTOR PLANT

The "Volnolom" FNPS with ABV reactor plant is intended for electricity, steam and heat supply to consumers, including operation as a part of seawater desalination complexes. They are economical and environmentally pure power sources satisfying the requirements of advanced reactors with enhanced safety, and have no limitations on installation.

Main Dimensions of "Volnolom" FNPS

Maximum length, m	96.8
Weight, m	21.6
Board height, m	10.3
Draught, m	4.5
Displacement, t	8 700

The FNPS comprises two main 6 MW nuclear power units and two reserve 2.8 MW diesel generators to provide replacement power unit during refueling or repair. Fuel storage for diesel generators is adequate for 45 days of operation.

The reactor plant was designed in compliance with national standards documents, IAEA recommendations (NUSS, INSAG-3, INSAG-6 series) and experience gained from improved NPP designs.

The design uses proven design and technologies of both a ground-based and marine reactor plants, including initially those for KLT-40 plants, whose operability has been confirmed by many years of successful operating experience.

High technical and economic features and quality of the plant are insured by the equipment building-block design and by implementation of requirements for quality assurance during all phases of its lifetime.

Design decisions for ABV plants are coordinated with existing Russian manufacturing and technological capabilities, which allows supply to the customer of the entire set of equipment for the nuclear power plant with a guaranteed high quality of fabrication and delivery schedule.

The RP has a traditional two-circuit layout using an integral type reactor vessel with all mode natural convection of primary coolant.

Enhanced safety of the plant is provided by inherent self-protection, application of the defence-in-depth concept, usage of self actuating devices, availability of engineering safety features and considerable time reserve for corrective actions by personnel.

Principal Specifications of ABV RP Power Unit

Reactor thermal power, MW(th)	38
Nominal electrical power, MW(e)	6
Maximum capacity of heat supply, Gcal	12
Primary circuit parameters:	
- pressure, MPa	15.4
- core outlet temperature, °C	330
Core lifetime, hours	22 000
Steam parameters:	
- steam pressure, MPa	3.14
- steam temperature, °C	290
Greed water temperature, °C	
- direct	120
- return	70
Service life, years	
- up to yard repair	10
- total	30-50

The integral design of the reactor and the application of natural convection of the primary coolant allows considerable reduction in primary circuit volume, simplifies power supply and plant control and decreases power consumption for its own needs.

The reactor and primary equipment are encapsulated in a special containment, insuring localization of radioactive products during design basis and beyond design basis accidents. Dedicated structural protection is envisaged to prevent containment damage due to extreme external impacts.

The availability of safety barriers and confinement systems exclude, practically completely, radioactivity release beyond the plant confines during design basis accidents. During beyond design basis accidents with postulated core melting, radioactivity release is considerably below standards.

The "Volnolom" FNPS project was the winner at a competition "Small Nuclear Power Stations-91" held by the Russian Federation Nuclear Society.

Currently, preparations for construction of a pilot FNPS at JSC "Baltiyskiy Zavod", St. Petersburg, are underway. Construction time is 4 years.

3. DESALINATION BARGE

The desalination barge comprises: water intake system, water pretreatment system, high pressure pump house, seawater desalination units and the system for cleaning and regeneration of the desalinating units.

Water intake, depending on the conditions of a particular complex, may be accomplished by either direct water intake through the barge Kingston valves or by water intake through a special pipeline from a remote water intake unit installed at some distance from the complex.

Main Dimensions of the Desalination Barge

Maximum length, m	72
Width, m	24
Board height, m	10
Draught, m	3.9
Displacement, t	6 400

Water supply to the desalination complex may be carried out by pumps having 1000 m^3/hr capacity each through two independent lines. Each independent line carries the full capacity of water supply for desalination.

At the plant inlet source, seawater is filtered and subjected to chemical treatment. Multi-media filters (one-two-three-layer) with various filtering materials are the main means for source water purification from suspended materials.

Coagulant is usually introduced to the source water prior to the filters to increase purification efficiency (salts of Fl or Al usually). Pretreatment filters are filled with expanded clay aggregate, coal, and quartz sand. After passing through the filters water is subjected to chemical treatment. Final (finishing) purification will be performed by cartridge filters.

An $NHSO_3$ solution which suppresses biological growth on the desalination plant surfaces is introduced to the feedwater system prior to the cartridge filters to protect synthetic materials used in cartridge filters and reverse osmosis components against the action of oxidizers, particularly Na_4ClO.

To prevent creation of scaling on membrane surfaces, acids or anti-scaling inhibitors are added (hexametaphosphate, tripolyphosphate. polyacryl, etc.). Selection of the specific method of chemical treatment, providing the required quality of source water, may be made based on the results of specific examination for the installation site of the complex.

Seawater is supplied to the desalination system by high pressure pumps which take water from the purified water tank and supply it to the desalination units at 6.5 MPa pressure. The tank is provided with regenerative heating of the water up to about 60°C. The pumps operate with 4 independent desalination trains each comprising 9 desalination units. The number of pumps is 4 (including a reserve).

Pump drive is by electric motors and hydro-turbines (Pelton turbines).

High pressure pumps supply seawater, which has been subjected to pre-purification and chemical treatment, to desalination units arranged within the dimensions of an international standard sea container (6.0 m × 2.5 m × 2.6 m).

Each block comprises 150 filter modules. Blocks are combined into trains (nine desalination units each) according to the seawater supply and discharge.

Main Characteristics of Single Train

Number of modules	1 350
Number of units	9
Desalinated water output, m^3/hr	445
Seawater consumption, m^3/hr	1 200

The use of Permacep B-10 type membranes from DuPont is envisaged.

It is anticipated that membrane replacement will be performed every 3 years (3-5 years according to manufacturer's data). To prolong membrane lifetime, a system for periodical membrane cleaning with fresh water is provided. PO "Proletarsky Zavod", St. Petersburg, is the supplier of the desalination units.

4. TRANSPORTATION OF THE COMPLEX TO THE OPERATING SITE

The dimensions of the FNPS and the desalination barge allow them to be placed in the hold of the Danube Sea Steamship Line's "Boris Polevoy" heavy lift ship.

If required, of if the option for transportation by heavy lift ship is not acceptable, delivery of the complex by towing is possible and the complex is provided with all required equipment for this purpose. This transportation scheme is analogous to the towing of docks and crane barges.

5. ECONOMIC ASPECTS

The approximate price of the seawater desalination complex is US$ 93 million, consisting of US$ 70 million for the FNPS and US$ 23 million for the desalination barge.

The approximate specific operating costs amount to US $0.86/$m^3$.

Calculation of the floating equipment construction price was performed with regard to conditions at JSC "Baltiyskiy Zavod", St. Petersburg. Prices were determined on the basis of stock exchange prices with recalculation for the ruble exchange rate.

Preliminary data from equipment suppliers were taken into account for such main components as desalination units, Pelton turbines and high pressure pumps.

Costs for the coastal structures and installation of the complex were determined under conditions of installation in a protected area (wind not greater than 20-25 m/s), at depths allowing installation not more than 20-30 m from the coast, and for duration of transport in the hold of the "Boris Polevoy" not more than 20 days. Arrangement of a system comprising

2 pipelines is envisaged on the coast, at a distance up to 250 m. Storage tanks are not included in the price of coastal structures.

Annual expenditures on the crew are evaluated assuming use of a Russian crew and a cost per crew member of US$ 80/d. Annual costs for repair, supply and maintenance of the complex (excluding replacement of membrane components) were evaluated in percentage of the total price, and amount to approximately 4%.

Costs for replacement of membrane components during the service life of the complex (30 years) are determined assuming their replacement every 3 years.

Prices of chemicals for pretreatment of source water and final treatment of fresh water, as well as of those for membrane component cleaning, were determined by data from DuPont - an anticipated supplier of these chemicals.

Currently, due to increasing the reactor thermal power up to 60 MW, an option is being considered for replacement of the reserve Diesel generators by two additional turbo-generators, increasing the FNPS power up to 24 MW. This would allow production of more than 65 000 m^3/d of fresh water and reduce specific operating expenditures to US \$0.53/m^3.

THE FLOATING NUCLEAR POWER PLANT WITH HIGH SAFETY ("CRUISE-M")

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Abstract

The results of conceptual development for a floating nuclear power plant (FNPP) of 50 MW(e) with a nuclear steam producing unit (NSPU) based on a fast reactor with lead-bismuth coolant were presented. A lead-bismuth coolant has a number of important safety advantages and it was developed in Russia for nuclear-powered submarines. This FNPP could be used as a power source for seawater desalination and electricity supply.

1. INTRODUCTION

After the Chernobyl accident, intensive development of new nuclear power plant concepts has been initiated all over the world. The safety of these plants is primarily based on the reactor's inherent fail-safe characteristics, allowing the most severe accidents to be deterministically eliminated not only in case of safety system failures and operator errors, but also in case of ill-intentioned actions, natural calamities, terrorist attacks, etc.

Fast neutron reactors cooled with liquid-metal coolants fall into this category of reactors whose safety is mainly provided by their inherent fail-safe features. This is a result of a number of typical fast reactor characteristics.

These characteristics, which include a lack of neutron poisoning effects, a low negative temperature reactivity worth coefficient, and compensation for fuel burn-up and fission product formation by plutonium build-up, make it possible to have a low operational reactivity margin and to minimize the risk of reactivity accidents.

Russia possesses unique experience in the development and use of lead-bismuth coolant. This experience has been gained through the development and operation of marine reactors using this coolant. The scientific supervision of this work was carried out by IPPE and the design by EDB "Gidropress".

2. THE CHARACTERISTICS OF A LEAD-BISMUTH COOLANT FAST REACTOR

To achieve a high degree of reactor plant (RP) safety, the choice of primary circuit coolant is of great significance because it determines, to a great extent, the main technical and economic characteristics of the RP design and its facilities. A lead-bismuth coolant has a number of important safety advantages. This coolant was developed in Russia for nuclear-powered submarines.

First, lead-bismuth demonstrates a high boiling point (1 670°C) that eliminates the possibility of a reactor thermal explosion caused by internal pressure, even when heated to a very high temperature. The high boiling point actually rules out the possibility of coolant boiling in the most stressed fuel sub-assemblies, even in case of severe beyond design basis accidents. The void coefficient of reactivity for lead-bismuth coolant is negative.

The high boiling temperature also makes it possible to prevent over-pressurization of the primary circuit due to overheating and to prevent the loss of coolant which would otherwise result from boiling and evaporation in the event of a large circuit loss of tightness. This makes it possible to prevent heat transfer crises and increase the reliability of core cooling.

A low primary circuit pressure permits the use of a fuel pin design with a clearance between the fuel and cladding calculated on the basis of fuel swelling without cladding load, increasing fuel element performance.

The lead-bismuth low chemical activity eliminates the possibility of fires and explosions in the event of a loss of coolant accident, the coolant leakage into the reactor room, steam generator tube leakage and liquid metal-water reactions. It is possible to implement a two-circuit reactor design and improve its technical and economic characteristics.

The low volume decrease with solidification and relatively high plasticity of lead-bismuth alloy permit, when necessary, a planned regime of "solidifying-melting" without deformation and damage to the reactor components.

The use of liquid metal coolant in combination with a monoblock reactor design allows passive decay cooling (when all other possibilities for decay cooling have been lost) through the reactor vessel to the naturally circulating air surrounding the vessel. This avoids excessive core overheating which would damage the core. It provides an additional barrier of protection while transporting the FNPP.

The features of the liquid metal cooled reactor, including the shutdown characteristics determined by reactor physics, the inherent safety and the reactor location in a strong leak tight containment, make it possible to set a minimum exclusion zone radius around the FNPP and to predict a minimum ecological damage under emergency conditions caused by natural calamities and terrorism.

These factors, together with the possibility of FNPP disposal at end-of-life or in the event of emergency failures without any significant environmental impact, make the FNPP highly acceptable from a social point of view, and make it possible to be located near large cities. Due to high fuel burn-up (10%) a fast reactor has a core lifetime without refueling of about 100,000 hours at a full power of 100 MW(th) with a ^{235}U loading of 1,100 kg at 18% enrichment. The parameters which determine the primary circuit and the reactor materials performance, the maximum temperatures, the coolant velocity, the core power density, the fast neutron fluence and the burn-up fraction are assumed to be equal to or less than the parameters usually observed in the course of long-life operation.

3. THE FLOATING NUCLEAR POWER PLANT

The main characteristics of floating nuclear power plant are as follows:

length	49.5 m
width	16.0 m
board height	12.0 m
average draught	8.0 m
displacement	5 000 t
staff members	30

The turbine generator unit (TGU) is based on proven technology. The TGU design has the following characteristics: the inlet saturated steam temperature is equal to 270°C at a pressure of 55 bar (abs), pressure in the condenser is 5 bar (abs), the steam flow rate is approximately 140 t/h and the rotation frequency is 3000 rev/min.

The following FNPP production capacities were achieved in the design using two nuclear power units:

- electrical capacity, MW(e) ~ 25
- rated flow of desalinated water, m^3/day ~ 80 000

4. EXPERIENCE

Studies on the eutectic lead-bismuth alloy and its utilization in nuclear power in Russia have been carried out since 1952. During this period all of the principal problems were solved, such as the development of reactor installations with this coolant, problems of heat exchange and hydrodynamics, coolant technology, corrosion resistance, mass transfer, and many others.

In particular, radiation safety problems in connection with the production of ^{210}Po have been solved. As a result, even with many years of lead-bismuth-cooled reactor operation and under conditions which included primary circuit equipment repair and cleanup of leaked lead-bismuth alloy, there have been no cases of personnel radiation exposure above permissible limits.

A good experimental base equipped with unique facilities has been created. Several industrial nuclear power installations (NPI) have been constructed. These have been used to develop allowable operating regimes, to carry out representative equipment testing, and to resolve reactor installation repair and reloading problems. The total operating time of NPIs with lead-bismuth coolant is approximately 80 reactor-years.

In the course of this work, highly skilled groups of researchers and operating staff have been formed, capable of carrying out in minimum time the development of reactor installations using lead-bismuth coolant.

THE FLOATING DESALINATION COMPLEX GEYSER-1

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Abstract

A conventional floating desalination complex, GEYSER-1, is presented which is capable of producing 40 000 cubic meters per day (m^3/d) of fresh water from brackish water or seawater. The complex includes a water intake system, a preliminary water preparation system, a high-pressure pump house and a power installation based on diesel or a gas turbines with service equipment. GEYSER-1 can be transported to the place of operation either by a heavy lift ship or by towing.

1. GENERAL FEATURES OF THE COMPLEX

The conventional floating desalination complex GEYSER-1 is designed for desalinating brackish water and seawater with a total dissolved solids (TDS) content of up to 41 grams per liter. The complex's output is 40 000 m^3/d of fresh water having a salinity of not more than 500 mg/liter according to international standards for fresh water.

The complex represents a floating installation on which the desalination and power equipment is mounted.

Block Dimensions

Length, m	96.4
Width, m	24.0
Depth, m	10.0
Draught, m	4.3
Displacement, tons	7 900

The dimensions are defined by the requirements for locating the water pretreatment equipment, desalination units, and power plant equipment and systems aboard the ship.

Total displacement and corresponding maximum draught are defined by the requirement for positioning on the inner bottom a series of fuel tanks with nearly 1000 tons of fossil fuel supply.

The complex has to be placed either in areas of naturally protected water (a fjord, a gulf, a lagoon), or a man-made sheltered facility. Water depth must be not less than 6 meters at low tide. The mooring system is capable of providing normal operating conditions for the equipment under sea conditions of up to Beaufort number 3 and wind forces of 40 meters per second.

Plant installation in areas where wind velocity does not exceed 25 m/s (according to historical statistical observations) is possible with application of either standard anchors or using conventional mooring to a floating wharf. Final choice of the type of mooring has to be made depending on the specific conditions at the site. If necessary, an option of mooring in the open seawater area could be considered, but in such a case additional investments would be required that have not been taken into account in the present economic evaluation.

All of the complex's characteristics comply with the rules of the Russian Register for sea vessels.

In addition to the equipment required for mooring in the operating location, the vessel's facilities include equipment for mooring fuel supply and technological service ships. A deck-mounted crane of approximately 3.2 tons rated load capacity allows for loading/unloading replacement equipment during maintenance work.

Fresh water supply, brine discharge and seawater intake are performed through pipes, and the method of laying them is devised to fit site specific conditions. To compensate for movement of the complex due to the sea motion, ball joints equipped with linear compensators, or special flexible hoses are provided. Systems for water intake and pretreatment, a high-pressure pump house and a diesel (or, possibly, gas turbine) power plant with service systems are components of the floating desalination complex. The complex's equipment is housed in four ship's compartments.

2. WATER INTAKE SYSTEM

Depended on site specific conditions, the water intake could be directly through the vessel's sea bays or through special piping from a remote intake.

Water supply to the desalination complex is performed by D1 600-90 type pumps of 1000 cubic meters capacity each, through two independent pipes, with each pipe being capable of providing full production capacity.

Water intake by pumps is carried so as to attain maximum removal of impurities in the water intake path. A specific layout of the water intake path would be chosen (e.g. with cyclone separators, outer filters, etc.) which would help provide maximum efficiency of water purification, as the situation requires.

3. FEED WATER PRETREATMENT SYSTEM

The raw seawater entering the feed water pretreatment system is filtered and put through a chemical treatment process.

The basic means of removal of suspended impurities from the raw water is multi-media filters (single-, double-, or triple-layer). To increase the efficiency of filtration, a coagulating agent, typically Fe or Al based salts, is injected into the raw water. The filters are filled with expanded clay aggregate, coal and silica sand. Once the water has been filtered, it is put through chemical treatment. The filters are placed in separate cases. Final purification would be done using cartridge filters.

To prevent synthetic materials (which form part of cartridge filters and reverse osmosis elements) from affecting oxidants (in particular, $NaClO$), a solution of $NaHSO_3$ (which also suppress the biological processes on the surface of the desalinating installation) is added to the feed water entering the filters.

The addition of acids or inhibitors to the raw water (hexametaphosphate, tripolyphosphate, polyacryl and others) eliminates the deposition of chemical elements, inherent in the raw water, on the membrane surfaces. The choice of specific water treatment regime providing the required quality of raw water can be established from the results of site specific tests.

4. HIGH-PRESSURE PUMP HOUSE

Seawater supply to the desalination units is performed by high pressure pumps. SPE1650-75 type pumps take water from the purified water tank and feed it to the desalination unit at a pressure of 6.5 MPa. The water in the tank is regeneratively preheated up to a temperature of 60 degrees Celsius. The pumps feed four independent assemblies, each of them consisting of nine desalination units. The pump's output is nearly 500 cubic meters per hour, and the total number of high pressure pumps is six, taking into account two reserve pumps.

5. DESALINATION UNITS

Pretreated seawater is fed by high pressure pumps to the desalination units arranged within the confines of an international class sea container having dimensions of 6.0 by 2.5 by 2.6 m. Each unit comprises 150 tubular membrane filtration elements, each having an output of 0.33 cubic meters per hour and 99 per cent salt rejection. To match the seawater supply and fresh water production rates, the units are grouped in four independent assemblies, of nine desalination units per assembly.

General Features of Assembly

Number of membrane elements	1 350
Number of units	9
Fresh water output, m^3/hr	445
Raw water consumption, m^3/hr	1 270

It is proposed to equip the desalinating units with DuPont membranes.

Detailed information on the desalination units can be provided by the manufacturer, PO Proletarsky Zavod, St. Petersburg.

6. ELECTRIC POWER INSTALLATION

Power requirements for the desalination unit's pumps are roughly 13 700 kW (8.2 kW·h/m^3). When used in the brine discharge line, an energy recovery turbine can reduce the electric power consumption to about 10 500 kW (6.2 kW·h/m^3).

An electrical power supply system consisting of five ADG-5000 diesel generators, manufactured by PO "Russky Diesel", St. Petersburg, is incorporated in the complex.

General Features of the ADG-5000 Diesel Generator

Rated power, kW	5 000
Electric current parameters	
Voltage, kV	6.4
Frequency, Hz	50
Specific fuel consumption, grams/kW·h	205
Overhaul period, hours	11 000
Original life, hours	60 000

The motors operate on a heavy fuel.

Using a set of spare parts and accessories supplied, it is possible to repair the diesel generators without removing the complex from operation. The electric power distribution system permits the paralleling of any three generators. In addition, a potion of the electric power can be supplied for shore loads, and a gaseous fuel could be used for the motors.

The fuel storage in the onboard fuel tanks guarantees 15 days of operation. The fuel storage can be expanded to 25 to 30 days, as an option, with a corresponding increase in draught and displacement.

7. TRANSPORTING THE COMPLEX TO THE PLACE OF OPERATION

The general dimensions of the complex permits placing it in the hold of the heavy lift ship "Boris Polevoy". Preliminary discussions regarding the transportation of an analogous object had been carried out in 1990, with a positive result. The speed of the heavy lift ship is 14 knots.

When the occasion requires, if transportation by heavy lift ship is too expensive, the complex could be towed by sea. The transportation scheme is analogous to the one for docks and non-propelled crane ships, and will be presented in the project.

8. ECONOMICAL ASPECTS

It is planned that the complex be manufactured at Baltsudoproekt, St. Petersburg. The cost of building the complex were calculated based on shipyard construction. Market pricing has been used to establish basic prices for raw materials and standard equipment.

The prices for desalination units, diesel generators, Pelton turbines and high pressure pumps reported by their manufacturers have been used in the evaluation. The cost of the complex would be US $22 million. The raw materials, spare parts and subcontractor services would cost about US $11.5 million. The costs for transportation, coast preparation and placement of the complex depend on the site specific conditions.

If a location is chosen where the wind force does not exceed 20 meters per second, and the depth allows for placing the complex no further than 50 to 100 meters from the coast, and if the transportation time by a heavy lift ship of the "Boris Polevoy" class does not exceed 20 days, then general expenses for manufacturing the desalination complex might run as high as US $23.5 million.

The price of fuel has been estimated both for the case of energy recovery (with a hydraulic turbine) and without energy recovery.

With the cost of the heavy fuel at US $120 per ton and a specific fuel consumption of 215 grams/kW, the annual expenses for fuel and lubricating oil would be:

–	with energy recovery	US $3.22 million
–	without energy recovery	US $2.29 million

The maintenance crew amounts to 21 men. The annual expenses for the crew are estimated, provided that a Russian crew is employed and the salary of a crew member is US $80 per day. General annual expenses for the crew would be US $610 000. The annual expenses for repair, technical services and maintenance, with membrane elements *replacement excluded, is estimated in terms of per cent and is equal to US$ 0.8 million.*

The annual cost of membrane element replacement during the 25 year service life would be equal to US $1.7 million, if the set of elements for a 40 000 m^3/d output is replaced every 3 years, and their cost is US $5 million.

The cost of chemicals for pretreatment of the raw water, final treatment of the fresh water and membrane element scale removal should be nearly US $0.33 million, according to information provided by DuPont.

The annual operating expenses are as follows:

–	with energy recovery	US $6.7 million
–	without energy recovery	US $5.83 million

The specific expenditures for desalinating 1 cubic meter of seawater with the proviso that the initial investments are repaid in 6.5 years, would be:

–	with energy recovery	US $0.78 per cubic meter
–	without energy recovery	US $0.70 per cubic meter

After examining site specific conditions, the options for accommodating the crew onboard the floating complex, expanding the fuel storage, and supply of a portion of the electric power for coastal loads can be studied to suit the client's requirements.

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A FLOATING COGENERATION SYSTEM USING THE RUSSIAN KLT-40 REACTOR AND CANADIAN REVERSE OSMOSIS WATER PURIFICATION TECHNOLOGY

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Abstract

As the global consumption of water increases with growing populations and rising levels of industrialization, major new sources of potable water production must be developed. To address this issue efficiently and economically, a new approach has been developed in Canada for the integration of reverse osmosis (RO) desalination systems with nuclear reactors as an energy source. The use of waste heat from the electrical generation process to preheat the RO feedwater, advanced feedwater pre-treatment and sophisticated system design integration and optimization techniques have lead to improved water production efficiency, lower water production costs and reduced environmental impact.CANDESAL Inc. has studied the use of its approach to the application of RO technology in the Russian APWS-80 floating nuclear desalination plant. Case studies show that water production efficiency improvements up to about 16% can be achieved. The energy consumed for the CANDESAL optimized APWS-80 design configuration is 4.2 kW·h/m³ compared to the base APWS-80 design value of 4.9 kW·h/m³. Although only a preliminary study, these results suggest that significant improvements in the cost of water production can be achieved. The potential benefits warrant further detailed evaluation followed by a demonstration project.

1. INTRODUCTION

As the global consumption of water increases with growing populations and rising levels of industrialization, major new sources of potable water production must be developed. Desalination of seawater is already in widespread use. However it is an energy intensive process which brings with it a demand for additional energy generation capacity. CANDESAL has developed a new approach for integrating reverse osmosis (RO) desalination systems with nuclear reactors as an energy source. This integrated system addresses both requirements through the optimized cogeneration of both water and electricity. Using waste heat from the electrical generation process to preheat the RO feedwater improves the efficiency of the RO process. By also using advanced feedwater pre-treatment and sophisticated system design integration and optimization techniques, an overall improvement in efficiencies, costs and environmental impact is achieved.

Originally developed using the CANDU reactor as an energy source in order to meet large scale water production demands, on the order of several hundred thousand cubic meters per day, the CANDESAL design approach has been developed in a manner which also allows its application to other reactor types and sizes. One such reactor of particular interest is the Russian Federation's KLT-40, which has been used successfully for many years as a marine nuclear propulsion plant. Russia has developed the APWS-80 floating nuclear desalination station design based on a pair of these reactors coupled with seawater desalination using a distillation process. They have also considered a design based on a conventional reverse osmosis process.

The unique CANDESAL approach can be utilized to develop a floating cogeneration station based on the KLT-40 reactor and Canadian RO water purification technology. Integrating the reactor and RO systems into a single cogeneration facility allows for a design in which the full benefits of design optimization and system integration, including RO feedwater preheat, can be fully realized. These benefits include reduced plant capital cost, longer RO membrane lifetimes resulting in a reduced membrane replacement requirement, reduced operating and maintenance costs, improved energy efficiency and reduced water production costs. This "marriage" of Canadian and Russian technologies 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 on the order of a hundred thousand cubic meters per day or less, and where a need for additional electrical generation exists but existing electrical grids can not absorb the supply from larger nuclear generating stations.

2. SYSTEM SCHEMATICS

Figure 1 shows a typical installation of a KLT-40 reactor installed as a base load generator, providing electrical supply to the grid with the condenser cooling water discharge serving as a preheated feedwater supply to an RO system. This simplified schematic is then integrated into the schematic RO desalination system shown in Figure 2, where both ultrafiltration (UF) and chemical pretreatment of the heated input water is used to provide feedwater to high pressure RO membranes. A concentrate energy recovery systems is included, reducing the electrical consumption required for water production. Chemical post-treatment provides the desired chemical quality in the potable water product stream before it enters the distribution system.

3. METHODOLOGY

Using previously reported characteristics for a KLT-40 type floating nuclear power station coupled with a desalination plant [1] as a guide, a "Base Case" RO system configuration was established. This Base Case represented a design configuration which would match the reported performance characteristics at ambient inlet seawater conditions of 18°C and 38 500 parts per million (ppm) of total dissolved solids (TDS). The RO system feedwater flow rate for the Base Case was set equal to the reactor's condenser cooling water flow rate, which was determined to be 241 200 m^3/d at a fixed Δt of 10°C. Three case studies were then conducted using this constant condenser cooling flow as the feed flow to the RO system. Table 1 summarizes the case study analysis conditions. The three cases considered were:

- Case 1: Potable water production with preheat alone
- Case 2: Preheat with some design reconfiguration
- Case 3: Optimized design configuration

The results of these case studies are displayed in Figure 3, which shows a significant increase in potable water production rate relative to the Base Case for each of the three case studies. Figure 4 displays the Case 1-3 results relative to the Base Case water production rate.

4. MEMBRANE PERFORMANCE

The results obtained from the case studies indicate a significant performance improvement as a result of preheating the RO system feedwater and the system design optimization. These analyses were carried out at the level of a fully configured system. To provide additional assessment of the effect of preheat, performance analyses were carried out at the membrane level. For these calculations an ambient seawater temperature of 25°C and a seawater TDS of 42 000 ppm were assumed.

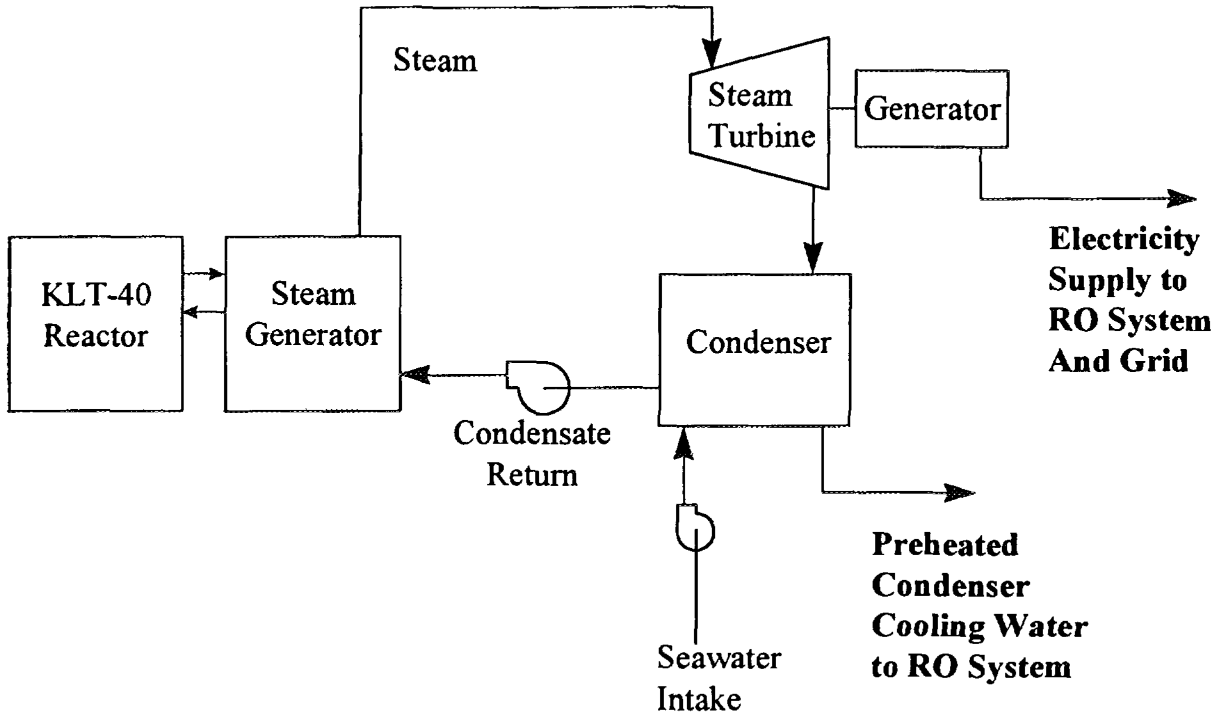

Fig. 1. Simplified schematic flow diagram of the KLT-40 reactor as an electrical generating station.

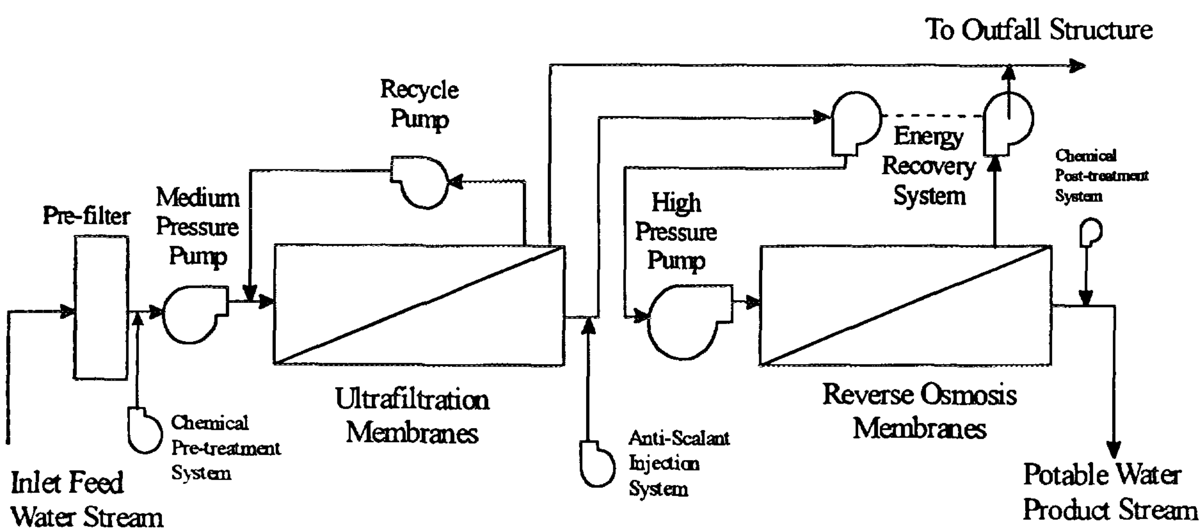

Fig. 2. Simplified schematic flow diagram of UF/RO desalination system.

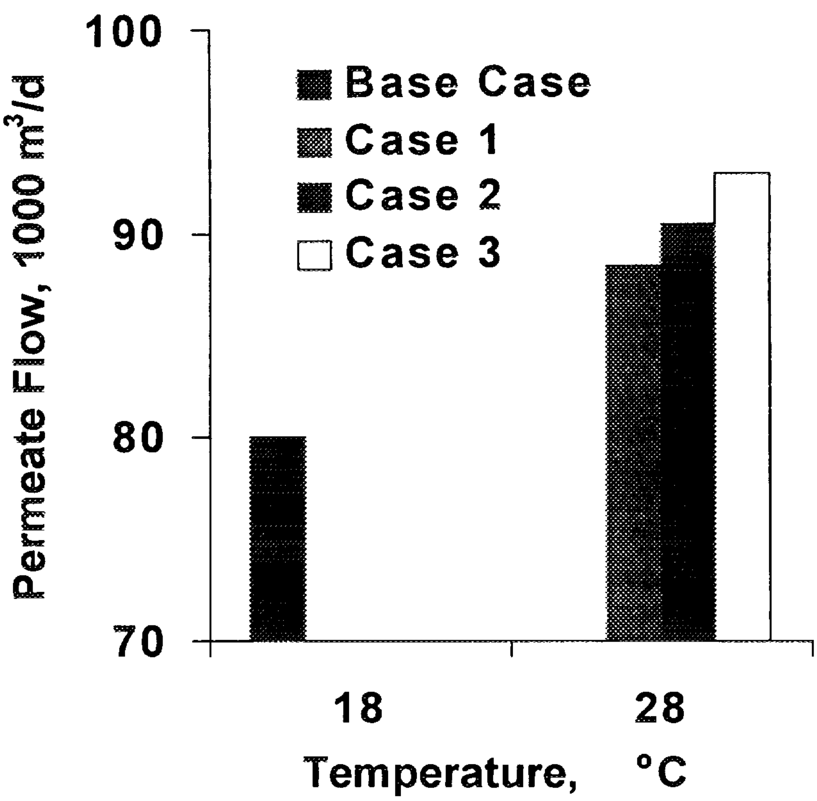

Fig.3. Effect of feedwater preheat and design optimization on permeate flow.

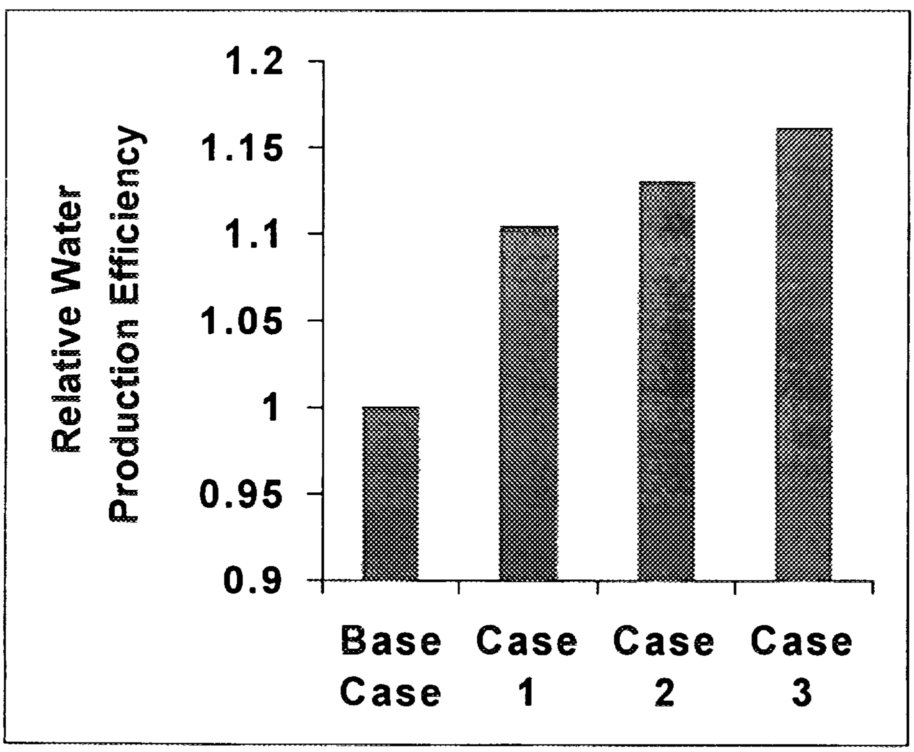

Fig. 4. Water production efficiency relative to base case.

TABLE 1. CASE STUDY ANALYSIS CONDITIONS AND ASSUMPTIONS

Reactor Plant Characteristics	
Reactor power, MW(th)	160
Net electrical power, MW(e)	65
Condenser cooling water flow, m³/d	241 200
Condenser Δt, °C	10
Ambient Seawater Conditions	
Temperature, °C	18
TDS, ppm	38 500
Desalination Plant Characteristics	
Feedwater flow (all cases), m³/d	241 200
Operating pressure, bar	69
Feedwater temperature (Base Case), °C	18
Potable water production (Base Case), m³/d	80 000
Specific energy consumption (Base Case), kW·h/ m³	4.9
Feedwater temperature (Cases 1-3), °C	28

Relative potable water production efficiency for an RO membrane was then calculated for feedwater preheat temperatures of 5, 10 and 15°C. The results are plotted, as a function of the resulting RO membrane feedwater temperature, in Figure 5 for a membrane operating at 1000 psi (69 bar). As an alternative characterization of membrane performance improvement, the RO feedwater flow requirement to maintain a constant value of membrane flux (i.e., potable water production rate) as a function of feedwater temperature was also calculated. The results of that analysis are displayed in Figure 6.

5. CONCLUSIONS

The results of these case study analyses are summarized in Table 2. The three case studies are presented along with the base case.

In view of these results it can be concluded that:

TABLE 2. SUMMARY OF CASE STUDY ANALYSES

	Base Case	Case 1	Case 2	Case 3
Total feed flow, m³/d	241 200	241 200	241 200	241 200
No. of UF/RO trains	8	8	9	9
Feed flow/train, gpm	4 974	4 974	4 421	4 421
UF/RO recovery, %	33.2	36.6	37.5	38.5
No. of RO vessels/train	176	176	140	150
Permeate flow/train, m³/d	10 000	11 050	10 050	10 320
Total permeate flow, m³/d	80 000	88 390	90 380	92 890
Relative permeate flow	1.0	1.104	1.129	1.161
Energy consumed, kW·h/m³	4.9	4.43	4.34	4.22

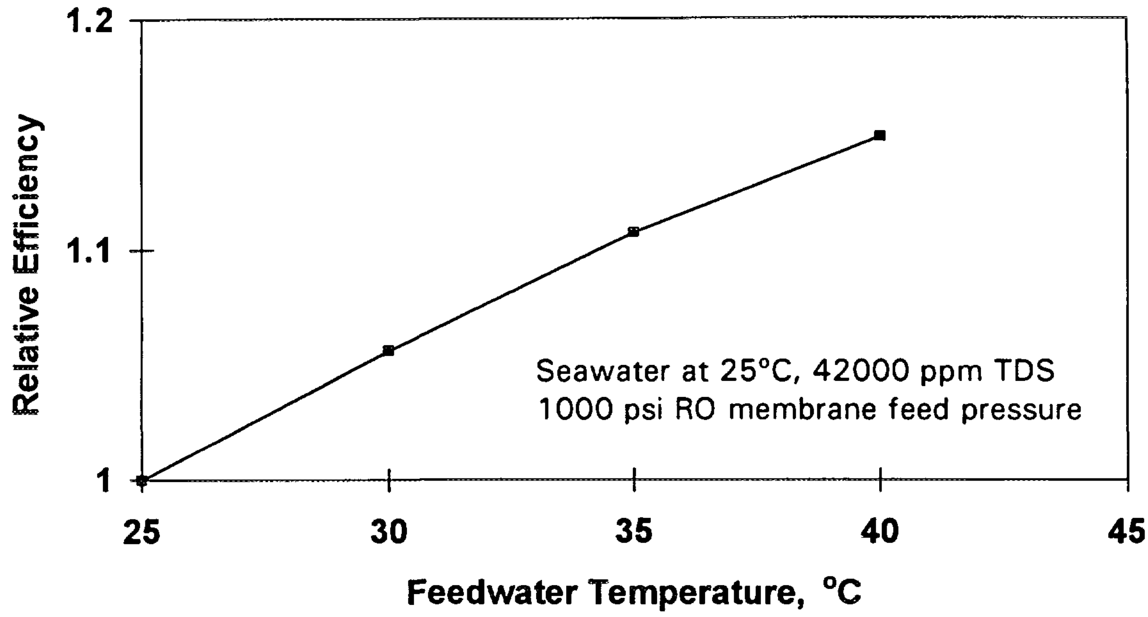

Fig. 5. Relative improvement in RO membrane due to feedwater preheat.

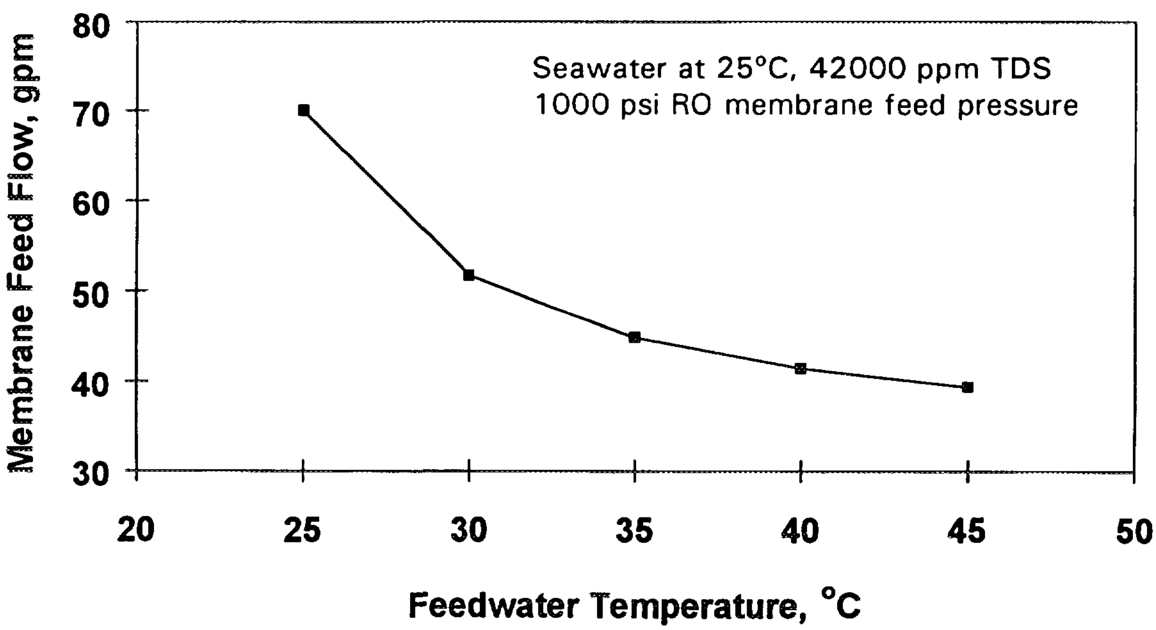

Fig. 6. Required membrane feed flow to maintain constant permeate flux.

1. Although this is a preliminary study, it has demonstrated clearly the improvements which can be achieved using the CANDESAL design methodology with the KLT-40 reactor.
2. Water production efficiencies are increased and energy consumption is reduced as a result of UF/RO system feedwater preheat and design optimization.
3. The "marriage" of Russian small reactor technology with Canadian RO technology leads to improved economics in small scale nuclear desalination systems.
4. The concept is equally viable for floating units or for small stationary units in developing areas where:
   a. Water requirements are less than 100 000 m^3/d
   b. The electrical grid is not adequate to absorb energy from a larger nuclear power station.
5. The net environmental burden is reduced by improving the efficiency of energy utilization.
6. The potential benefits identified in this study warrant further detailed evaluation followed by a demonstration project.

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A SMALL FLOATING SEAWATER DESALINATION PLANT USING A NUCLEAR HEATING REACTOR COUPLED WITH THE MED PROCESS

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Abstract

A small floating seawater desalination plant using a nuclear heating reactor coupled with a multi-effect distillation (MED) process was designed by the Institute of Nuclear Energy Technology, Tsinghua University of China. It was intended to supply potable water to remote coastal areas or islands where both fresh water and energy are severely lacking, and also to serve as a demonstration and training facility. The design of a small floating plant coupled two proven technologies in the cogeneration mode: a nuclear heating reactor (NHR-10), with inherent, passive safety features based on NHR-5 experience, and a low temperature MED process. The secondary loop was designed as a safety barrier between the primary loop and the steam loop. With a 10 MW(th) heating reactor, the floating plant could provide 4 000 m³/d of potable water and 750 kW of electricity. The design concept and parameters, safety features, coupling scheme and floating plant layout are presented in the paper.

1. INTRODUCTION

Some remote coastal districts or islands, or some coastal or island tourist areas, which are lacking in both potable water and energy source have shown strong interest in potable water production by seawater desalination using nuclear energy. In cases where there is not an adequate infrastructure for constructing nuclear installations, or nuclear a complex is not intended to be permanently installed, a small floating nuclear plant for seawater desalination may be a suitable solution.

In this paper a small floating plant for seawater desalination using a 10 MW(th) nuclear heating reactor (NHR-10) coupled with the multi-effect distillation process is proposed and is recommended as a demonstration and training facility.

The following multi-purpose usage of this demonstration project would be considered as the design objective:

- For potable water production: supply 4 000 M³/d of potable water to a small coastal district, while supplying 750 kW of electricity for the plant itself;
- As a technical personnel training center on design, construction and operation of an advanced nuclear heating reactor, providing a small nuclear power plant with heat/electricity cogeneration and a seawater desalination plant using nuclear energy;
- As a short term, mobile full scope demonstration facility for seawater desalination using nuclear energy.

The design of the seawater desalination plant using a nuclear heating reactor presented in this paper is based on the proven technology and experience of NHR-5 (a 5 MW prototype nuclear heating reactor) [1], developed by the Institute of Nuclear Energy Technology (INET), Tsinghua University. The NHR-5 has been successfully operated for 6 winter seasons since 1989. Heat and electricity cogeneration with NHR-5 [2] was also carried out from 1991 to 1992. Very good operating characteristics and excellent safety features are demonstrated, with high operational availability, inherent safety and self-regulating characteristics. Operating in cogeneration mode, the total complex (NHR-5 coupled with a turbine generator and heat grid) exhibited perfect operating stability, self-regulating performance and load-following characteristics. The MED process is a commercially well established and proven technology.

In order to verify adaptability (suitability) of the hydro-driving system (HDS) for control rods under marine conditions, a research program [3] on behavior of the HDS under inclining and rocking conditions was executed in 1992.

In order to investigate the coupling scheme and technology the nuclear seawater desalination experiment using NHR-5 coupled to a small MED unit is currently being carried out and adopted as a limited scope demonstration.

Based on the technology and experience of NHR-5 and of the limited scope demonstration, the floating NHR-10 MED project for seawater desalination would also be logical as a satisfactory full scope demonstration plant and could be successfully implemented in the short term.

2. BRIEF DESCRIPTION OF THE NHR-10 NUCLEAR HEATING REACTOR

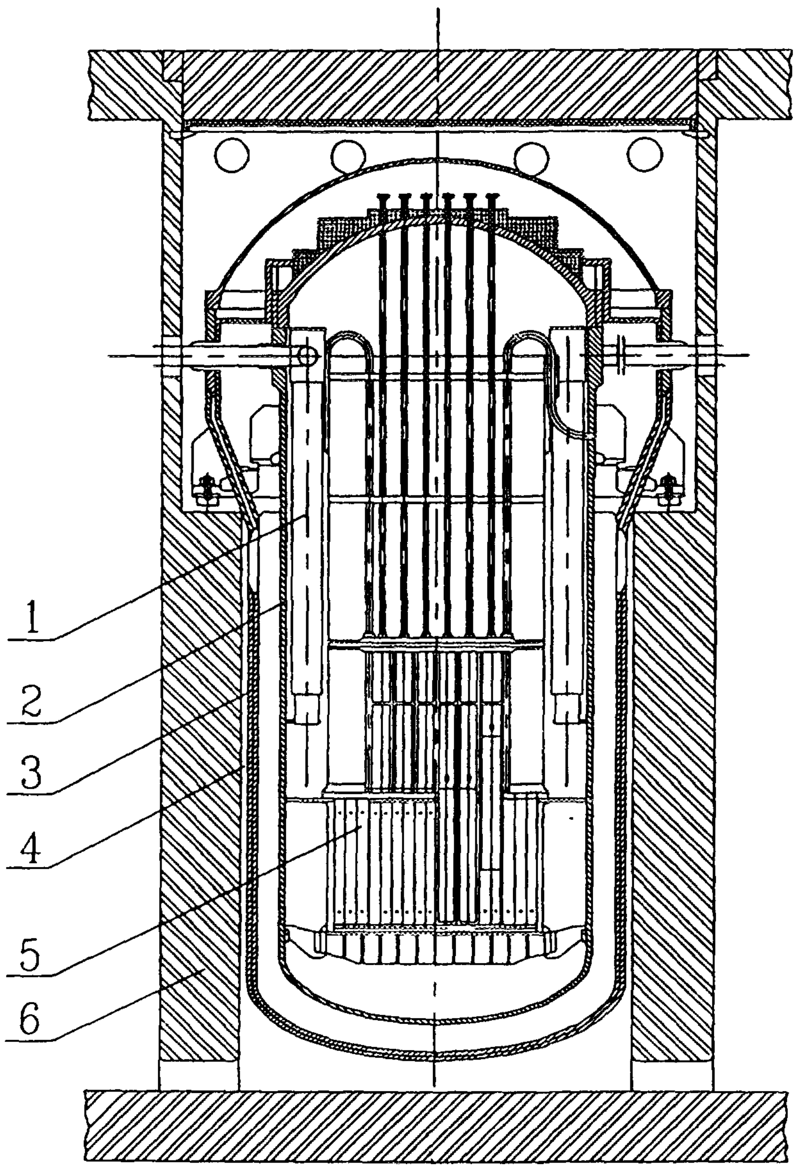
The NHR-10 is a vessel type, pressurized water reactor with integrated design of primary circuit in pressure vessel. The reactor core is cooled by light water with natural circulation and the primary system is with self-pressurization performance. The reactor structure is shown in Fig. 1.

The reactor vessel is designed with a 2.5 MPa operating pressure. The core is located at the bottom of the vessel. There is a riser above the core outlet used to increase the driving force for natural circulation. There are eight primary heat exchangers arranged in the annular space between the riser and vessel. The heat carried over from the core is transferred to the intermediate circuit via primary heat exchangers.

There are 25 fuel assemblies and 16 cruciform control rods in the core. Two kinds of assemblies are used, with 96 fuel elements and 35 fuel elements respectively. The active length of a fuel element with cladding of Zircaloy-4 is 750 mm. The diameter is 10 mm. The nuclear fuel is uranium dioxide with an enrichment of 3% .

The reactivity is controlled by a combination of fixed burnable poison, movable control rods and the negative temperature coefficient of reactivity. The control rods are driven with a specially designed hydraulic driving system, which consist of a hydraulic circuit located outside the containment, a hydraulic step cylinder in the core and two control units. When reactor shutdown is needed, the control rods would drop down into the core, driven by gravity (designed on a "fail-safe" principle). A borate solution injection system is designed as the reserve shutdown system, initiated from a pressurized gas source in the event of an ATWS.

The heat transfer system of the NHR-10 is composed of three circuits, including the integrated primary circuit in the pressure vessel, the intermediate circuit and the steam circuit. The intermediate circuit, in between the primary circuit and the steam circuit, is set with an operating pressure higher than that in the primary circuit. Therefore, it would serve as a barrier and protect the steam circuit from radioactive contamination.



1. Primary heat exchanger 2. RPV 3. Containment

4. Thermal isolation 5. Reactor core 6. Biological shield

Fig. 1. Vertical section of the NHR-10.

A passive residual heat removal system connected with the intermediate circuit is designed to safely disperse residual heat.

The main parameters of the NHR-10 are shown in Table 1.

TABLE 1. MAIN PARAMETERS OF THE NHR-10

Reactor power (th)	MW	10
Pressure in primary circuit	MPa	2.5
Core outlet temperature	°C	213
Core inlet temperature	°C	165
Number of fuel Assembles in core		25
Enrichment of fuel	%	3
Diameter of the fuel rod	mm	10
Average power destiny	kW/l	27

3. SAFETY CONCEPTS AND FEATURES OF NHR-10

The NHR-10 is a new generation nuclear reactor. It's main design features are selected to emphasize inherent and passive safety characteristics, and to improve availability through simplification of systems.

(1) Integrated design and self-pressurization.

The main components of the primary circuit, such as the reactor core and primary heat exchangers, are integrated into the pressure vessel so as to avoid the risk of large pipe breaks. A large volume filled with steam and gas in the upper part of the pressure vessel of NHR-10 is used for self-pressurization to keep the reactor at a pressurized condition. The self pressurization is achieved by the partial pressure principle of inert gas and steam.

(2) Compactly arranged dual pressure vessel.

(3) Natural circulation in primary circuit.

The reactor core is cooled by water with natural circulation. A riser is set on top of the core to increase the driving force for natural circulation. The use of natural circulation can reduce reliance on a primary circulation pump and lead to increased reactor operating reliability.

(4) Low power density and large water inventory of reactor.

The core power density of the NHR-10 is 27 kW/l, about 1/3 ~ 1/4 that of typical PWR power density. The water inventory in the pressure vessel is quite large. The ratio of water volume to core power is about 1 m^3/MW, which is about 20 times that of a PWR. As the water inventory in the primary system of NHR-10 is much larger than that of a PWR and the pressure, as well as the temperature, of NHR-10 is much lower, it has good characteristics to protect the reactor from a loss of coolant accident.

(5) Hydraulic control rod driving system with passive safety.

A specially designed hydraulic control rod driving system is adopted in NHR-10. It is enclosed in the pressure vessel without penetration of the pressure vessel head. Hence a control rod ejection accident can be avoided. The hydraulic control rod driving system has been successfully operated in NHR-5 for six years. Operating results have shown that it is safe, reliable and simple in structure.

(6) Passive residual heat removal system.

A passive residual heat removal system is adopted for NHR-10. The residual heat can be dissipated from the core to atmosphere by natural circulation.

(7) Intermediate circuits are set up to protect the steam circuit from radioactive contamination.

(8) Emergency core cooling and emergency water make-up systems are not needed due to the above mentioned inherent and passive safety features, leading to a system that is simpler and lower cost.

4. NHR-10 DESALINATION PLANT

The NHR-10 desalination plant consists of a 10 MW heating reactor coupled to a seawater desalination facility using a low temperature, horizontal tube type MED process. The NHR-10 is used as the heat source, operating in a cogeneration mode. A power conversion system is installed in the intermediate circuit to supply electricity to the plant.

TABLE 2. MAIN PARAMETERS OF THE SDP

Reactor thermal power	MW(th)	10
Electrical power	MW(e)	0.75
Core outlet temperature	°C	213
Core inlet temperature	°C	165
Outlet temperature at intermediate circuit	°C	170
Inlet temperature at intermediate circuit	°C	155
Steam temperature at outlet of steam generator	°C	153
Steam temperature at inlet of steam turbine	°C	150
Turbine back pressure	MPa	0.0386
Steam temperature at MED first effect	°C	75
Capacity of unit	m^3/d	2 000
Number of units		2
Number of effects		15
GOR		12
Maximum water production	m^3/d	4 000

Steam from the steam generator flows to a turbine with a back pressure 0.0386 MPa of P_B . Saturated steam with a temperature 75°C of T_B from the last stage of the turbine is supplied to the first effect of the MED process. A schematic diagram of the small desalination plant (SDP) with cogeneration is shown in Fig. 2, and the main parameters listed in Table 2.

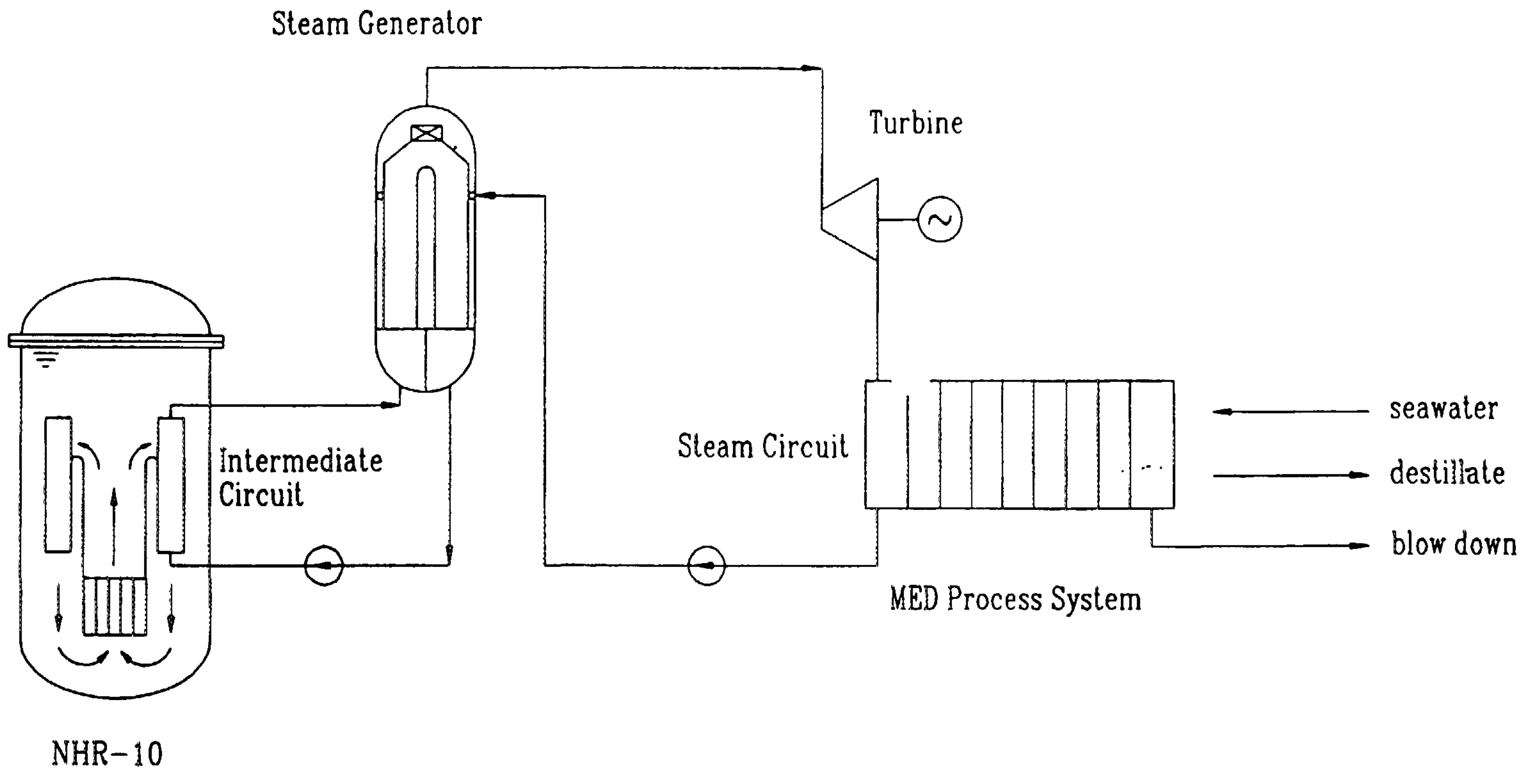


Fig.2. Schematic diagram (cogeneration) of the NHR-10 desalination system.

In the cogeneration operating mode, the desalination plant could supply 750 kW of electricity for the plant itself, and therefore be much less dependent on the local power grid.

The NHR-10 nuclear desalination system is mounted on a ship. It could also be considered for mounting on a barge. The conceptual plant layout diagram is shown in Figs 3 and 4. The size of the floating plant is listed in Table 3.

TABLE 3. PARAMETERS OF THE FLOATING DESALINATION PLANT

Length	m	80
Hull height	m	10
Width	m	16
Draught	m	6
Total Displacement	ton	5 000

5. SPECIAL CONSIDERATIONS

Suitability of the control rod hydro-driving system (HDS) for shipboard application should be verified. For this purpose a research program was executed in 1992. The HDS was fixed on a rocking tet facility with 6 degrees of freedom, and a series of experiments were performed. The test results show that the HDS can operate normally and safely under rocking conditions:

(a) The hydraulic step cylinder has a good hydraulic locking property. It can keep the control rod in a fixed position under rocking and pitching conditions.
(b) With a rocking angle of ±5°, the control rod can normally move up and down step by step.
(c) With an inclining angle 45° or a rocking angle less than 45°, the control rod can smoothly fall into reactor core by gravity.

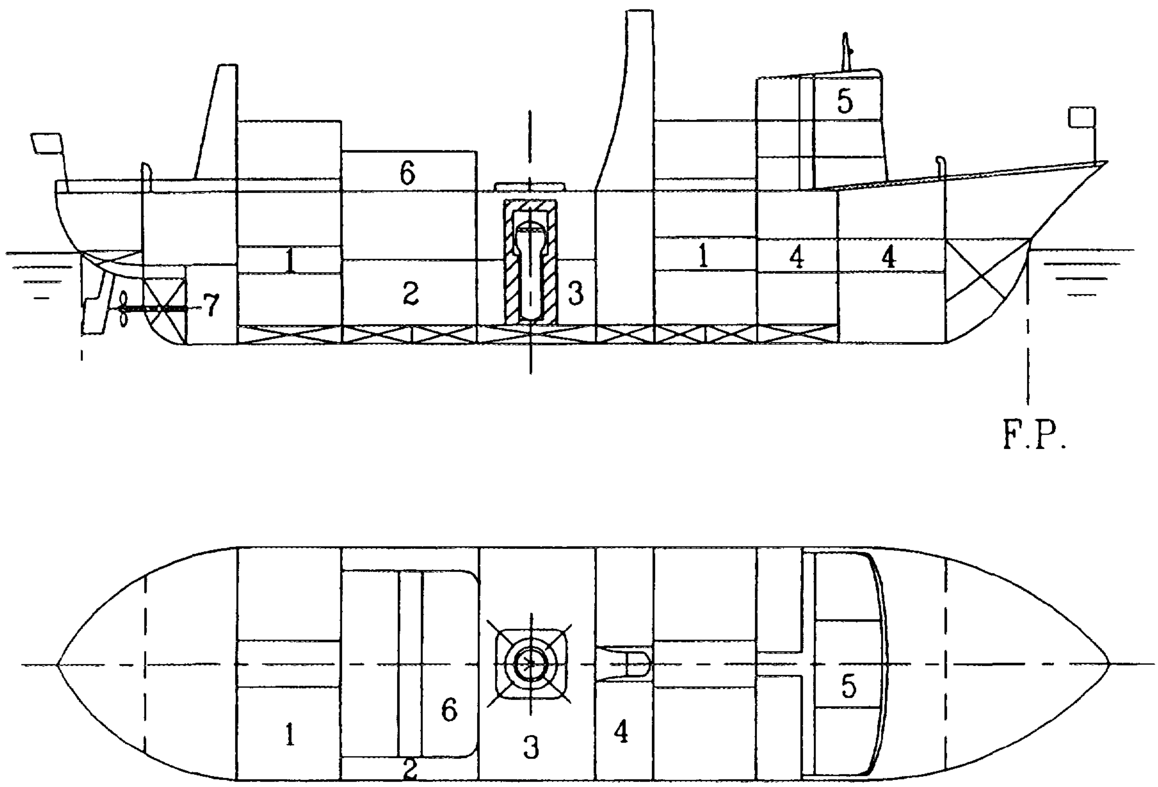
The suitability of natural circulation for marine conditions needs to be analyzed and investigated. The preliminary results show that under a rocking or inclining angle within 30° and with low frequency rocking conditions, the behavior of natural circulation would not be significantly influenced by rocking or inclining.

6. REGULATORY AND LOCAL PARTICIPATION

6.1. Regulatory

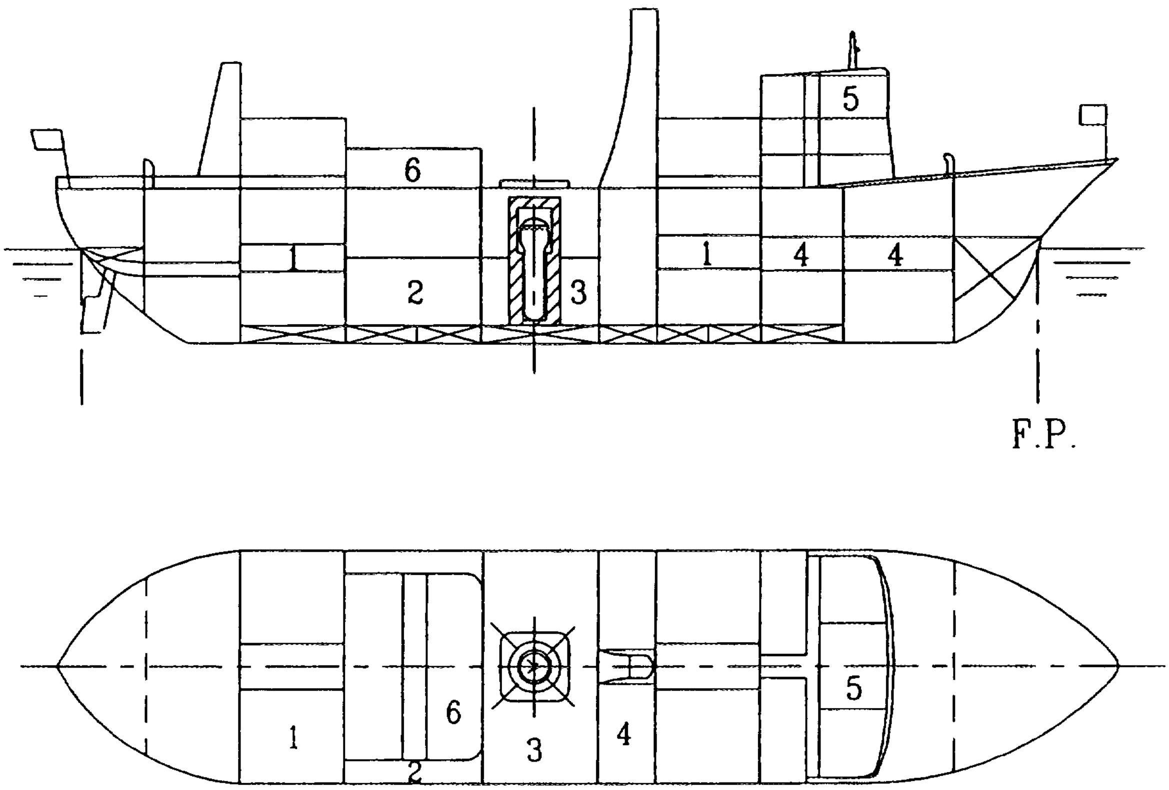
The rules, codes, guidelines and technical documents used in the design, construction, manufacturing and operation of the NHR-10 heating reactor are approved and issued by the China Nuclear Safety Administration (CNSA), and are compliant with those of the IAEA for light water reactors.

The codes adopted in the design and manufacturing of the NHR equipment are in compliance with the prevailing ASME code.



7	Engine compartment
6	Control room
5	Driver's cab
4	Living compartment
3	Reactor compartment
2	Auxiliary system compartment
1	Desalination plant

Fig. 3. Layout of the NHR-10 floating plant.



6	Control room
5	Driver's cab
4	Living compartment
3	Reactor compartment
2	Auxiliary system compartment
1	Desalination plant

Fig. 4. Layout of the NHR-10 floating plant.

6.2. Manufacturing capability requirements for the NHR-10

Due to the lower design parameters (low pressure, low temperature) and the simplification of the NHR-10 system, a sophisticated manufacturing infrastructure is not required. It would not be difficult for any country with the ability to manufacture a 15 MW conventional power plant to manufacture the components of the NHR-10. The following manufacturing capability would be required:

- Crimping machine for steel plate over 50 mm in thickness.
- Vertical lathe over 3 m in diameter.
- Thermal treatment furnace with 2.5×2.5 section , 7 m long.
- Crane with 50 T of lifting capacity.
- X-ray inspection equipment for steel plate over 50 mm in thickness.

6.3. Favorable for local participation

A number of advantages in the design of the NHR-10 desalination plant would facilitate local participation of a developing country:

(1) Requirement for technical personnel.
The passive safety performance, lower parameters and simplified system of the NHR-10 desalination plant would be beneficial for training technical personnel in design, construction, operation and maintenance.

(2) Small size of plant.
For a small floating seawater desalination plant using the NHR-10 heating reactor coupled to a small MED system having a 4000 m^3/d potable water production capacity, the capital investment cost of the complex would be rather easily funded and the project could be implemented in the short term.

(3) The reduced requirement for manufacturing infrastructure, as mentioned above, could facilitate the building and management through local participation.

(4) Prevailing regulatory.

7. CONCLUSION

A small floating seawater desalination plant using the nuclear heating reactor NHR-10 coupled with an MED process could be a suitable solution to supply potable water to remote coastal districts or islands due to its inherent safety, simplification in structure, proven technology, acceptable investment cost and water cost. It is also recommended as a short term, full scope demonstration and training facility.

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THE EFFECT OF MSF OPERATING CONDITIONS IN A DUAL PURPOSE PLANT ON THE SYSTEM FLEXIBILITY

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Abstract

Methods used to combine MSF (Multistage Flash Evaporator) to a nuclear power plant are studied and evaluated. While the back pressure turbine scheme is better for base load, the "steam extraction in condensing turbine" scheme is more flexible with partial load. Simple thermodynamic relations are used to study the effect of changing the water demand and the top brine temperature (TBT) on the specific energy consumption per ton of product water. The energy cost of product water in a typical dual purpose plant design is calculated for each scheme using recirculation type MSF. In the calculations, it is assumed that the energy consumed in the MSF is compensated by additional steam supplied to the turbine from the Nuclear Steam Supply System (NSSS). The cost of energy consumed by recirculation pumps and air ejectors is taken into consideration.

1. INTRODUCTION

With rising costs and decreasing supply, the energy consumed by a desalination plant has taken an increased importance in optimization studies. One of the ways to save energy is the use of dual purpose plants for power production and water desalination. In a dual purpose plant, substantial energy savings can be achieved by the use of extraction steam from a steam turbine to heat the brine [1, 2].

The maximum brine temperature in a distillation plant is limited by having an economic means of scale control. On the other hand, the generating costs of electric power plants are lowest when the steam is produced at higher temperatures. Early studies proved the thermodynamic and economic advantages of dual purpose plants [3-5]. Recently, studies based on the second law of thermodynamics showed that about 60°C of thermal energy required for MSF plants may be saved in the case of dual purpose plants using steam turbines [6]. Moreover, cheaper water may be produced in plants using waste heat from gas turbines [7].

The water cost in a dual purpose plant is strongly affected by the method of desalination as well as the water to power ratio. This ratio is changeable to give enough flexibility to both power and water demands. Researchers concerned with the economics of desalted water investigated the costs of water produced by different desalting methods [8-11].

For nuclear dual purpose plants, both water and power costs are optimized. Studies for optimization of dual purpose plants include the water to power ratio [12, 13], the temperature of exhaust steam extracted for desalination [14] or the use of hybrid systems for desalination which increases the flexibility of the plant [15, 16].

In the present work, the energy consumption for variable water demand is investigated for both the back pressure turbine and the condensing turbine schemes in a nuclear dual purpose plant. The effects of changing the water demand and the top brine temperature on the specific energy consumption and the product water energy cost are studied for each scheme through a typical design of dual purpose plant.

2. GOVERNING EQUATIONS

The thermal energy consumed in MSF to produce a certain amount of desalted water m_d from a nuclear dual purpose plant is calculated as;

$$Q_t = m_s (h_e - h_c) (1.04)$$

$$Q_t = m_d / R (h_e - h_c) (1.04) \qquad (1)$$

Noting that 4% of the thermal energy added to allow for steam jet air ejectors [8], the enthalpy of extracted steam (h_e) depends on TBT in the MSF plant. Also, the gain ratio R, is optimized up to the steam cost [17].

Electrical power is needed to drive the MSF pumps. The major part of the pumping power is used to recirculate the brine, m_r. The required pumping power (Q_p) is calculated from the relation:

$$Q_p = \frac{m_r \Delta P}{\rho \eta_h \eta_m} (1.4) \qquad (2)$$

where ΔP is the pressure drop in the brine recirculation pump and the factor (1.4) is used to account for the power consumed in other pumps and auxiliaries of the MSF, as estimated from the literature [8, 17] noting that the recirculation brine flow rate is changed to follow the water demand.

Thus the total energy required to operate the MSF is:

$$Q = Qt + Q_p / \eta_p \qquad (3)$$

where η_p is the overall electrical generation efficiency.

The specific energy consumption can be calculated from equation (3) as

$$\text{specific energy consumption} = Q / m_d$$

The energy Q is equivalent to a certain reduction in the electrical output of the plant. This reduction is compensated by increasing the steam flow to the turbine; this increase is approximately:

$$\Delta S = Q / \eta_T (h_e - h_e) \qquad (4)$$

The price of the steam, ΔS, represents the energy cost of desalted water. Thus, the specific energy cost of water can be calculated as:

$$\Delta S\ CS / m_d \quad (\$/t).$$

When m_d is changed to satisfy the water demand, m_s will be constant in the case of a back pressure turbine scheme but can be changed in a condensing turbine scheme. The enthalpy of extracted steam is controlled by the operating temperature T_s. In the present work

T_s = TBT + 8°C. The difference between T_s and TBT depends on the heat transfer surface in the brine heater [6].

3. SAMPLE CALCULATIONS

In a sample calculations, a typical design of dual purpose plant, containing a moderate size reactor, is used to illustrate the effect of operating conditions of the MSF.

The main data used in the study are the following:

Pressure of steam at the steam generator outlet, bar	88
Temperature of steam at the steam generator outlet, °C	500
Pressure of steam at the condenser inlet, bar	0.05
Pressure drop in the brine recirculation pump, bar	4
Density of recirculated brine, kg/m³	1 030
Thermal energy cost(supplied as steam), ¢/kW·h	1.2
Electrical energy cost, ¢/kW·h	4.1
Overall electrical generation efficiency	0.35
Turbine efficiency	0.8
Brine recirculation pump hydraulic efficiency	0.8
Brine recirculation pump mechanical efficiency	0.95

Two cases of MSF operating conditions were investigated. The data used for each case are:

	Case A	Case B
Water production rate, t/h	980	794
Operating steam temperature, °C	120	98
Top brine temperature, °C	112	90
Gain ratio	8	7.35
Brine recirculation ratio	9.5	12.6

The condensing turbine and the back pressure turbine schemes are shown in Fig. l(a, b). The flow schematic of a recirculation type MSF is shown in Fig. 2.

The specific energy consumption for each scheme is calculated for cases A and B. The difference in the specific energy consumption due to change of TBT is rather small. However, it is considerable for high capacities. The sensitivity of specific energy consumption to water demand is much larger in case of the back pressure turbine scheme than the condensing turbine scheme. This is clear from the calculation procedure, hence the back pressure steam is totally consumed in the MSF for any production rate of desalted water.

As shown on Figs 3 and 4, the specific energy consumption in the back pressure scheme is more than that in the condensing turbine scheme except when the water demand exceeds 95% of the design value. However, the energy savings from a back pressure scheme for 100% water demand is about 6%. The thermal energy consumed per ton of product at full capacity is about 36 kW·h/t (about 12.6 kW(e)·h/t) for the condensing turbine scheme and about 34 kW·h/t (about 11.9 kW(e)·h/t) for the back pressure scheme. These results differs only by 10% from those in the literature for similar cases [6, 18].

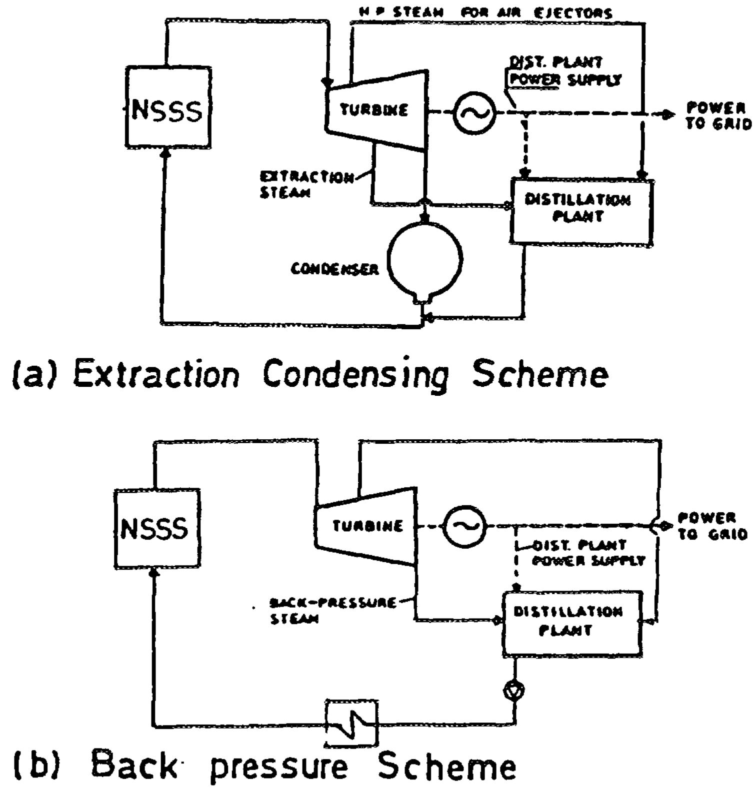

Fig. 1. Dual purpose plant schemes.

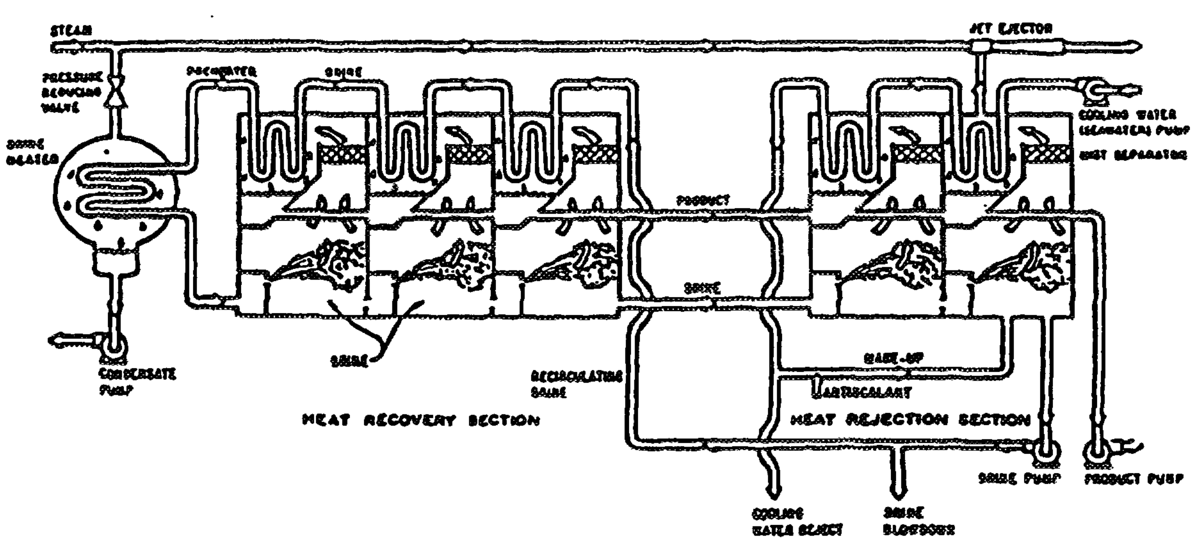

Fig. 2. Typical flow schematic of brine recirculation MSF plant.

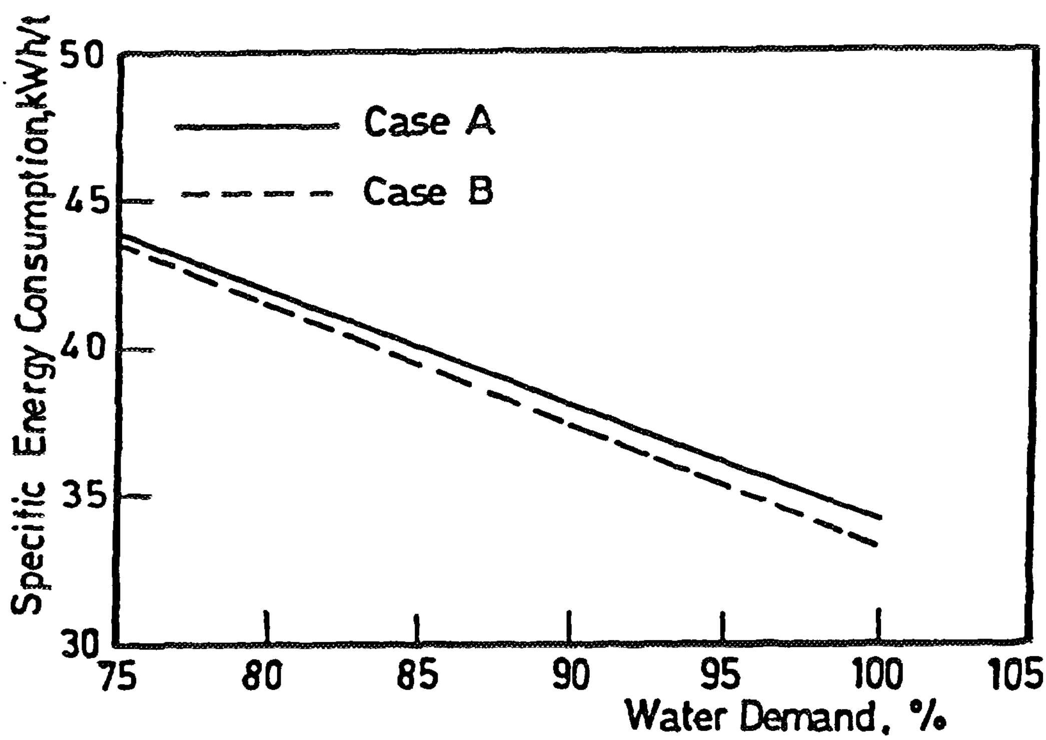

Fig. 3. Specific energy consumption for back pressure turbine scheme.

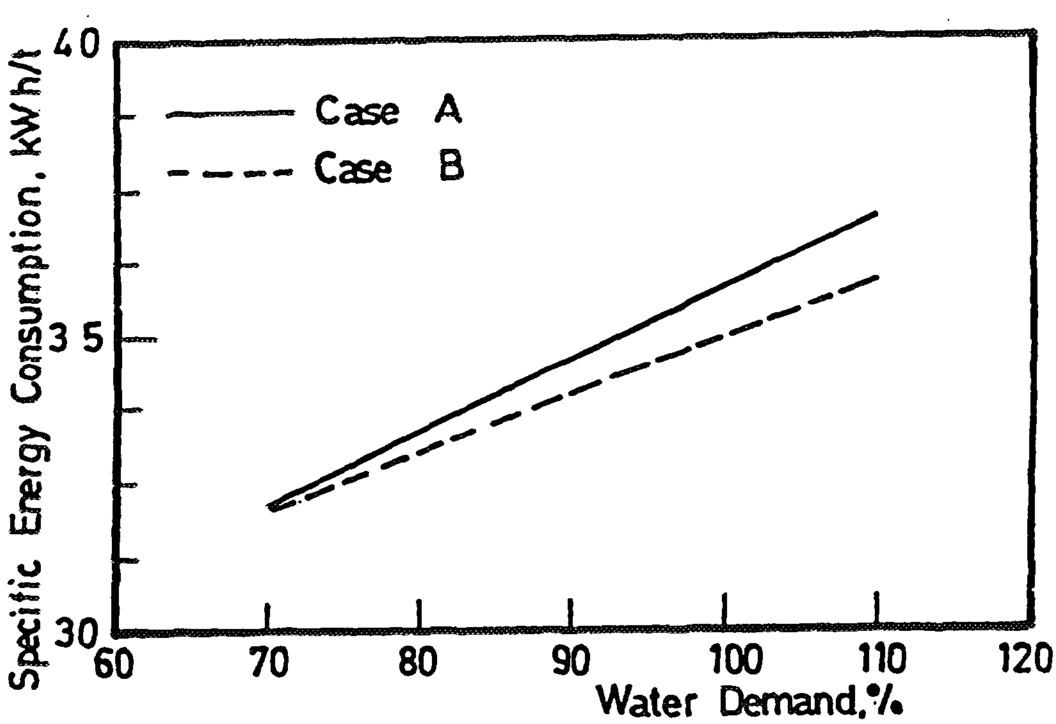

Fig. 4. Specific energy consumption for extraction-condensing turbine scheme.

The water energy cost is shown on Fig. 5. This cost depends on the fuel price. For the current prices, the cost of thermal energy is about 1.2 ¢/kW·h. This value leads to water energy cost of about 40-42 ¢/t at the full capacity of the MSF. Still the extraction-condensing scheme is advantageous except for water demand >95% of the full capacity. An increase of the water demand from 100% to 110% using the extraction scheme will increase the specific energy cost by only 1 ¢/t.

The power loss due to operation of the MSF is shown on Fig 6. This loss is almost constant in the case of a back pressure scheme, hence a decrease of the water demand from 100% to 70% will decrease the power loss by 1 MW(e). For the condensing turbine scheme, the loss is almost proportional to the water demand. The condensing turbine scheme has the advantage of increasing the water production to more than 100%, depending on the design of the MSF.

4. CONCLUSIONS

1. The specific energy consumption and the water energy cost of the MSF is less for the condensing turbine scheme than for the back pressure scheme for water demands <95%.

2. The flexibility of the power plant is much more in the case of the condensing turbine scheme, hence the water demand can be changed within a wide range without significant increase in water cost.

NOMENCLATURE

Symbols

CS	cost of steam, ¢/ kW·h
h	steam enthalpy, kJ/kg
m	mass flow rate, kg/h
Q	rate of energy consumption, kJ/h or kW·h
R	gain ratio
T	temperature, °C
TBT	top brine temperature, °C
ΔP	pressure drop in the reticulation pump, N/m^2
ΔS	increase in steam flow rate, kg/h
η	efficiency
ρ	density, kg/m^3

Subscripts

b	steam to the turbine
c	condenser
d	desalted water
e	extracted steam
f	feedwater
h	hydraulic
m	mechanical
r	recirculated brine
s	steam
T	turbine
t	thermal

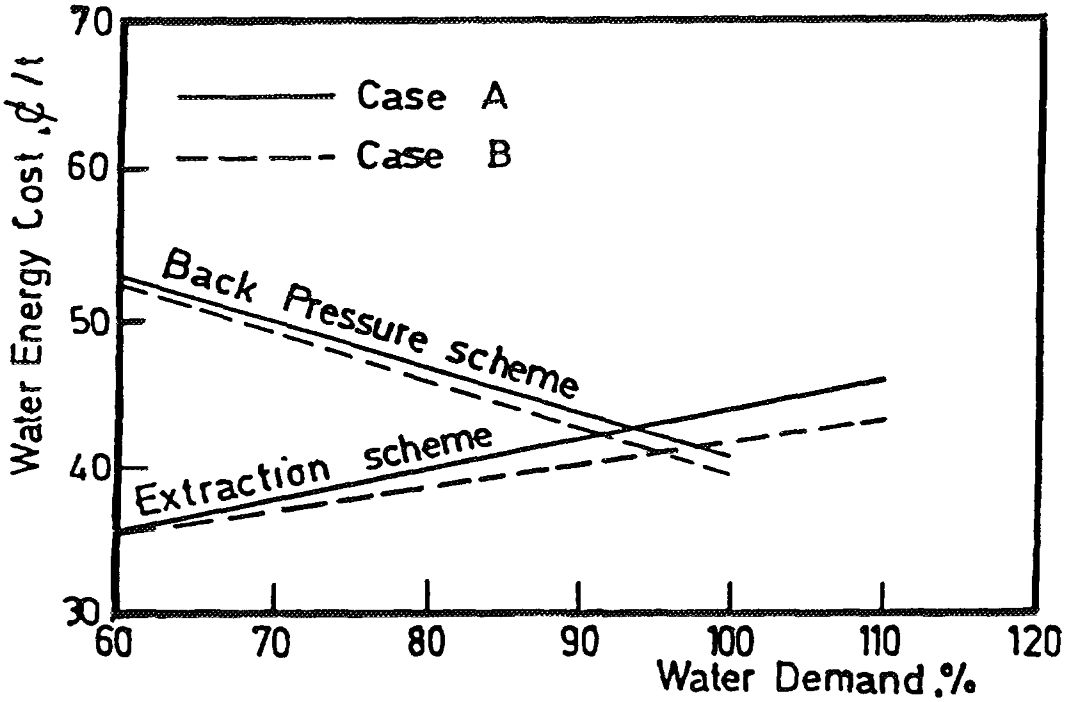

Fig. 5. Water energy cost for back pressure and condensing turbine schemes.

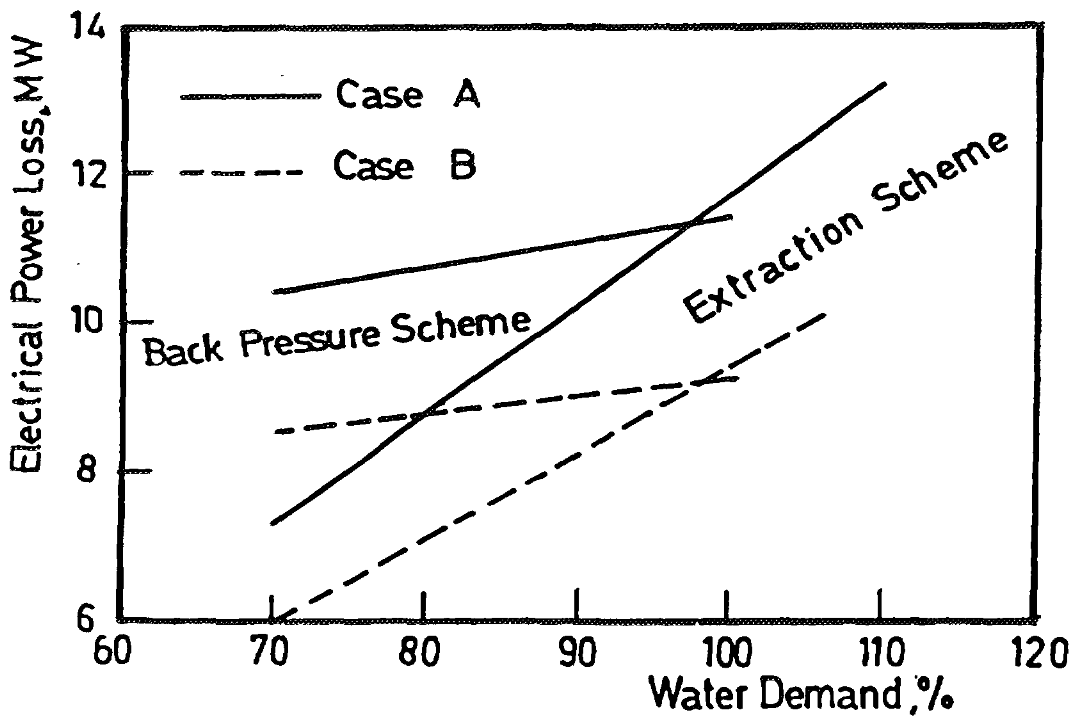

Fig. 6. Electrical power loss due to operation of MSF with different conditions.

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FRESH WATER GENERATORS ONBOARD A FLOATING PLATFORM

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Abstract

A dependable supply of fresh water is essential for any ocean going vessel. The operating and maintenance personnel on offshore platforms and marine structures also require a constant and regular supply of fresh water to meet their essential daily needs. A seawater thermal desalination unit onboard delivers good quality fresh water from seawater. The desalination units developed by Bhabha Atomic Research Centre (BARC) suitable for ocean going vessels and offshore platforms have been discussed. Design considerations of such units with reference to floating platforms and corrosive environments have been presented. The feasibility of coupling a low temperature vacuum evaporation (LTVE) desalination plant suitable for an onboard floating platform to a PHWR nuclear power plant has also been discussed.

1. INTRODUCTION

The adequate availability of power and water is a primary requirement for the overall development of a country. Uneven distribution of water resources, population growth, rising living standards, rapid industrialization and urbanization have escalated the demand for good quality water. The list of water scarcity areas is increasing day by day since the local demands are increasing faster than the possible increase in water availability from various water resources development schemes. Many areas of the world are likely to face water shortage in the next century. The future water demand for different purposes in India is given in Table 1.

TABLE 1. ANNUAL WATER CONSUMPTION FOR VARIOUS NEEDS IN INDIA (1000 m^3)

S. No.	Needs	Year 2000	Year 2025
1.	Irrigation	630.0	770.0
2.	Domestic	24.2	40.0
3.	Industries	30.0	120.0
4.	Power	5.8	15.0
5.	Miscellaneous	60.0	105.0

It is noted that the water consumption for industries and power sectors will increase at a much faster rate than the water requirement for irrigation, domestic and other uses. Desalination and water recycling could contribute significantly to augmenting the water resources.

A dependable supply of fresh water is also essential for ocean going vessels. The operating and maintenance staff on offshore platforms and marine structures require a constant and regular fresh water supply to meet their essential daily needs. Transport of water from onshore areas is generally difficult and also expensive. A minimum critical threshold fresh water supply, which varies with the climate and activity onboard, is a must.

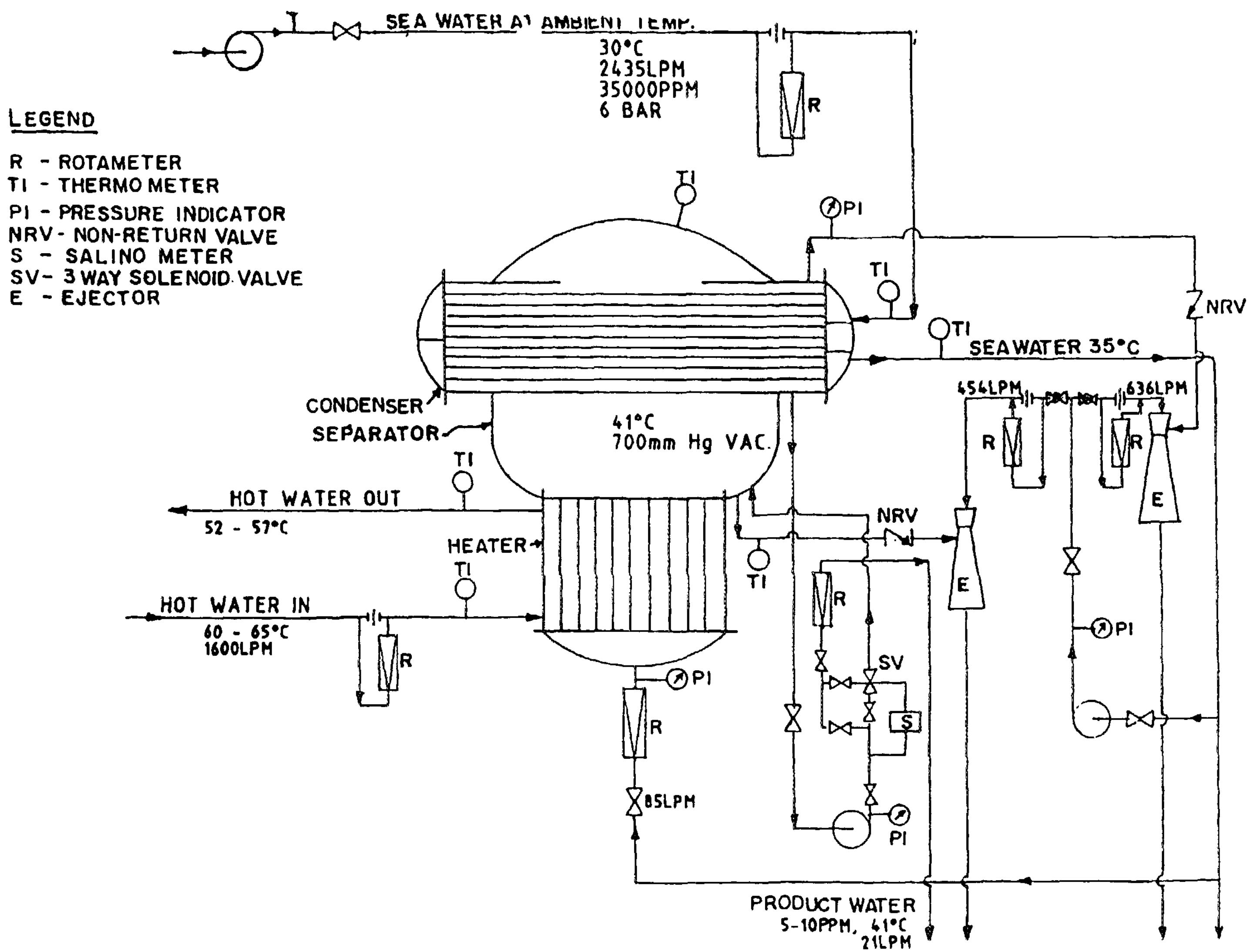

Fig. 1. Schematic diagram of 30 tonnes/day fresh water generation (FWG).

The seawater desalination units on floating platforms not only meet the above requirement but also have the added advantage of fulfilling the emergency water demand in coastal areas in case of a water crisis resulting from failure due to monsoon.

2. DESIGN CONSIDERATIONS FOR THE DESALINATION PLANTS ONBOARD FLOATING PLATFORMS

A desalination plant (also known as a fresh water generator) onboard a floating structure is quite different from a land-based desalination plant. It operates in a very corrosive environment and under varied conditions of hostilities from nature. Rolling and pitching of the mobile floating platform is also taken into consideration while designing the desalination plant. To avoid cavitation problems, an adequate quantity of water at required pressure is always made available at a pump suction. The vapours which are condensed on the condenser tubes are collected in a product water sump. A sloping product water sump may be provided depending on the extent of rolling to enable the product water pump suction to be always full of liquid and avoid cavitation problems or dry running of the pump. A brine pool above the heater section tube bundle is provided with about 80-100 mm high perforated strips to reduce the free surface effect on the brine pool during rolling of the floating structure. A high degree of corrosion allowance is given to take care of the corrosive environment. Marine duty motors are used, keeping in view the protection of personnel against contact with live parts and harmful dust deposits. The protection of motor against ingress of water from the sea in harmful quantities is also required. All motors are totally enclosed, fan cooled (TEFC) drip proof marine type with class E insulation. Space is one of the major constraints in floating structures, hence the desalination unit is designed for the maximum compactness depending on space availability. The type of floating structure determines the weight and size of the desalination unit. The unit is designed for easy dismantling, quick repair and assembly. It is ensured that the pipe connections do not cause any strain to the plant.

The desalination unit may be mounted on rubber pads to give noise and shock insulation. Reliability and plant availability are very important considerations for desalination plants onboard a floating platform.

3. LOW TEMPERATURE VACUUM EVAPORATION (LTVE) DESALINATION UNIT FOR FLOATING PLATFORMS

A low temperature vacuum evaporation (LTVE) desalination unit utilizing waste heat for producing fresh water from seawater onboard floating platforms has been developed at BARC. A 1 tonne/day (TPD) LTVE desalination unit suitable for floating platforms was earlier designed, fabricated and operated. A product water quality of 10 ppm total dissolved solids (TDS) was achieved. The performance data of this unit were used for the design of a 30 TPD LTVE desalination plant for floating structures. It was designed, installed, commissioned, operated round the clock and tested for endurance. The unit was fabricated under the supervision of M/s. Lloyd Register industrial Services India Limited as per the design to ensure the suitability of using the plant onboard floating platforms. It utilizes waste heat (60 - 65°C) for producing pure water from seawater as shown in Fig. 1. Feed seawater enters into heater tubes and a part of it evaporates by the time it comes out at the top of the vertical tube bundle. The vacuum evaporation of seawater takes place at 40°C to 45°C. The vapour enters the horizontal tube bundle at the top of the vertical shell and condenses on the condenser tubes. The tubes are cooled by seawater flowing inside. The product water is pumped out. The design parameters of the 30 TPD desalination plant are given in Table 2.

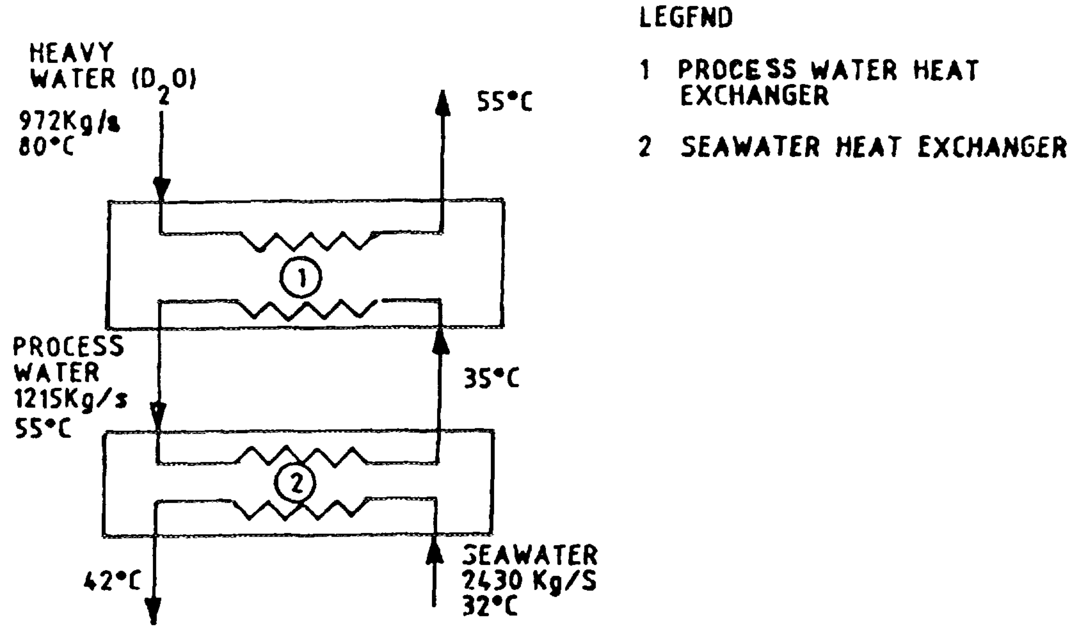

Fig. 2. Existing system for moderator cooling in a coastal 500 MW(e) PHWR.

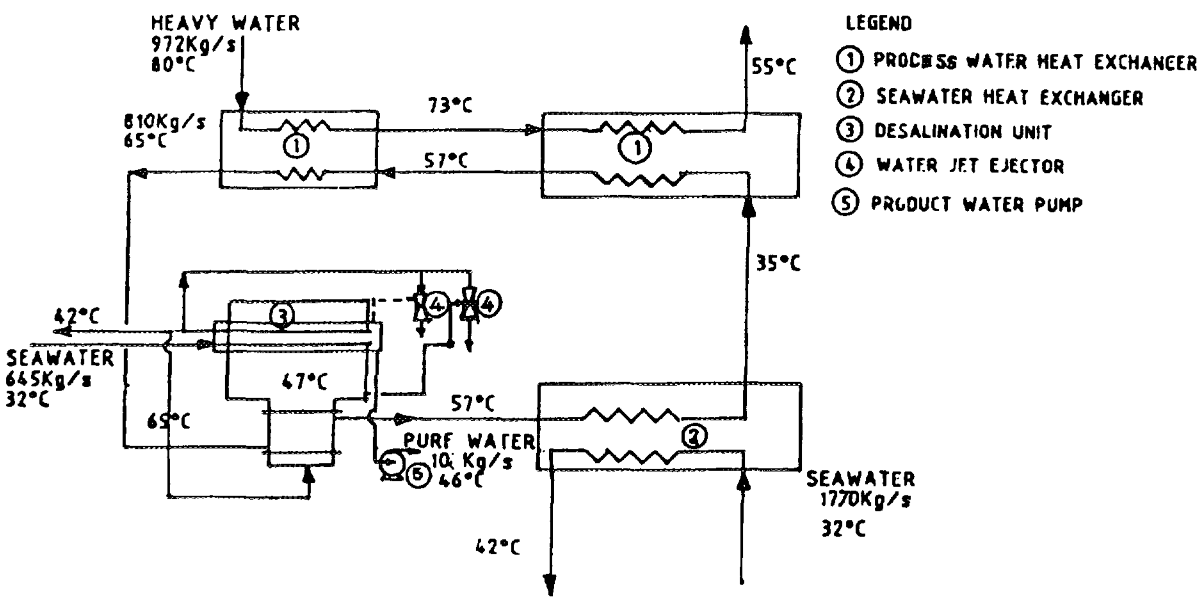

Fig. 3. Modified system for waste heat utilization of heavy water moderator for seawater desalination in a 500 MW(e) PHWR.

TABLE 2. SALIENT DESIGN FEATURES OF A DESALINATION PLANT ONBOARD A FLOATING PLATFORM

1.	Capacity (TPD)		30
2.	Flow rate (kg/s)		
	2.1	Condenser coolant	40
	2.2	Feed	1.25
	2.3	Seawater to vacuum ejector	10
	2.4	Seawater to brine drain ejector	7.5
	2.5	Recirculating hot water	25
	2.6	Product water	0.35
3.	Temperature (°C)		
	3.1	Water as heating media	
		(a) Inlet.	65
		(b) Outlet	57
	3.2	Condenser coolant	
		(a) Inlet	30
		(b) Outlet	35
4.	Operating pressure (bar (abs))		0.08
5.	Salinity (ppm)		
	5.1	Feed water	35 000
	5.2	Product water	10
6.	Waste heat requirement (MW(th))		0.9

It is a self-contained unit suitable for installation on a stationary structure or floating platform. Apart from the electrical energy requirement for the pump, no other power or fuel is required except waste heat at 60-65°C. Scale formation is practically eliminated due to low boiling temperature and brine density. Tube cleaning is required at long intervals. Water jet ejectors having no moving parts are used to create and maintain vacuum in the evaporator and pump out concentrated brine from the evaporator. It does not require any chemical pretreatment of seawater unlike other desalination processes. It gives a product water purity of 10 ppm TDS or better directly from 35 000 ppm TDS seawater. The unit is very reliable, practically maintenance free and environmentally friendly.

4. LTVE DESALINATION PLANT COUPLED TO PHWR NUCLEAR POWER PLANT

India is actively considering the use of nuclear reactors for producing power as well as fresh water from seawater in water scarcity areas. Several alternatives such as a large size seawater desalination using steam from a back pressure turbine in a PHWR nuclear power plant, a dual purpose nuclear desalination system producing electricity and fresh water from seawater using low pressure steam from the extraction turbine and waste heat utilization of heavy water moderator for producing pure water from seawater using an LTVE desalination plant have been worked out.

Technical/economic studies have been carried out to look into the feasibility of coupling an LTVE desalination plant onboard a floating platform to a 500 MW(e) PHWR nuclear power plant for utilizing the waste heat of the moderator. The existing system for moderator cooling in a coastal 500 MW(e) PHWR is shown in Fig. 2. The heavy water moderator is cooled from 80°C to 55°C in a process water heat exchanger. The process water is heated from 35°C to 55°C which in turn is cooled by seawater from 55°C to 35°C in a seawater heat exchanger and recirculated to the process water heat exchanger. Seawater is heated up from 32°C to 42°C and this heat is discharged to the sea as waste heat. It is noted that a significant part of the 100 MW(th) waste heat of the moderator can be utilized to produce about 900 TPD of better than 10 ppm TDS product water from seawater in coastal regions. The modified system for using the waste heat of the moderator for seawater desalination is shown in Fig. 3. The product water can be used as makeup demineralized water after passing through the mixed bed polishing unit. The demineralized water thus produced from seawater is cheaper than the same quality water produced from raw water using a cation, anion mixed bed exchanger due for the following reasons:

1. Thermal energy cost, which is a major component in water cost calculation and contributes about 50-60% of water cost, is nil due to waste heat utilization.
2. Cation and Anion exchangers, including the regeneration chemical requirement, have been eliminated.
3. Chemical pretreatment of feed seawater is not required, hence it is environmentally friendly. The chemical requirement for pretreatment of the seawater is nil.
4. It is very reliable having no moving parts except the product water pump, leading to low maintenance and repair costs.
5. Seawater is available at 6 bar in a PHWR coastal nuclear power plant. A small part of it is directly used as the motive fluid for water jet ejectors for creating vacuum and pumping out concentrated brine from the evaporator.
6. Low scaling and corrosion probability due to low temperature vacuum evaporation.
7. Electrical power is required only for the product water pump and relevant instruments.
8. The quantity of product water produced is about 25% higher than the total makeup water requirement for the 500 MW(e) PHWR nuclear power station.
9. The desalination unit is suitable for installation onboard floating platform.

5. CONCLUSIONS

The design considerations for a desalination plant onboard a floating platform are quite different from a land based desalination plant. The limitations due to hostile marine environment, space availability and weight requirement are taken care of in the design stage. Considerations with respect to chemical requirement for the pretreatment of seawater, cavitation, vibration and hydraulic problems are also incorporated while designing the fresh water generators onboard a floating platform. It is feasible to produce in-house low cost makeup demineralized water directly from seawater in coastal nuclear power stations.

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PROSPECT OF FLOATING DESALINATION FACILITIES USING NUCLEAR ENERGY IN INDONESIA

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Abstract

This paper summarizes studies on the water demand and supply problems in Indonesia in the last few years. During the dry season in 1990, it was reported that lack of fresh drinking water in Java and Bali amounted to 2.4×10^6 ton/month . Since Indonesia consists of more than 13 000 islands, more problems are faced by other islands The studies are focused on certain regions (groups of islands) which may have a potential for using a floating desalination facility. Water reservoirs in each island and delivery systems from the floating desalination facilities need to be assessed to see the prospective uses of the systems. Cheap, self-forgiving and easily operated systems, using transportable ship mounted desalination facilities, may be required as a solution to the water supply shortages for these islands. Conclusions based on current problems in water demand and supply and comments on the prospective future market using floating desalination facilities in Indonesia are also given.

1. INTRODUCTION

1.1. Background

Water is an essential substance for life and has certain strategic value. Human beings, society and even the ecosystem will not function without water. It is an irony that most people, including Indonesian, are still thinking that water is not a valuable thing and nothing to worry about it, as though it will always be sufficiently available.

Indonesia is located in the wet tropical zone. Therefore Indonesia should have a lot of water resources. Unfortunately water resources are not always available at the right time and locations [1, 2, 3]. In addition, geographically water resources are not distributed well enough. There have been drastic changes recorded over time and season. The western parts of Indonesia have enough water resources throughout the year. But some other parts of Indonesia have abundant water resources only in rainy season (September to February). This can cause flooding and some times extensive damage. These areas can potentially be very dry during dry season (March to August). In eastern parts of Indonesia, there is a natural shortage of water, such as in Madura, the East Nusa Tenggara archipelago and East Timor.

Indonesia is now starting the second long term development program (PJP-II). It can be considered that Indonesia will have serious and complex problems with water resources in the near future [1, 2, 4]. Water is not only needed to supply human beings who live in towns and villages, but water should also be able to supply agriculture, fisheries, forestry and industry in enough quantity and quality.

Generally, many towns and industrial areas in Indonesia are located along river side or seashore because these areas offer a good place for transportation, water supply and of course these areas are also considered good places for waste disposal. Recently, the development rates have sharply increased in many sectors, such as industry, agriculture, housing, etc. Again, these have caused some ecological damage. The current studies show that nature water sources are nearly unable to supply the demand during the year, and that the river can not clean itself of waste. Since groundwater is pumped out by many people excessively, the result is intrusion of seawater to tens of km inland from the seashore in some big cities in Indonesia, such as Jakarta, Medan, Semarang, Surabaya and Ujung Pandang [1, 2, 5, 6]. The seawater intrusion problems will become more serious in the near future, not only to decrease the quality of the groundwater but also to corrode the foundations of steel buildings [5].

Today, in Indonesia, water is more valuable than petrol. One liter of drinking water is more expensive than one liter of petrol.

1.2. The need for desalination

The fact that water resources are not evenly distributed in all areas of Indonesia. The area with lower wetness are East Java, Bali West Nusa Tenggara, East Nusa Tenggara, East Timor, South East Maluku and Marauke [1, 2]. It is estimated that about one third of the Indonesian population suffers from lack of safe drinking water. Since the Indonesian population is growing quickly and there is a tendency to change from an agriculture society to an industrial society, it can be expected that Indonesia will have water shortage problems in the near future. This problem becomes worse if we take into account the increasing population and reduction of existing ground and surface water. Those problems are likely to happen in the arid regions of eastern Indonesia.

The eastern parts of Indonesia have in general few untapped potential water resources. Costly investments will be needed for the development of new potable water supply options such as improvements to the water distribution infrastructure, water transport from surplus to shortage areas, brackish water desalination, new dams, water treatment and reuse facilities, and seawater desalination.

As the less expensive supply alternatives are exhausted, seawater desalination becomes the option of choice for small islands, towns and villages within a reasonable transport distance from the sea, especially in the eastern part of Indonesia. Seawater is indeed the largest water resource available in Indonesia, as an archipelagic country. Compared with existing fresh water resources, its availability is essentially unlimited, and it is still reasonably unpolluted except in specific areas near industrial areas in Jakarta and Surabaya.

Nuclear energy has been considered as an energy source for seawater desalination. Among the reasons are included the production of less expensive energy as compared to other options [7, 8], overall energy supply diversification, conservation of limited fossil fuel resources, promotion of technological development and, lately, environmental protection through the reduction of emissions causing climate change and acid rain which originate from the burning of fossil fuels.

The purpose of this paper is to report the water demand and supply problems in Indonesia, and to review the prospect for floating desalination facilities, especially in those areas which have low rainfall and low wetness.

2. WATER DEMAND AND SUPPLY PROBLEMS IN INDONESIA

2.1. Hydrological cycle

Actually, Indonesia has all the forms of water resources such as (1) rain water, (2) surface water, (3) groundwater, (4) soil moisture, and (5) lava water. Rain water and lava water are primary water sources, but these sources are not included in our water resource management system. Surface water, groundwater, soil moisture are secondary water sources and only these water sources (except seawater) are in the water resource management system. Although seawater is used in arid areas of Middle East and North African, seawater is still not included in the water resource management system because seawater is very abundant. For Indonesia, rainfall is the primary water source.

The relationship among rain water, surface water, groundwater and soil moisture continuously as a single process is called the hydrological cycle. In this process part of the rainwater returns to the atmosphere through evaporation, is stopped by the tree's leaves, and returns to the surface of earth. A part of this rainwater reaching the earth's surface stagnates or collects in lower areas to form lakes or swamps. Part of the rainwater flows along the mountain wall to form rivers or to fill lakes or swampy areas. The rest penetrates into the ground. A part of this will be soil moisture and the remainder will form groundwater. This soil moisture is used by the plants in their circulation process.

The hydrological cycle determines the water balance on the earth, that is the amount of water stored in all forms. The water balance differs from one place to another, and differs from time to time, although the amount of water on the earth is constant. The purpose of the water resources management system is not to increase the amount of water, but to adjust and manage the water balance to reach a more efficient usage in order to meet the water demand.

Furthermore, the value of water is determined by the balance between water supply and water demand. Therefore water can considered as a commodity. Water value (NA) is a function of place (r), time (w) and technology (t). Mathematically this can be describe as NA = f(r,w,t). This concept was used first to determine the primary water source from rainfall [1, 3].

2.2. Water resources

2.2.1. Surface water

The information concerning availability of primary water resources is usually expressed in the form of data on rainfall per month or per year. Rainfall distribution in Indonesia is highly varied, in both time and location.

The calculation for the availability of secondary water resources, as well as surface flow, are based on the empirical equation $R = 0.94 \times P - 1000$, where R is the average flow per year (mm/year), P is the average rainfall per year (mm/year) [1]. By using this formula, the average potential flow of the surface water in each province of Indonesia can be approximated. It is well known that Indonesia has many rivers (5886 main rivers), lakes and water reservoirs from dams (53 water reservoirs from dams have been built since 1914) as surface water sources distributed in all parts of the country. But these potential water resources can not always be used, because the rainfall pattern is not well distributed during the year, and the availability of primary water resources is very low during dry season. The availability of water during dry season represents the minimum surface flow capacity. Tables 1 and 2 show the estimated water resources in Indonesia. Table 3 shows the river water debit in each province (1991: 16 provinces) of Indonesia. The average availability of primary water resource per year in each province per person in that area is shown in Table 4. It shows that people in Jakarta have the most serious lack of water, with not more than 0.15 m^3/person/day. It also shows that Java and Bali are areas with low water availability.

TABLE 1. AVAILABILITY OF PRIMARY WATER RESOURCES [1]

NO	PROVINCE	AREA (km^2)	RAINFALL (mm/year)	MINIMUM AVAILABLE (10^6 m^3/month)
1	DI Aceh	57,037	2,708	725
2	North Sumatra	72,561	2,633	880
3	West Sumatra	41,612	3,479	780
4	Riau	96,346	2,509	1,075
5	Jambi	48,518	2,760	637
6	South Sumatra	101,118	2,654	1,242
7	Bengkulu	20,876	3,692	426
8	Lampung	33,345	2,560	385
9	DKI Jakarta	656	1,800	4
10	West Java	46,352	2,954	678
11	Central Java	34,531	2,816	468
12	DI Yogyakarta	3,212	2,047	24
13	East Java	48,267	2,105	386
14	Bali	5,655	2,111	45
15	West Nusa Tenggara	19,740	1,774	106
16	East Nusa Tenggara	46,100	1,750	240
17	East Timor	14,799	2,013	108
18	West Kalimantan	147,872	3,431	2,717
19	Central Kalimantan	154,831	3,200	2,565
20	South Kalimantan	36,079	2,523	406
21	East Kalimantan	196,291	2,849	2,712
22	North Sulawesi	27,193	2,596	322
23	Central Sulawesi	61,629	2,499	683
24	South Sulawesi	62,884	2,591	742
25	Southeast Sulawesi	35,372	2,205	310
26	Maluku	78,180	2,509	872
27	Irian Jaya	413,951	3,337	7,803

Most of the Indonesian rivers have been physically damaged or degraded by polluted from the disposal of industrial and household wastes. This has decreased the quality of water, especially during the dry season. Some effort to clean the rivers was made by the Government through an international joint-venture with "aquatics" Unlimited International Equipment Cooperation. This project has targeted 12 rivers to alleviate pollution resulting from the dumping of industrial, municipal and domestic waste [9].

As described above, seawater sources are still not included in the national water resource management system. In the near future, as water consumption increases day by day, seawater sources, which are abundant and relatively clean, should be considered as one of the alternative sources for water treatment purposes.

2.2.2. Groundwater

Indonesia is an archipelago country which consists of 5 large islands and thousands of small islands. Among these, some are very mountainous and include volcanoes. These conditions make Indonesian groundwater slightly different than other countries, and Indonesia has all types of groundwater. Some estimate of national groundwater reserve was made, as shown in Table 5. This estimate is used due to the lack of information about groundwater in Indonesia.

The hydrological cycle is a natural process to supply the water for human beings. Many people still believe that groundwater is a renewable water resource. With this mistaken attitude, they can pump out the groundwater as much as they want. The big cities suffer from the seawater intrusion. Even in Jakarta, as the biggest city, the seawater intrusion is about 11 km from the seashore [1-3, 6]. This is a dangerous condition. In the urban areas, agricultural use of fertilizers and pesticides has been increasing. Lack of care in the use of this material causes chemical residues, which are very dangerous to health and the environment. Moreover, those agriculture areas are also affected by the lack of waste management systems.

All institutions and peoples, especially in the threatened areas like a Jakarta, should work together to resolve these problems. The cooperative must not be limited only to water resource management, but also must include developing alternative technologies and/or alternative water sources such as seawater desalination.

TABLE 2. THE AVAILABILITY OF WATER RESERVOIR (DAM) [1]

NO	PROVINCE	WATER RESERVOIR (10^6 m^3)
1	North Sumatra	6.0
2	Lampung	122.0
3	West Java	4,825.0
4	Central Java	2,223.0
5	East Java	759.0
6	B a l i	6.5
7	West Nusa Tenggara	17.0
8	South Kalimantan	1,200.0
9	East Kalimantan	3.3
10	Central Sulawesi	10.0
	JAVA	7,807.0
	INDONESIA	9,171.8

TABLE 3. WATER DEBIT IN SOME RIVERS IN INDONESIA (1991) [1]

NO	PROVINCE	FLOW RATE	
		AVERAGE (m^3/s)	(10^6 m^3/year)
1	DI Aceh	1,061.39	33,513.00
2	North Sumatra	1,132.63	23,994.00
3	West Sumatra	---	---
4	Riau	1,889.83	36,602.00
5	Jambi	---	---
6	South Sumatra	---	---
7	Bengkulu	118.14	3,718.60
8	Lampung	551.24	6,677.50
9	DKI Jakarta	---	---
10	West Java	415.86	14,614.80
11	Central Java	525.74	16,603.20
12	DI Yogyakarta	988.80	18,738.50
13	East Java	---	---
14	Bali	15.72	490.00
15	West Nusa Tenggara	16.82	330.95
16	East Nusa Tenggara	9.71	300.60
17	East Timor	---	---
18	West Kalimantan	92.40	2,913.00
19	Central Kalimantan	---	---
20	South Kalimantan	64.72	2,041.00
21	East Kalimantan	---	---
22	North Sulawesi	---	---
23	Central Sulawesi	74.83	2,370.00
24	South Sulawesi	774.84	12,415.87
25	Southeast Sulawesi	102.00	3,208.00
26	Maluku	---	---
27	Irian Jaya	---	---
	JAVA	1,930.40	49,956.50
	INDONESIA	7,834.66	188,531.02

TABLE 4. AVAILABILITY OF PRIMARY WATER RESOURCES INDEX (1991) [1]

NO	PROVINCE	m^3 Flow/person/day
1	DKI Jakarta	0.15
2	DI Yogyakarta	2.80
3	East Java	4.00
4	Central Java	5.50
5	B a l i	5.50
6	West Java	6.40
7	West Nusa Tenggara	11.00
8	Lampung	21.00
9	North Sumatra	29.00
10	South Sulawesi	35.00
11	North Sulawesi	43.00
12	East Timor	48.00
13	South Kalimantan	52.00
14	West Sumatra	65.00
15	South Sumatra	66.00
16	DI Aceh	71.00
17	Southest Sulawesi	77.00
18	Jambi	105.00
19	R i a u	109.00
20	Bengkulu	120.00
21	Central Sulawesi	134.00
22	Maluku	157.00
23	West Kalimantan	279.00
24	East Kalimantan	481.00
25	Central Kalimantan	610.00
26	Irian Jaya	1,488.00

TABLE 5. SOME ESTIMATES OF GROUNDWATER RESERVES (1993) [1]

NO	PROVINCE	VOLUME (km^3)	TOTAL (10^2 m^3/km^2)
1	DI Aceh	55,392	22.97
2	North Sumatra	70,787	28.13
3	West Sumatra	49,778	10.32
4	Riau	94,562	66.18
5	Jambi	44,924	14.36
6	South Sumatra	103,688	83.32
7	Bengkulu	21,168	8.96
8	Lampung	33,307	5.18
9	West Java & Jakarta	46,300	31.20
10	Central Java	32,206	22.82
11	DI Yogyakarta	3,169	1.10
12	East Java	47,992	14.93
13	Bali	5,561	0.58
14	West Nusa Tenggara	20,177	1.74
15	East Nusa Tenggara	47,976	1.65
16	West Kalimantan	146,760	103.98
17	East Kalimantan	202,440	89.20
18	Central Kalimantan	152,600	125.25
19	South Kalimantan	37,660	23.99
20	North Sulawesi	19,025	3.29
21	South Sulawesi	72,781	22.01
22	Central Sulawesi	69,726	17.47
23	Southeast Sulawesi	27,686	2.87
24	Maluku	74,505	16.09
25	Irian Jaya	421,981	539.59
26	East Timor	14,874	0.90

2.3. Water demand

By Indonesian regulation there are three categories of water demand as follows:

a. Category A: drinking water, household water, defense and security water, praying water, city water system.
b. Category B: agricultural water, cattle water, farm water, fisheries.
c. Category C: power plant water, industrial water, mine water, transportation water and recreational waters.

The production capacity of water for domestic, industry and cities (including small cities) in urban areas is 56.2 l/s; the largest share is produced from surface water (64%), and the remainder from groundwater and other sources. The water demand for domestic, industrial and city usage, with its projection into the future, is shown in Table 6. In 1992, production capacity increased to 59.967 l/s. Based on that level, water demand can be satisfied for about 27.75 million, or 50%, of the cities' population and 50 million, or 47.37%, of the urban populations [1].

The water demand for other uses such as irrigation and fresh water fishery, with its projection into the near future, is shown in Tables 7 and 8. Surface water also has potential uses for power plants (natural or manmade waterfalls), recreation and transportation in Kalimantan and Sumatra.

Water balance is defined as the difference between water requirements (excluding water for washing, etc.) and the water available, with its projection into the future. This is shown in Table 9. This data is based on the availability of water in the dry season. The Table shows that certain areas in the eastern part of Indonesia will suffer a lack of drinking water in the near future. Even for Java island itself, the deficit is about 130% in 1993 and about 153% in the year 2000 [2, 4, 6].

Based on these estimates, we should do something to solve these water problems, looking for alternative water sources. Seawater desalination promises to be a good alternative for the supply of high quality potable water.

3. SELECTED AREA AND TECHNOLOGY

3.1. Selected area

Although Indonesia is located in wet tropical regions which have a large potential for water reserves, the growth of population and increasing development has affected the availability of water resources. These assessments are focused on arid areas in the eastern part of Indonesia, from Java to Merauke.

Geographically, these areas cover thousands of km^2 consisting of medium and small sized islands such, as Bali, Lombok, Sumba, Flores, Timor, etc., with a population approaching 40 million people. Naturally, during the year these areas suffer from the lack of fresh water, especially in dry season, as described before. In addition to the lack of water resources in these areas, some of them were also polluted by household, agriculture and industrial wastes. Since development in all sectors is expected to continue in the near future, a large amount of water will be needed, either for supply to people in towns and villages or for other purposes such as industrial, agricultural, etc.

TABLE 6. WATER DEMAND FOR DOMESTIC, CITY AND INDUSTRY [1]

NO	PROVINCE	WATER DEMAND (10^6 m^3/year)		
		1990	2000	2015
1	DI Aceh	38	83	157
2	North Sumatra	211	391	558
3	West Sumatra	53	104	148
4	Riau	54	120	233
5	Jambi	25	59	104
6	South Sumatra	113	221	322
7	Bengkulu	15	38	76
8	Lampung	63	136	180
9	DKI Jakarta	457	701	902
10	West Java	784	1,619	2,622
11	Central Java	436	820	1,122
12	DI Yogyakarta	59	111	123
13	East Java	547	1,007	1,365
14	Bali	41	78	104
15	West Nusa Tenggara	38	79	107
16	East Nusa Tenggara	31	66	94
17	East Timor	3	16	22
18	West Kalimantan	38	85	126
19	Central Kalimantan	12	38	75
20	South Kalimantan	41	78	113
21	East Kalimantan	40	86	161
22	North Sulawesi	32	63	92
23	Central Sulawesi	15	44	92
24	South Sulawesi	102	20	82
25	Southeast Sulawesi	12	38	69
26	Maluku	21	53	89
27	Irian Jaya	21	47	78
	Total	3,302	6,388	9,391

TABLE 7. THE IRRIGATION WATER DEMAND FOR RICE FIELDS [1]

NO	PROVINCE	WATER DEMAND (10^6 m^3/year)		
		1990	2000	2015
1	DI Aceh	2,293	2,293	3,328
2	North Sumatra	4,307	4,307	5,755
3	West Sumatra	2,495	2,495	3,012
4	Riau	364	364	2,878
5	Jambi	644	644	1,586
6	South Sumatra	933	933	5,169
7	Bengkulu	729	729	982
8	Lampung	2,022	2,022	2,597
9	DKI Jakarta	148	148	148
10	West Java	14,234	14,234	15,597
11	Central Java	12,444	12,444	13,677
12	DI Yogyakarta	865	865	933
13	East Java	14,675	14,675	15,597
14	Bali	1,464	1,464	1,528
15	West Nusa Tenggara	2,404	2,404	2,635
16	East Nusa Tenggara	999	999	1,300
17	East Timor	95	95	426
18	West Kalimantan	1,537	1,537	3,196
19	Central Kalimantan	736	736	3,682
20	South Kalimantan	593	593	3,227
21	East Kalimantan	96	96	2,237
22	North Sulawesi	772	772	328
23	Central Sulawesi	1,511	1,511	1,834
24	South Sulawesi	4,984	4,984	6,357
25	Southeast Sulawesi	469	469	774
26	Maluku	155	155	1,041
27	Irian Jaya	33	33	9,737
	Total	72,003	72,003	110,102

TABLE 8. THE WATER DEMAND FOR FRESHWATER FISHERY (1991) [1]

NO	PROVINCE	WATER DEMAND (10^6 m^3/year)		
		1990	2000	2015
1	DI Aceh	62	69	78
2	North Sumatra			
3	West Sumatra			
4	Riau	3	3	4
5	Jambi			
6	South Sumatra			
7	Bengkulu			
8	Lampung			
9	DKI Jakarta			
10	West Java	503	553	628
11	Central Java	1,179	1,297	1,474
12	DI Yogyakarta			
13	East Java	846	930	1,057
14	Bali	79	87	99
15	West Nusa Tenggara			
16	East Nusa Tenggara			
17	East Timor			
18	West Kalimantan			
19	Central Kalimantan			
20	South Kalimantan			
21	East Kalimantan	44	49	56
22	North Sulawesi			
23	Central Sulawesi			
24	South Sulawesi	1,169	1,286	1,461
25	Southeast Sulawesi			
26	Maluku			
27	Irian Jaya			
	Indonesia	3,885	4,274	4,856

TABLE 9. WATER BALANCE WITH ITS PROJECTION [1,9]

NO	PROVINCE	AVAILABILITY		WATER DEMAND			WATER BALANCE		
		AVERAGE 10^6 m^3/year	Dry Season Debit (10^6 m^3/year)	1990	2000	2015	1990	2000	2015
				10^6 m^3/month			10^6 m^3/month		
1	DI Aceh	87,024	725	199	238	297	526	487	428
2	North Sumatra	105,558	880	377	440	526	503	440	354
3	West Sumatra	93,643	780	212	234	263	568	547	517
4	Riau	128,953	1,075	35	124	260	1,040	950	815
5	Jambi	76,385	637	56	90	141	581	546	496
6	South Sumatra	149,087	1,242	87	237	458	1,155	1,005	785
7	Bengkulu	51,150	426	62	72	88	364	354	338
8	Lampung	46,238	385	174	199	231	212	186	154
9	DKI Jakarta	440	4	50	71	88	- 47	- 67	- 84
10	West Java	81,413	678	1,293	1,409	1,561	- 615	- 730	- 883
11	Central Java	56,188	468	1,172	1,255	1,356	- 703	- 786	- 888
12	DI Yogyakarta	2,903	24	77	84	88	- 53	- 59	- 64
13	East Java	46,277	386	1,339	1,415	1,502	- 953	- 1,030	- 1,116
14	Bali	5,454	45	132	138	144	- 87	- 92	- 99
15	West Nusa Tenggara	12,774	106	204	215	229	- 97	- 106	- 122
16	East Nusa Tenggara	28,798	240	86	99	116	154	141	- 124
17	East Timor	12,907	108	8	20	37	99	87	70
18	West Kalimantan	326,083	2,717	131	190	277	2,586	2,527	2,441
19	Central Kalimantan	307,826	2,565	62	163	313	2,503	2,403	2,252
20	South Kalimantan	48,766	406	53	144	278	354	263	128
21	East Kalimantan	325,380	2,712	15	91	204	2,696	2,621	2,507
22	North Sulawesi	38,630	322	67	75	85	255	247	237
23	Central Sulawesi	81,907	683	127	140	160	555	542	523
24	South Sulawesi	89,005	742	521	585	674	221	156	68
25	Southeast Sulawesi	37,240	310	40	52	70	270	258	240
26	Maluku	104,660	872	15	47	941	857	825	778
27	Irian Jaya	876,309	7,303	5	332	823	7,298	6,970	6,480
	Total	3,220,977	26,842	6,600	8,159	10,363	20,242	18,683	16,478

TABLE 10. SUMMARY OF SELECTED DESALINATION PROCESSES [2, 8]

NO	PARAMETER	RO	MSF	MED	MED/VC
1	Energy consumption: el./mech. (kW(e).h/m³) thermal (kW(th).h/m³)	 5 - 7 none	 4 - 6 55 - 120	 2 - 2.5 30 - 120	 7 - 9 none
2	Electric equivalent for thermal energy (kW(e).h/m³)	none	8 - 18	2.5 - 10	none
3	Total equivalent energy consumption (kW(e).h/m³)	5 - 7	12 - 24	4.5 - 12.5	7 - 9
4	Possible unit size (m³/day)	24,000	60,000	60,000	24,000
5	Limiting factors	pumps vacum units	pumps, valves	erection and construction aspects; plant reliability	compressors
6	Total capital costs	lowest	highest (at same GOR)	low	medium
7	Fully automatic and unattended operation	possible	possible	possible	possible
8	Tolerance to operator faults	low	medium	high	medium
9	Tolerance to changing sea water composition and pollution	very low	medium	high	high maintenance
10	Maintenance requirements	high	medium	low	medium
11	Spare parts or replacement parts requirements	high (delicate, large pumps expensive membrane replacement every 3-5 years)	medium (large special pumps)	low (only small pumps required)	high (vapour compressor required)
12	Heat transfer area	not applicable	high	low	low
13	Failure potential if corrotion occurs	high (some membrane are sensitive to dissolved metals)	medium	low	low
14	Scaling potential when solutes in seawater are above precipitation level	high	medium	low	low
15	On-site assembly/erection requirements	low	medium	medium	medium
16	Engineering requirements (quantitative)	low	medium	medium	high
17	Manufacturing requirements	high (especially for membrane)	medium	low	medium
18	Ratio between product and total seawater flow	0.3 - 0.5	0.08 - 0.15	0.1 - 0.25	0.4 - 0.6
19	Experience available	medium	highest	high	medium
20	Potential for further improvements	high	low (at technological limit)	medium	medium

Actually the water resources are available there, much more than the estimated need, in the form of seawater. The next problem is selection of suitable technology for the production of low cost, high quality product water.

3.2. Selected technology

The desalination process has been utilized for many years to produce potable water from seawater sources. Among the various existing desalination processes described in IAEA-TECDOC-666 [7], the following processes have been recommended for selection as the most interesting for medium and large scale water production: reverse osmosis (RO), multi-effect distillation with vapor compression (MED/C), multi-effect distillation (MED), and multistage flash distillation (MSF). All are proven and commercially available from a variety of suppliers.

The cost for the RO, MED, MED/VC and MSF processes have been assessed. The RO and MED/VC processes required only mechanical energy in the form of electricity. Electrical consumption of 5-7 and 7-9 $kW\cdot h/m^3$, respectively are required to produce one m^3 of potable water, depending on the design, unit sizes and site conditions (excluding energy for water transport and distribution). For distillation processes (MED and MSF) the energy input is mainly in the form of heat (hot water or steam) and some electricity (2-2.5 and ~4 $kW\cdot h/m^3$ respectively). The heat consumption depends on the design, in particular the number of effects and the gain-output ratio (GOR). For the MED process, the specific heat consumption is in the range of 30-120 $kW(th)\cdot h/m^3$ for heat source inlet temperature of 120°C to 70°C and for MSF process about 55-120 $kW(th)\cdot h/m^3$.

Water of sufficiently high quality can be produced using membrane technologies such as RO and ultra filtration (UF). The RO process works on the principle of operating at a pressure higher than the osmotic pressure of the seawater, so that only the solvent (pure water) can pass through the membrane pores and migrate to the more dilute permeate solution. The UF process works on the principle of separating out the high molecular weight particles such as colloids, microbes and suspended solids. Economically, the RO process is cheaper. Table 10 shows the summary of selected desalination processes. This table describes the advantages and disadvantages of each process.

3.3. Floating facilities

Geographically, the arid regions cover many islands which are distributed far from each other. Therefore floating desalination facilities in form of barges or moving facilities (ships) are considered to be suitable for those areas.

The ship should be sufficiently large, and powered with either nuclear or fossil fuel. All the desalination equipment is on the ship and connecting water system to the island's harbors. Each island is provided with a water reservoir (tank or dam), harbor and connecting water system to the ship.

Desalination facilities should operate continuously, whether in transit or moored. The ship should travel to all of the arid regions with rigorous scheduling throughout year, in particular during the dry season. When the ship stops at one of the islands, the fresh water is pumped out through the water connecting system. The potable water is collected at water reservoir (tank or dam) and then distributed to the water consumers on that island.

All the systems on the ship and on land (in the harbor) should be easy to operate, easy to maintain, inexpensive and safe. Desalination facilities should also be designed with "self forgiving" safety system components.

4. FUTURE PROSPECTS

On the one hand, the main causes of water demand and supply problems in Indonesia are wasteful uses of water, the attitude of the Indonesian society which still thinks that water resources are renewable, an inadequate water resources management system and, physically, a lack of concern with the water hydrological cycle on the part of developers. These are all problems in management systems and are only a temporary condition, although it may need some years to improve the situation.

On the other hand, the population growth and the increase of development in all sectors will continue in the foreseeable future, requiring large amounts of water to sustain the quality of life. This seems more serious and complex than the system management problems. Besides, the water resources can not be used to their maximum again, at least temporarily, until their damages (salt intrusion, pollution, etc.) have been completely improved. It is time to look for alternative water resources, one of which is seawater, as a source of water for Indonesia. Seawater desalination systems show much promise in the near future to supply the shortfall of water capacity from the conventional water treatment systems.

Supplying potable water in enough quantity and quality to the arid regions of Indonesia will promote the economic growth of the peoples in those areas. The national development program in all sectors such as home industry, agriculture, industry etc. in those areas will be maintained continuously. Lastly, these improvements will affect the quality of life of peoples who live in those arid regions.

The estimates for desalination water production costs show that the nuclear alternative is in general favored for larger sizes and lower interest rates, while fossil is less expensive for smaller sizes and higher interest rates [7]. For large units (900 MW(e)), nuclear power shows cost advantages versus fossil fuel, for medium sizes (300 to 600 MW(e)) the costs are similar, and for smaller sizes (50 MW(e)) fossil power (diesel engine) is favored. Overall water production costs for nuclear plants are in general between US \$0.7-1.1 per m^3 for desalination plants combined with a dual purpose (electricity and heat) or electricity (only) generating plant. Combinations with a heat only plant results in considerably higher (US \$1.20-2.00 per m^3) water production costs. As a comparison, the price of one liter of bottled water in Indonesia is higher than the price of one liter of petrol.

Desalination processes also produce certain elements such as NaCl, Mg, Br, etc. as by-products. The removal of those elements in the pretreatment step will decrease the overall potable water production cost.

For these reasons it is clear that seawater desalination systems offer a good prospect for supplying potable water in Indonesia, especially in the arid regions of the eastern part of Indonesia.

5. CONCLUSIONS

1. The growth of development in all sectors without concern for the hydrological cycle will damage Indonesian water resources.
2. The main problems of water demand and supply in Indonesia are water management and water resource problems.
3. Seawater as a source of water is considered to be able to meet the water demand for Indonesia in the near future.
4. Floating desalination facilities are possible to operate in arid areas of the eastern part of Indonesia.

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WATER DESALTING PLANTS' EXPLOITATION EXPERIENCE ON THE NUCLEAR POWERED ICEBREAKERS AND THE NUCLEAR-POWERED FREIGHT-CARRIER "SEVMORPUT"

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Abstract

The experience from water desalting plants M4C-1 on nuclear-powered icebreakers and M3C on the nuclear-powered freight-carrier "Sevmorput" are discussed. The specific design features, including those for maintaining distillate quality, to be considered under conditions of roll, heel and hull impact loading are highlighted

1. DISCUSSION

The water-desalting plants used on the nuclear-powered icebreakers and the nuclear-powered LASH-carrier "Sevmorput" are the replenishment source for virtually all shipboard demands for fresh water:

- primary fill and makeup water for the steam cycle of the steam-turbine plant (with additional purification);
- working water for the charging and recharging systems for the steam cycle ion exchange filters;
- working water for automatic control system;
- working water for the control system for remote-controlled accessories;
- primary fill and makeup water for the primary and secondary circuits;
- humidification in the air-conditioning system;
- fresh water for domestic needs.

Furthermore, the fresh water is used:

- for water treatment for the primary circuit and secondary cooling circuit for the reactor plant (with appropriate additional purification and treatment);
- for treatment of potable water (with mineral addition and bactericide treatment).

The above mentioned uses on a nuclear-powered icebreaker of the "Arktika" class consume on the average 80 t/d of fresh water. This demand is met by two M4C-1 water-desalting plants, one of which is reserved; on the freight-carrier "Sevmorput" and nuclear-powered icebreakers of the "Taimyr" class by two M3C plants, one of which is also reserved.

Because the desalinated water is used for the nuclear power plant, it shall be of extremely high purity, and the water-desalting plants of increased reliability.

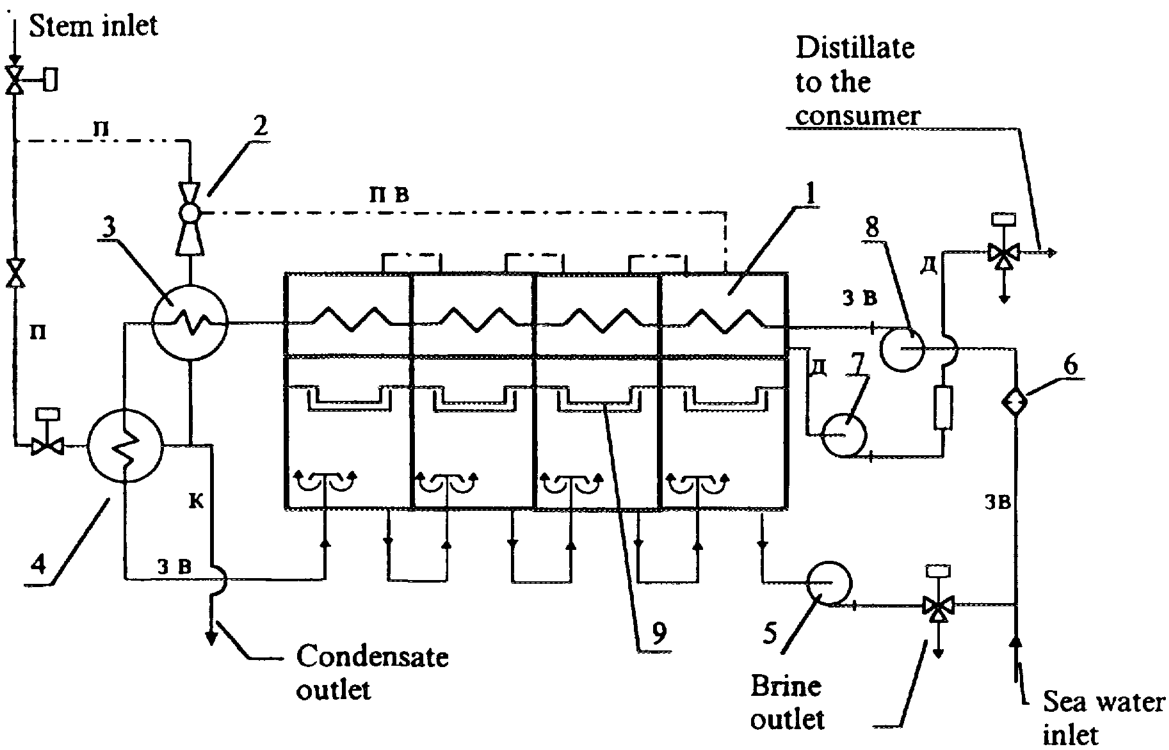
Their reliable operation is ensured under following conditions:

- static fluctuations to either side up to 15° without time restriction;
- dynamic inclinations (rolling) at an amplitude of 45° and a period of 7-14 seconds.

The water-desalting plants used on the nuclear-powered icebreakers and nuclear-powered freight-carrier “Sevmorput” are of the flash distillation type (Fig. 1).

The operating principle of the plant is based on partial flashing of seawater in the evaporator stages. In each stage the water enters heated to a temperature above the saturation temperature corresponding to the pressure in that stage, resulting from the condensation of secondary steam generated by flashing in that stage. In accordance with requirements imposed by the nuclear power plant, design features of the plant are such that a high quality of distillate at the outlet is achieved in comparison with the other desalination plant types.

The plant offers a special system for chemical cleaning of heat-exchange surfaces and is equipped with an automatic control, protection and monitoring system.

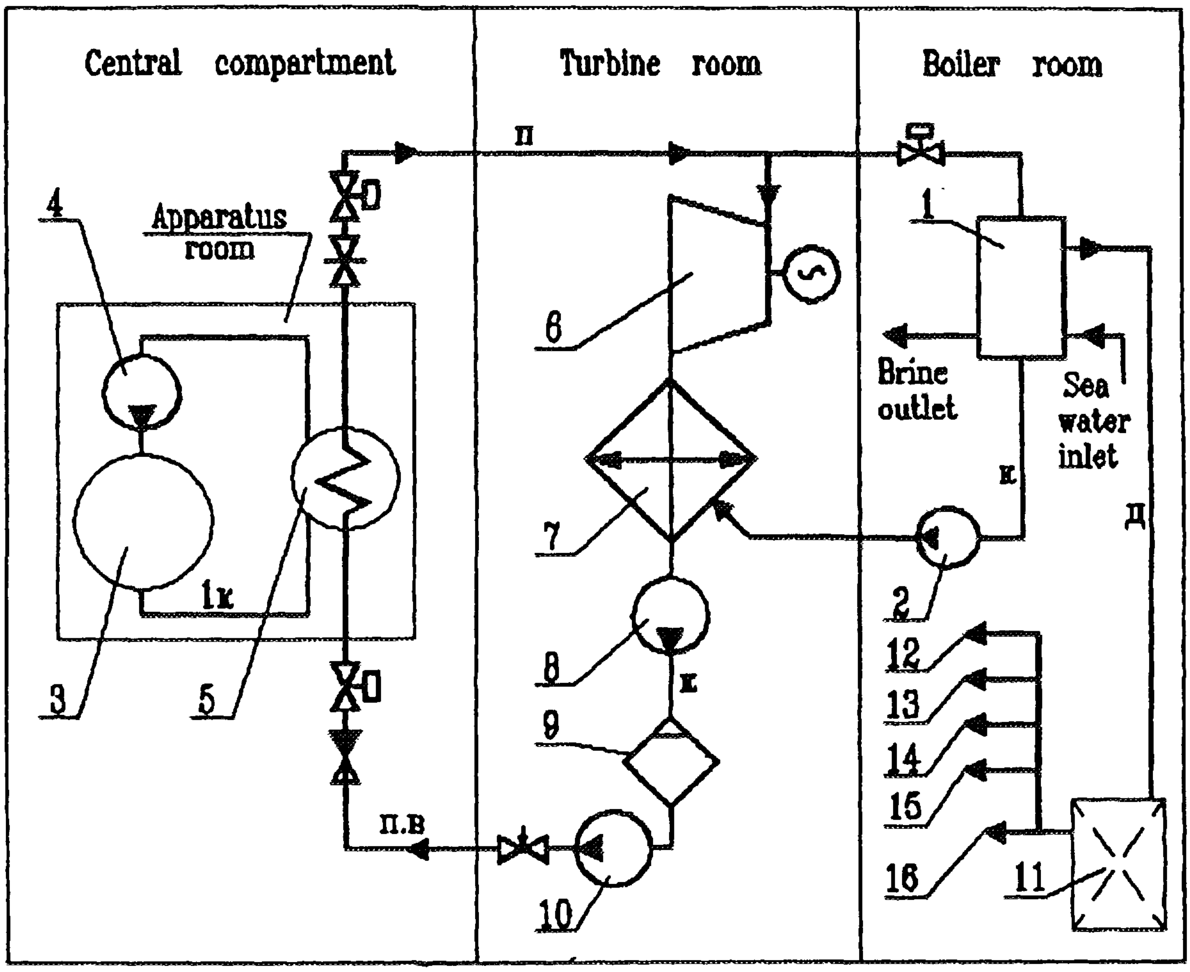


1- evaporator, 2 - steam ejector, 3 - ejector condencer,
4 - water heater, 5 - brine pump, 6 - filter,
7 - distillate pump, 8 - feed pump,
9 - washing device.
п - steam, **пв** - vapeur-air mixture, **зв** - sea water,
д - distillate, **к** - condensate.

Fig. 1. Diagram of the M4C-1 water desalting plant.

The working medium of the water-desalting plants is secondary circuit steam, generated by the reactor plant steam generators. The steam condensate, upon exiting from the surface heaters and ejectors of the water-desalting plant, is directed to the condensers of the main or auxiliary turbo-generators and returns to the "steam-condensate" cycle of the steam-turbine plant (Fig. 2).

The design and reliability of the reactor plant and a special steam-generator valve which, if necessary, is automatically or remote switched off, ensures the absence of radioactivity in the secondary circuit.



1 – water-desalting plant M4C-1 ,
2 – OY condensate pump, 3 – reactor, 4 – primary circuit water pump,
5 – steam generator, 6 – turbine, 7 – condenser, 8 – condensate pump,
9 – deaerator, 10 – feed pump, 11 – feed water reserve tank,
12 – distillate to the consumers of ПТУ , 13 – distillate for domestic needs, 14 – distillate to the potable water system, 15 – distillate for ВВЧ of primary circuit, 16 – distillate for replenishing steam-condensate cycle,

п – steam, k – condensate, д – distillate, п.в – feed water,
1k – primary circuit water.

Fig. 2. Switching diagram of water desalting plant in the steam-condensate cycle.

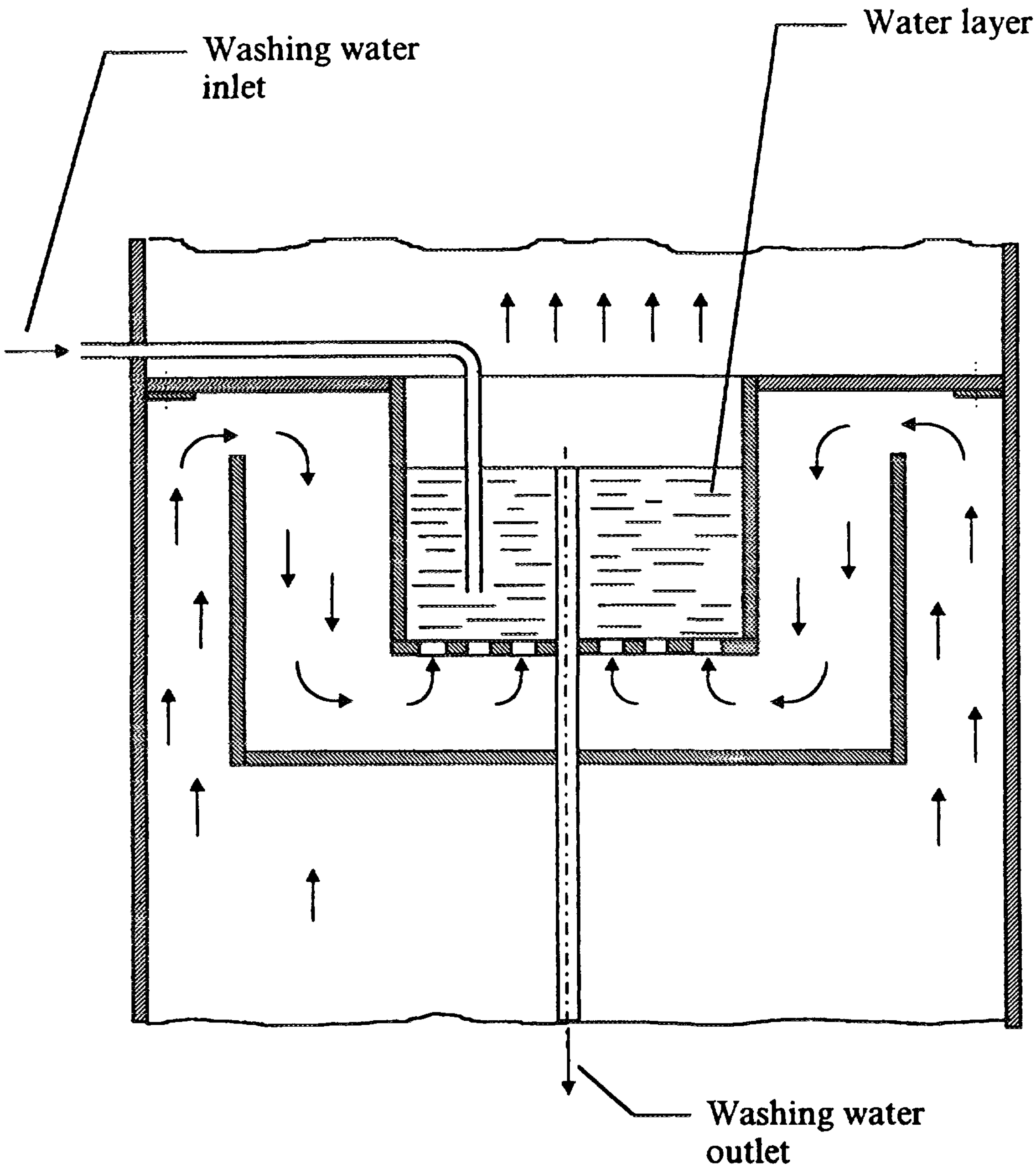


Fig. 3. Washing device.

At the present time 10 M4C-1 plants are working on nuclear-powered icebreakers of the "Arktika" class, and 6 M3C plants on the nuclear-powered icebreakers of the "Taimyr" class and the nuclear-powered LASH-carrier "Sevmorput". In total more than 50 M4C-1 and M3C plants are operating on ships of these types.

Based on the results of operating experience, an array of modifications was introduced in the design of plants in order to ensure or enhance the above mentioned main characteristics.

MAIN TECHNICAL CHARACTERISTICS OF WATER DESALTING PLANTS

Designation	Unit of measurement	Plant M4C-1	Plant M3C
Capacity	t/day	120	60
Content of salt in distillate	mg/l	1,5	2,0
Content of chlorine ions in distillate	mg/l	0,1	0,3
Distillate outlet temperature	°C	43	50
Steam pressure before plant	MPa	2,5 - 3.0	1
Steam temperature	°C	290	250
Steam consumption	kg/h	3,200	1,635
Sea water consumption	t/h	110	58
Sea water salinity	g/kg	41	41

Special attention was paid when running-in the plants to achieving stable distillate quality at the outlet. This depends on factors disturbing the evaporation processes, such as rolling, heeling and the ship's impact on ice.

Solving this problem required special washing devices (Fig. 3) which prevent mixing of salt steam with the separated clean steam. These devices do not allow the raising steam to leave the washing water layer even at ship's inclinations of up to 45°, or for capacity increases of 15-20%.

The effect of ship's roll and heel, if no special measures are taken, results in drastic changes to the thermal processes in the plant's horizontal heat-exchangers due to the exclusion of part of the surface from active heat exchange. This is solved through an appropriate arrangement of the horizontal tube bundles and design measures ensure a complete condensate removal from the apparatus even when inclined to either side.

Summarizing the 20-year experience of the first two M4C-1 plants built on the nuclear-powered icebreaker "Arktika", it is worth noting that during this time about 400 000 tons of distillate have been produced by the plants. After repair, consisting mainly of replacement of automatic control and protection system components, the plants continue to operate as designed.

The operating time between chemical cleanings is influenced by the quality of seawater. For example, on icebreakers operating in the northern latitudes the duration between cleanings amounts 2500-4000 operating hours. During operation of the M3C plants on ships which have spent long times in Mediterranean Sea, South Atlantic and Indian Ocean areas, the cleanings took place after 500-700 hours.

When operating water-desalting plants the quality of distillate produced can be negatively influenced by contamination of seawater with petroleum products, noxious substances, sewage, algae, etc.

In the event of such seawater intake conditions for the desalting plants, as a rule specific restrictions are placed on plant operation, especially when the distillate is to be used for domestic needs, preparation of potable and washing water.

2. CONCLUSIONS

1. The M4C-1 and M3C water-desalting plants installed on the nuclear icebreakers and freight-carrier "Sevmorput" have proved the full requirement for distillate and potable water. No emergency situations have arisen in the course of their use during the 20 years these plants have been in operation.
2. The designs implemented in the plants have provided reliable operation under shipboard conditions, with a service life of 100 000 hours.
3. The use of these plants in the offshore zone for producing distillate for technical needs is possible. To obtaining potable water, more extensive design measures are needed for pretreatment of seawater containing adverse materials and bacteria.
4. The presence of a nuclear plant on the ship does not result in any adverse effect on the quality of the distilled water. The water-desalting plants are isolated from the reactor plant; the secondary steam circuit has no direct contact with the distilled water.

EXPERIENCE IN THE DEVELOPMENT AND MASTERING OF LARGE DISTILLATION DESALTING PLANTS

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Abstract

At present there are more than 30 desalination plants, including the first nuclear desalination plant in Aktau, developed by SverdNIIchimmash are in operation. This report gives a short description of the experience in the investigation, development and mastering of the Russian water distillation technique and the future investigations. Based on the past 40 years experience and scientific investigations, the multistage distillation desalting plants with horizontal tube film evaporators is recommended for the floating nuclear desalination complexes.

1. INTRODUCTION

In 1992 the Sverdlovsk scientific research Institute of chemical machine-building (SverdNIIchimmash) took part in the conceptual development of a floating nuclear desalination complex consisting of a large ship with a nuclear energy source (the KLT-40 reactor), a distillation desalting plant (DDP), a unit for water conditioning and all necessary auxiliary services. The Institute was the developer of the DDP. The questions regarding choice of plant type, its specifications and coupling with the reactor are reflected in the corresponding technical reports and also are described in this report.

2. SVERDNIICHIMMASH DEVELOPMENTS IN THE FIELD OF THE TECHNIQUE AND PROCESS OF THERMAL DESALINATION

The Institute is the leading developer of DDP in Russia. Most of the seawater desalination plants and those for industrial effluent treatment operating in the former USSR are erected as SverdNIIchimmash projects.

Between 1964 and 1985 twelve DDPs were built and commissioned in the town of Shevchenko (now Aktau) with a total output of about 160 000 m^3 of distillate water per day. The plants formed a desalination works, that from the first half of the 70's consumed heat energy from a fast breeder nuclear reactor and up to now is the only nuclear desalination complex in the world. Three generations of Russian thermal desalination techniques have developed there.

The first generation refers to the 60's, and is not worth consideration here, as it is old and does not comply with the requirements of the evaporator arrangement on a floating ship.

The second generation (70's) is represented by two types of DDP: one of them being improved plants of the first generation with a greater number of evaporation stages (10), equipped with vertical tube evaporators with forced circulation; the second being the so-called multi-stage flash plants (MSF), with 34 to 42 stages. Both of them are characterized by distillate output per ton of steam in the range of 7.5-8.5 t. To lower the metal content heat transfer intensification was incorporated for the first time through the use of heat exchanges tubes with fine-fluted surfaces.

The third generation (from the end of 70's) is also based on the principle of multi-stage evaporation, but with the application of horizontal-tube evaporators being sprinkled by saline water to cause heated steam to condense inside the horizontal tubes. The advantages of this principle are well known.

These include its high intensity of heat transfer at low temperature differences between the heat-carrier and a thin film, flowing down the outer tube surface, and the practical absence of temperature difference losses from water superheating in the heat exchangers and from the incomplete boiling-away, which is characteristic of the MSF-type plants. This allows plants with a large number of evaporation stages (10-20 or more) and high distillate output per ton of steam consumed (9-17 t) to be developed. Absence of tedious evaporation chambers (water evaporation and initial steam separation processes occur directly in a tube bundle) results in a sharp decrease in metal content and high equipment compactness. An additional safety factor appears: distillate is not "salted" even through corrosion cracks in the heat exchanger tubes, as operating pressure drop on the tube wall between the heating steam and the evaporating film of saline water is always positive.

Standard size plant for outputs of 240, 600, 1 200, 4000, 8400 and 16 800 m³/day have been developed by the Institute. Their characteristic feature relative to similar plants of well-known European, Japanese and American companies consists of the application of pressureless sprinklers for tube bundles. This allows different process diagrams for multistage evaporation to be realized: with concurrent feed, concurrent-cascade feed and others which take the best approach for the specific operating conditions. It also allows arranging horizontal-tube stages one over another into multistage evaporators' modules, which is particularly important for siting on a ship. Pressureless sprinklers have been studied and developed in cooperation with the Nuclear Research Center in Grenoble (France).

At present not less than 30 desalination plants, with a total output of 11 500 m³/h or about 262 000 m³/d of distillate, developed by SverdNIIchimmash are in operation. Their unit output is from 240 to 15 000 m³/d. Their application is for fresh water production from seawater, production of high purity make-up water for boilers and steam generators and processing of saline effluents, as well as any combination of these applications. The main first generation plants, with the except of DDP, the are given in the table below.

Abbreviations in the table are as follows: ВПЦ – multi-stage evaporation, forced circulation evaporators; MSF - flash evaporation; HTFE - multistage evaporation, horizontal-tube thin-film evaporators (with tube bundles being sprinkled); ВП – multistage evaporation, vertical-tube evaporators with climbing film; OMB - seawater desalination for fresh water production; ПК - boiler and steam generator make-up; OC - desalination of saline industrial effluents.

Apart from those mentioned above, nearly twenty DDP are being built and projects for approximately the same number of plants have been established with the customers. Practically all the developments of the Institute over the past few years are based on the use of third generation thermal desalination equipment with the application of horizontal tube evaporators. Two 21-stage DDP, each with an output of 840 m³/h, are suggested as the equipment for a floating nuclear desalination plant.

Region commissioning year	Type	Stage number	Output m^3/d	Distillate output per 1 t steam, m^3	Energy consumption kwh/t distil.	Application
Shevchenko (Aktau) 1971-1975	ВПЦ	10	3 x 14400	7,8	3.2	ОМВ, ПК
Shevchenko (Aktau) 1980-1992	ВПЦ	10	5 x 15000	8.1	3.3	ОМВ, ПК
Krasnovodsk 1980	ВПЦ	10	1 x 14400	7.8	3.2	ПК
Fergana 1979-1986	MSF	34	3 x 13000	7.7	3.0-3.5	ОС, ПК
Bekdash 1974	MSF	42	1 x 2400	7.9	3.0-4.0	ОМВ, ПК
Shevchenko (Aktau) 1987	HTFE	6	1 x 12000	5	1.5	ОМВ
Novocherkassk 1991	HTFE	10	2 x 200	8.5	1.5	ОС
Urengoi 1993	HTFE	10	1 x 220	8.8	1.5	ПК
Tobolsk 1987-1989	ВП	9	2 x 10000	7.8	1.7	ПК
Mari 1984-1994	ВП	8	5 x 2400	7.0	1.7	ОС, ПК

Equipment manufacturers for the desalination plants in Russia are large well-equipped enterprises in the chemical and power machine-building industry, familiar with modern engineering: Uralkhimmash in Ekaterinburg, Atommash in the Rostov region and others.

3. SCIENTIFIC INVESTIGATIONS

While working on the development of desalination plants of all three generations, great attention was paid to the level of technical decision optimization, based on the necessary scientific evidence. In laboratory, as well as industrial plants of different scale, experimental investigations into the main thermal, physical and hydro-mechanical processes occurring in the DDP equipment were carried out. These included heat and mass exchange during boiling and condensation, gas- and hydro-dynamics, steam separation, vacuum deaeration, prevention of scale formation and corrosion protection of construction materials. The most important results are given below.

3.1. Thermal-physical investigations

A method of improving the heat exchange from steam condensation by means of using vertical tubes with fine fluted outer surfaces was developed for the second generation plants. This ensures an increase in heat transfer from the steam to the tube wall by a factor of 3-5 as compared to smooth tubes. The production process for such tubes has been optimized. They are manufactured at two plants in Russia, and for the first time have been used in large DDP.

The characteristics of the steam condensation process in the presence of non-condensable, gases both on fluted and smooth tubes, has been studied; methods of tube bundle ventilation and heat exchange calculation have been developed.

Kinetics of the evaporation process in the case of superheat in the absence of equilibrium has been investigated; equations have been obtained for the evaluation of such a residual superheat as a function of initial superheating, boiling temperature and other process parameters as applied to ASP chambers and overflow devices of different shapes.

Thorough investigations were carried out into heat transfer and hydrodynamics for the development of horizontal tube and vertical tube film evaporators (with rising and falling films); engineering techniques to calculate heat exchange as a function of the main process parameters have been developed.

The problems of hydro- and gas dynamics for tube and inter-tube spaces have been studied for HTFE-evaporators, with which the plants of the third generation are equipped. Different variations of tube bundle arrangement and methods of surface sprinkling have been investigated; construction of pressureless sprinklers, mentioned above, have been developed.

Theoretical and experimental investigations into steam separation have been carried out. Two types of water drop entrainment with steam at boiling and evaporation have been studied: transport liquid entrainment and toss. Characteristics of these processes are found and described for three models: boiling in the water volume with a free level, evaporation in the chambers of the MSF plant and evaporation in a horizontal tube bundle being sprinkled. Boundary conditions and small flow separator efficiency have been experimentally determined.

Research work on steam drop condensation in the DDP equipment, as well as the use of thin-walled polymer tubes as heat transfer surfaces, has been carried out.

3.2. Scale formation control

A method of preventing scale formation based on the recirculation of fine crystalline seed in seawater evaporators was developed, experimentally tested and applied in a number of industrial DDP, including the desalination plant in Aktau.

The rate of calcium carbonate scale precipitation was studied under the operating conditions of the desalination plant heat exchange equipment. The results are summarized in the form of equations, giving the relation of the scale precipitation rate to the process driving force and mass transfer coefficients, permitting calculation of this rate for the seawater heating and evaporation processes under "actual" conditions (without the anti-scale agent) and with the use of scale control systems and metering anti-scale polyelectrolytes in particular.

The mechanism and the anti-scale effect of a number of anti-scale agents (polyelectrolytes, synthesized in the Urals Wood Engineering Academy) were investigated. In Russia and Kazakhstan industrial synthesis of two anti-scale agents has been mastered: ПАФ-13А and ИОМС, which are used both in desalination plants and in thermal heating and hot water supply networks. Both anti-scale agents have one and the same basis: sodium salt-polyethylene-polyamine-N-phosphoric acid, and as commercial products represent a liquid with a density higher than that of water. They are non-corrosive when used with ocean water and Mediterranean sea water in DDP with horizontal sprinkled tube bundles. They are highly efficient at operating temperatures up to 110°C and with TDS of 3-5 mg/kg (ppm). An annual consumption of such an anti-scale agents for the operation of a nuclear-desalination complex KLT-40 is about 100 m^3.

3.3. Construction materials, corrosion and corrosion protection

Thorough investigations of the kinetics and corrosion mechanism of construction materials in seawater and other neutral salt solutions were carried out. The theoretical basis for corrosive electrochemical interaction of metals and alloys with a flow of heated seawater was developed. On this basis new construction materials were created. The corrosion resistance of a number of stainless and low alloyed steels, copper-base alloys, aluminum and titanium alloys was investigated and tested under conditions typical of the operation of industrial equipment. Corrosion protection methods were developed.

For the desalination plant of a floating complex, the following materials are recommended: for heat transfer surfaces - aluminum brass, stabilized by arsenic and titanium alloy; for cases and inner elements in contact with seawater - 316L type stainless steel.

4. FUTURE INVESTIGATIONS

One of the most recent scientific research works of the Institute is the development of the method and process for heat exchange intensification in the modern type of evaporators, DDP horizontal tube thin-film evaporators (HTFE). Only these evaporators are now offered by the Russia for the use in the floating KLT-40 desalination plant.

It is known that heat exchange intensification is the most efficient method for decreasing the metal content and dimensions of the equipment, which is highly advantageous for any desalination plants arranged on ships where there are limitation on the size and weight of the plant.

The heat exchange intensification method is based on profiling the outer surface of the horizontal sprinkled tubes, ensuring a decrease in thermal resistance. Resistance to heat transfer from the wall to the flowing liquid film, which is a factor of 2-3 higher than that for steam condensation inside the tubes, is limiting for HTFE.

The scientific development was established on the theoretical and experimental investigations into the mechanism of heat exchange when liquid film flows along the horizontal tubes with either smooth or fluted outer surfaces. The results were based on systematic experimental investigations into local and average heat transfer in a broad range of process and design parameters characteristic of the behaviour of industrial HTFE.

Such a thorough study of this type of heat exchange process has not performed in other countries. There is no documented substantiation in publications on the choice of the surface profiling to intensify heat transfer to the liquid film. Data obtained as a result of these experiments allowed, for the first time, a definite type of longitudinal fluting of the outer tube surfaces in HTFE to be suggested.

As applied to evaporators, a correlation based on parameters related to fluting geometry was found. This provides for increase of the heat transfer to a liquid film by a factor of 1.4-1.9 compared to a smooth surface. Such values were obtained over a wide range of process parameters; in so doing the increase in overall steam-liquid heat transfer rate amounts to a factor of 1.3-1.5, with a negligible surface increase (on the average by a factor of 1.08).

In the course of testing the various shapes, an additional aspect of the benefit of using longitudinally fluted tubes was found. Their use allows improvement in the uniformity of tube bundle sprinkling by the liquid, increasing film stability on the tubes and widening the operating flow rate range. It was found that the lowest permissible flow rate values (to achieve complete wetting of the tube surface by liquid film) decrease by a factor of 1.5-2 as compared to the smooth tubes. The upper values of the operating flow rate also increase. At this flow rate almost all liquid is kept on the tubes without its dropping from the heat exchange tubes. Both of these effects are due to surface tension, spreading liquid along the tubes and holding it on the fluted surface.

Therefore the application of longitudinally fluted tubes is especially advantageous for evaporators for floating desalination plants, as it allows increased reliability of operation even with possible changes in the liquid flow rate along a tube bundle caused by the ship's oscillating motions.

This new method of convective heat exchange intensification is suitable not only for DDP evaporators but also for any heat-operated equipment which involves gravitational flow of vaporizing, heating or cooling liquid film along horizontal sprinkled tube bundles: preheaters, condensers, deaerators, cooling units and others.

5. CONCLUSION

The 40 year experience of SverdNIIchimmash and its partners in the development of thermal desalination techniques provides a basis for recommending that multistage distillation desalting plants with horizontal tube film evaporators be used for floating nuclear desalination complexes, as they are the most modern, compact and efficient in the consumption of thermal and electric energy. In the author's opinion, this type of DDP is more adaptable than MSF to installation and operation in a floating complex, and is characterized by the absence of large moving water masses with a free surface, which would be sensitive to a ship's oscillating motions during operation. Longitudinally fluted outer tube surfaces providing additional compactness and sprinkling reliability are recommended for heat exchange surfaces of HTFE type DDP.

Russian development centres and machine-building enterprises are capable of providing the complete development, manufacture and supply of desalination plants for floating nuclear desalination complexes.

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