A FLOATING DESALINATION/CO-GENERATION SYSTEM USING THE KLT-40 REACTOR AND CANADIAN RO DESALINATION 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 resulting nuclear desalination/cogeneration plant makes 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. These innovations have led to improved water production efficiency, lower water production costs and reduced environmental impact.

The Russian Federation is developing the KLT-40 reactor for application as a Floating Power Unit (FPU). The reactor is ideally suited for such purposes, having had many years of successful operation as a marine propulsion reactor aboard floating nuclear powered icebreakers and other nuclear propelled vessels. Under the terms of a cooperation agreement with the Russian Federation Ministry of Atomic Energy, CANDESAL Enterprises Ltd. has evaluated the FPU, containing two KLT-40 reactors, as a source of electrical energy and waste heat for RO desalination. A design concept for a floating nuclear desalination complex consisting of the FPU and a barge mounted RO desalination unit has been analyzed to establish preliminary performance characteristics for the complex.

The FPU, operating as a barge mounted electrical generating station, provides electricity to the desalination barge. In addition, the condenser cooling water from the FPU is used as a source of preheated feedwater for the RO system on the desalination barge. The waste heat produced by the electrical generating process is sufficient to provide RO feedwater at a temperature of about 10°C above ambient seawater temperature. Preliminary design studies have indicated that under these conditions approximately 100,000 m^3/d of potable water can be produced. The use of preheated feedwater results in an improvement in water production efficiency of up to about 15% relative to a system operating at the ambient seawater temperature.

This preliminary design study has shown that significant improvements in the cost of water production can be achieved through this "marriage" of Russian small reactor technology and Canadian RO technology. The potential benefits warrant further detailed evaluation followed by a demonstration project.

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1. INTRODUCTION

In many regions of the world the supply of renewable water resources is inadequate to meet current needs, and that from non-renewable sources is being rapidly depleted. Since the worldwide demand for potable water is steadily growing, the result is water shortages that are already reaching serious proportions in many regions, with the threat of global water starvation continuing to grow. To mitigate the stress being placed on water resources, additional fresh water production capability must be developed. For many regions seawater desalination is the best alternative. The main drawback of desalination, however, is that it is an energy intensive process. Therefore, the increasing global demand for desalted water creates a tremendous collateral demand for new sources of electrical power. Since water is an undeniable life sustaining resource, improvements in the efficiency of energy utilization must be considered a significant benefit to both the environment and the consumer. CANDESAL Enterprises Ltd. is a Canadian company working internationally to improve the energy efficiency and economics of fresh water production and to deliver that technology to markets where such facilities are most required.

In December 1994 the International Atomic Energy Agency (IAEA) sponsored one of a series of conferences on nuclear desalination in Cairo, Egypt. The Russian delegation at that conference met with the CANDESAL delegation to discuss a project that was in the planning stages by the Ministry of Atomic Energy's (MINATOM) Design and Engineering Bureau, OKBM. The project was to design and build a series of floating barges using nuclear reactors for electrical generation and as an energy source for desalination. The initial objective was to meet the requirements of the resource industries working in Russia's northern littoral, and then to use these floating desalination/cogeneration barges to help meet the world demand for additional energy and water production, particularly in the Middle and Far East. In the conceptual stages of the project, primarily distillation systems were being considered. However, the work done by CANDESAL was clearly showing the potential for significantly reducing the production costs of potable water through the use of reverse osmosis (RO) technology. In view of the potential benefits, it was agreed that a cooperative venture should be undertaken to evaluate the use of RO desalination with the Russian power barges. Following these preliminary discussions a Memorandum of Understanding (MOU) between MINATOM and CANDESAL was signed in 1995 for a period of two years. This MOU has recently been extended for a period of five years.

2. WATER SCARCITY, A GROWING GLOBAL CONCERN

There is a growing international recognition that the shortage of adequate supplies of potable water, which has already reached critical proportions in many areas of the world, is one of the major problems facing society as the 21st century approaches. There is also an acknowledged need for additional electrical generation capacity throughout the developing world. Frequently, these shortages in potable water supply and electrical energy exist together.

The supply of naturally occurring fresh water available for human use is limited. It consists of non-renewable sources such as aquifers and other reservoirs that are not recharged as they are used, and renewable sources such as lakes, rivers, reservoirs and other sources that are replenished by the annual water, or hydrologic, cycle. However, the amount of water available in a given location as a result of the natural water cycle is essentially fixed. Thus as the population increases, the annual water supply per person, which is a general indicator of water security, decreases. The per capita water supplies worldwide are approximately one third less now than in 1970 due to population growth since that time.[1] The water supply crises which already exist and are projected over the next few decades have received much attention recently.[1-6] Population Action International expressed the concern quite succinctly when they stated[6] that "without water, economic development becomes virtually impossible and conflict over scarce resources virtually inevitable" and "availability of and access to clean water and sanitation are among the most important determinants of the health of individual human beings."

Figure 1[7] illustrates the percentage of urban populations with access to safe drinking water. It is estimated that around the world approximately one billion people do not have access to safe water, and 1.8 billion do not have adequate sanitary facilities. The lack of water is a detriment to human health to these people.

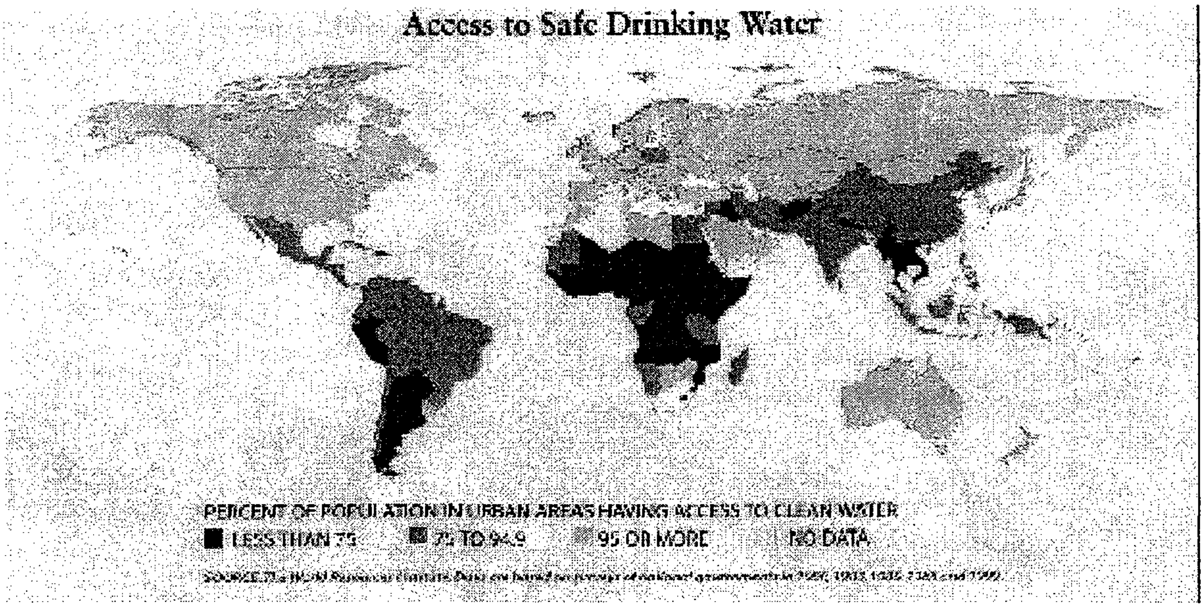


Figure 1
Percentage of Urban Population Having Access to Safe Drinking Water

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

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

Since renewable fresh water resources are essentially constant, the per capita availability falls as population rises, pushing more and more countries over time into water stress and water scarcity. Figure 2 illustrates on a global basis the countries projected to experience water stress or water scarcity by the year 2025, based on a United Nations medium population projection.[6]

3. DESALINATION AS A SOURCE OF POTABLE WATER

Seawater is the largest source of available water. It is estimated that only 2.5% of the earth's 1.4 billion km^3 of water is fresh water, and 69% of that is in the form of ice (polar ice caps and glaciers) or in underground aquifers too deep to tap. The amount of fresh water that is available is essentially fixed, and as the population continues to grow, the per capita availability shrinks. Seawater, on the other hand, is available in essentially unlimited quantities in the foreseeable future, and is still relatively unpolluted compared with natural fresh water sources many regions of the world.

As other sources of water have become increasingly scarce and increasingly expensive to make available, desalination of seawater has become a more attractive option for the production of potable water. By the late 1960s commercial units of up to 8,000 m^3/d were beginning to be installed in various parts of the world. These were primarily thermal distillation units, but by the 1970s commercial membrane processes were also becoming available. Figure 3 illustrates the rapid growth

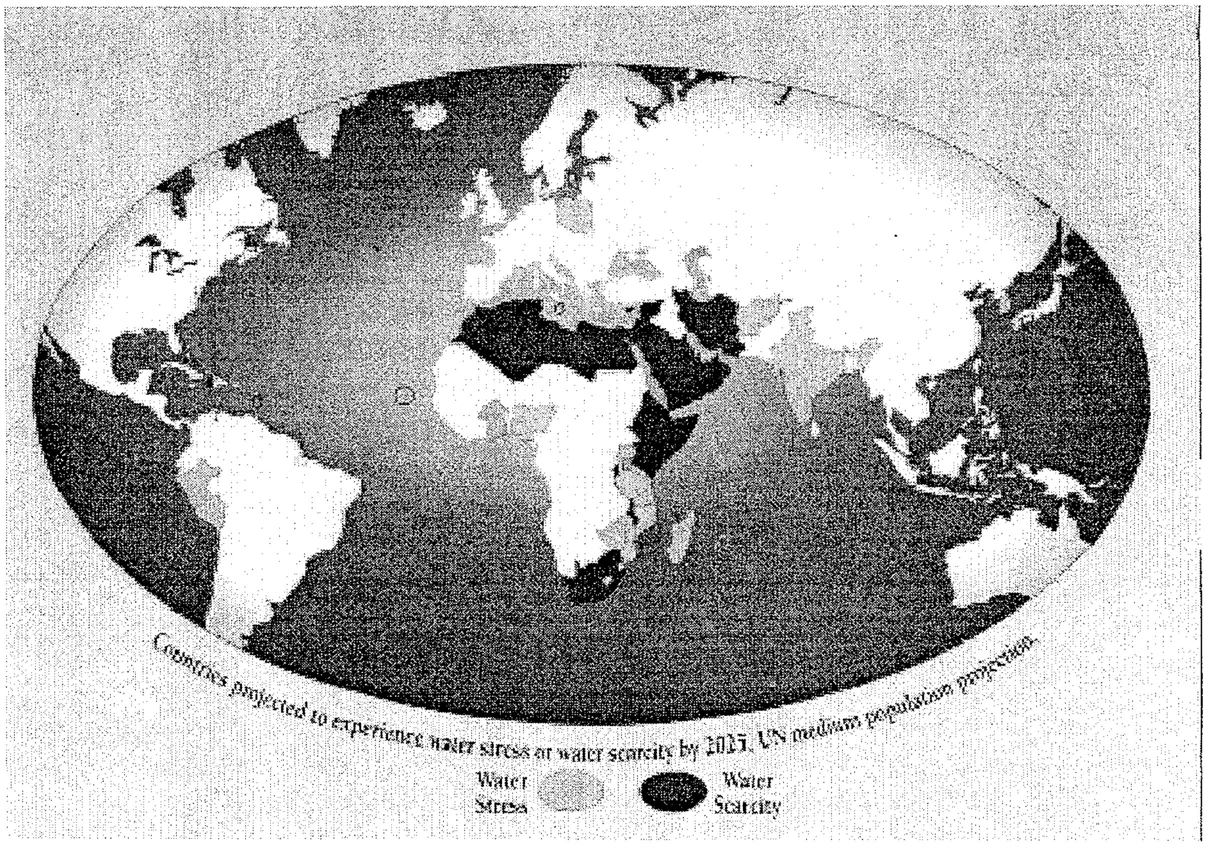


Figure 2
Population and Water Availability

of desalination as a source of potable water since that time. As of 1995, there were about 20 million m^3/d of desalination capacity either installed or contracted for around the world. That number is expected[8,9] to increase to well over 35 million m^3/d over the next ten years.

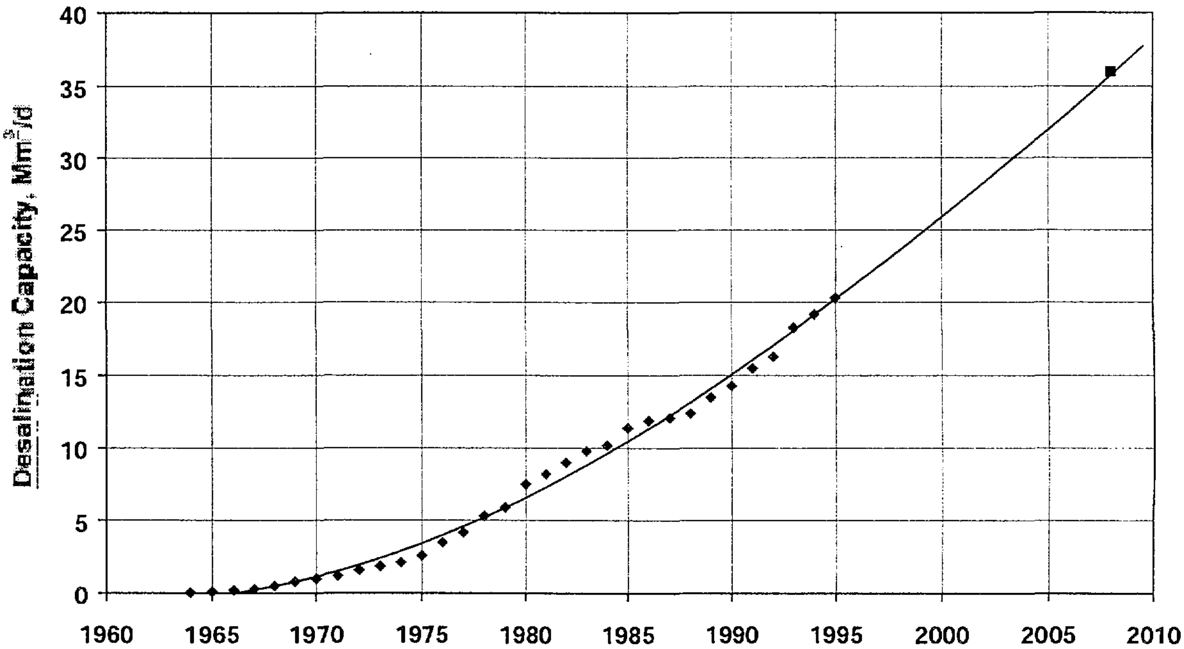


Figure 3
Worldwide Contracted Cumulative Seawater Desalination Capacity

Recognizing the severity of the problem of global water shortages and the immensity of the energy requirement necessary to adequately address the problem, the International Atomic Energy Agency (IAEA) has been working since 1989 to assess the technical and economic potential for using nuclear reactors as a source of energy for seawater desalination. The results of studies[8-10] carried out by the IAEA and its Member States have shown that the use of nuclear energy for desalination is technically feasible and in general economically competitive with fossil-fueled energy sources. As a result of the success of its efforts to date, the IAEA is expanding its nuclear desalination program, and is actively supporting efforts amongst Member States to introduce nuclear desalination demonstration projects.

4. A FLOATING NUCLEAR DESALINATION/COGENERATION SYSTEM

4.1 Development of the CANDESAL Design Approach

Because of the pressing need for additional large scale water production capability, the focus of CANDESAL's early design concept development work was placed first on the use of the CANDU nuclear reactor as an energy source for desalination. Two approaches were considered in preliminary studies: the use of electrical energy for reverse osmosis (RO) and the use of process steam from the nuclear steam supply system to provide the energy for a multi-effect distillation system. This latter approach was found to require changes to the balance of plant design that were both expensive to implement and led to reduced electrical generating efficiency to such a degree that the total water and electrical production capacity was not as great as that which could be achieved using RO.

Having selected the RO process, it was then recognized that improvements in the efficiency of energy utilization could be achieved by taking advantage of waste heat normally discharged from the reactor through the condenser cooling system. Use of the condenser cooling water as preheated feedwater to the RO system improves the efficiency of the RO process, and therefore the economics of water production. As the development work progressed, it was also found that further improvements could be achieved by taking a systems approach to optimizing the design. Hence a strong emphasis has been placed on the integration of the energy and water production systems into a single, optimized design for the cogeneration of both water and electricity. Details of the CANDESAL approach to the application of RO seawater desalination technology have been described elsewhere[11-15].

This approach to the integration of seawater desalination systems with nuclear reactors has the advantage of maximizing the benefits of system integration while at the same time minimizing the impact of physical interaction between the two systems. In essence, the reactor operates without "knowing" that there is a desalination plant associated with it. Transients in the desalination plant do not have a feedback effect on reactor operation. This is extremely important, since there must be a high degree of assurance that unanticipated operating transients in the desalination unit do not have an adverse impact on either reactor safety or operational reliability. Conversely, it would also be undesirable to have reactor shutdowns, whether unanticipated or for planned maintenance, that would require shutdown of the water production plant.

Hence as the CANDESAL nuclear desalination/cogeneration system design has developed, it has evolved in a direction which allows standardized reactor systems to be used without modification, while at the same time accruing significant benefits from the systems integration due to improved performance characteristics and energy utilization. Furthermore, because of the "loose" coupling to the reactor system, the use of RO with preheated feedwater is ideally suited for application with small marine reactors such as the Russian KLT-40, since it allows the economic benefits of integrating the energy generation and desalination systems without sacrificing the flexibility of the smaller reactors, including its use in floating systems.

4.2 The Floating Nuclear Seawater Desalination/Cogeneration Complex

The floating nuclear seawater desalination/cogeneration plant consists of two floating structures: a floating power unit (FPU) and an RO seawater desalination barge. This arrangement, which separates power generation and potable water production, has certain advantages over an arrangement in which they are combined on one floating structure. It allows either of the two systems to be used independently, and it allows manufacture in two separate shipyards if desired. It also simplifies a solution to the problem of preserving efficient potable water production from the complex when the reactors are shutdown by supplying the desalination ship with electric energy from a shore grid. Advantages of a floating desalination/cogeneration complex relative to a shore-based installation include:

- the possibility of plant manufacture and testing at a shipyard in the Supplier country;
- high fabrication quality at a shipyard and "turn-key" delivery in a short period of time;
- 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;
- the possibility of installation in different coastal regions of the world; and
- ease of redeployment of the facility to other locations if the need should arise.

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

The second structure, the desalination barge, is a non-self-propelled structure housing systems and equipment providing for the supply of seawater to the desalination system, pretreatment of the feed supply, desalination, supply of desalinated water to the on-shore distribution system, and cleaning of the desalination units.

Based on this two barge concept, OKBM has established design and performance characteristics for the FPU sufficient to allow preliminary design work to proceed on the desalination barge. These characteristics have been provided to CANDESAL for use in the desalination system analysis. The conditions taken as input to the analysis were:

Reactor/Condenser Design Parameters

• Number of reactors per system	2
• Electrical power production, per reactor	35 MWe
• Total electrical production	70 MWe
• Electrical power consumed as "house load"	5 MWe
• Condenser cooling water flow rate, per reactor	5400 m^3/hr
• Total condenser cooling water flow rate	10,800 m^3/hr
• Temperature rise across condenser	10°C

Seawater Conditions

• Seawater temperature (design value)	18°C
• Seawater total dissolved solids (TDS)	38,500 ppm

4.3 RO System Conceptual Design Analysis

The RO system design is based on using spiral wound Dow FilmTec high rejection membranes for seawater desalination. Condenser cooling water being discharged from the reactor's condenser cooling water system at a temperature 10°C above ambient seawater temperature is used as feedwater for the system. The water first passes through ultrafiltration (UF) pretreatment modules. The filtrate from the UF units is sent to capacitance tanks, from which suction is taken for the RO modules. The feedwater is pumped to high pressure (1000 psi) and then passes through the RO modules. The permeate from the RO membranes is discharged temporarily into potable water storage tanks, and from there goes to an off-ship distribution system. Brine concentrate from the RO system is discharged back into the sea. Chemical pretreatment of feedwater and post-treatment of potable water is included as necessary.

The RO system design has been for optimum water production at 28°C, while still maintaining the capability for water production within the design specification of the RO membranes when operating at ambient seawater temperature. Based on the design inputs specified above, the desalination plant, consisting of a UF pre-treatment system and the RO desalination system has the following characteristics:

UF System

•= Feed flow into UF modules	259,000 m^3/d
•= UF system recovery	90 %
•= UF filtrate flow	233,000 m^3/d
•= Number of UF vessels	1800
•= UF membranes per vessel	4
•= Total number of UF membranes	7200

RO System

•= Feed flow into RO system (UF filtrate)	233,000 m^3/d
•= RO system design temperature	28 °C
•= RO system operating pressure	1000 psi
•= RO system recovery (at 28 °C)	43.3 %
•= Permeate flow	101,000 m^3/d
•= Number of RO vessels	1500
•= RO membranes per vessel	7
•= Total number of RO membranes	10,500

Overall System Characteristics

•= Number of 10 vessel by 10 vessel UF arrays	18
•= Dimensions of 10x10 UF array (Includes 4m x 5m x 6m space at end of array for pumps, headers, etc.)	4mW x 5mH x 14mL
•= Number of 10 vessel by 10 vessel RO arrays	15
•= Dimensions of 10x10 RO array (Includes 4m x 5m x 6m space at end of array for pumps, headers, etc.)	4mW x 5mH x 14mL
•= Weight of membrane and vessel arrays (Includes water contained in the membranes/vessels)	1000 metric tons
•= Total weight of system	15,00-20,00 metric tons
•= Electrical power consumption for water production	18-19 MWe

4.4 High Ambient Seawater Temperatures

The above design characteristics are based on 18°C seawater. Calculations have also been carried out for seawater temperatures of 30°C (40°C preheated RO feedwater), which is more representative of temperatures along the coastline of some of the countries where a floating nuclear desalination system would have potential application. Analysis results are very similar, except that only 1200 RO vessels, containing a total of 8400 membranes, would be required. Hence only 12 RO arrays would be required under these conditions. However, since it is important that the design be able to accommodate a range of seawater temperatures, at this preliminary stage the 18°C seawater temperature has been retained as a design basis. The UF section remains essentially unchanged at the higher temperatures.

4.5 Performance Analysis

In order to ensure that the RO system design meets all specified design conditions over the entire range of operating temperatures, without exceeding any design or performance limitations imposed on the RO membranes by the manufacturer, parametric design calculations over a range of operating temperatures are required. Figure 4 shows the potable water production capability at elevated temperatures relative to that at the 18°C ambient seawater temperature. As can be seen from Figure 4, the potable water production capability with 10°C of RO feedwater preheat is about 13% higher than that for ambient seawater temperatures under these conditions.

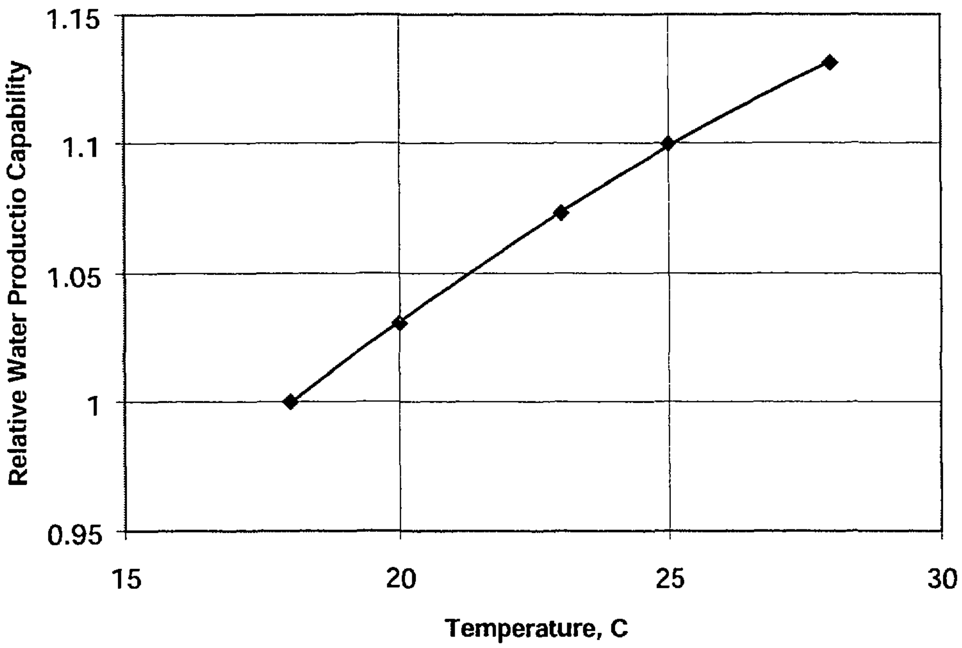


Figure 4
Relative Potable Water Production Capability as a Function of RO System Feedwater Temperature

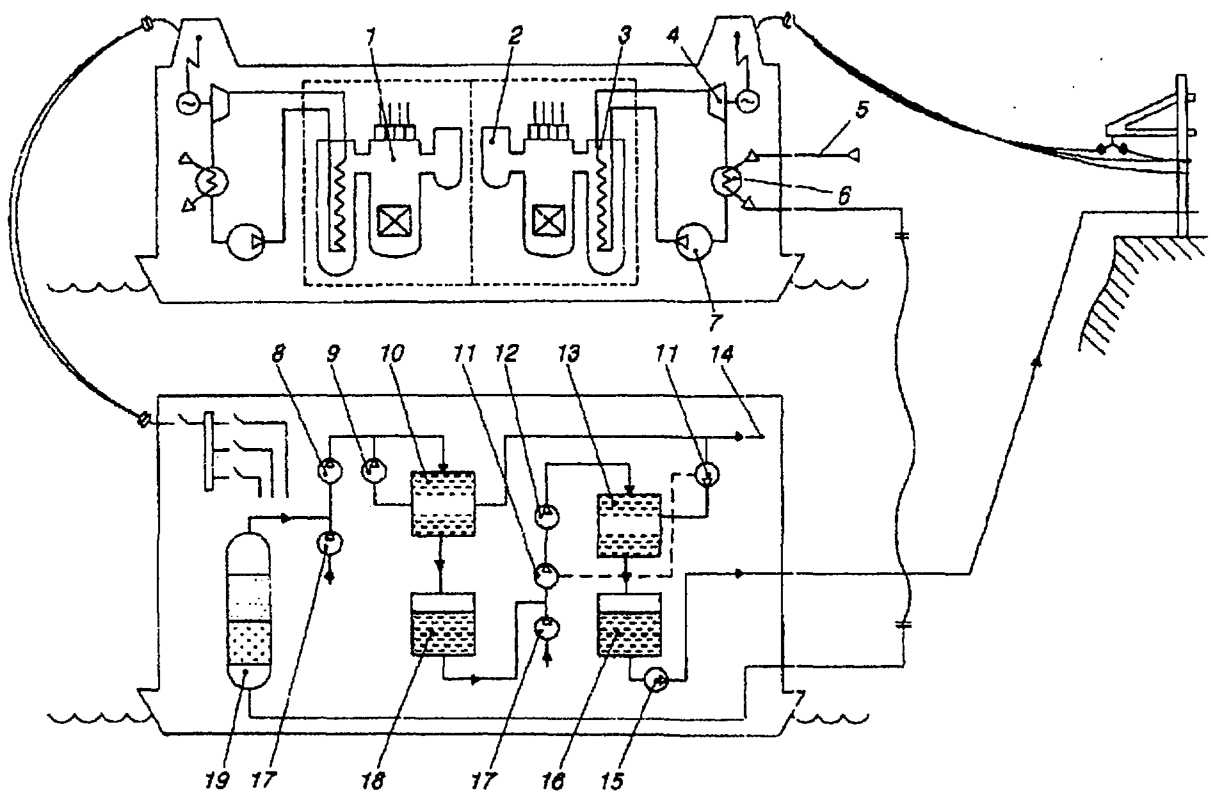
The detailed results from the analysis of RO system characteristics as a function of temperature are presented in Table 1 below.

Table 1
RO System Design Characteristics as a Function of Feedwater Temperature

Temperature, °C	18	20	23	25	28
RO System Feed Flow, m^3/d	233088	233088	233088	233088	233088
Recovery, %	38.4	39.5	41.2	42.2	43.4
Potable Water Flow, m^3/d	89459	92175	96000	98375	101186
Potable Water TDS, ppm	339	357	388	410	442
Energy consumed, MW (approximate)	18.5	18.5	18.5	18.5	18.5
Energy consumed, $kW \cdot h/m^3$	4.96	4.81	4.63	4.51	4.39
Relative Water Production	1.0	1.030	1.073	1.100	1.131
Relative Energy Consumption	1.0	0.97	0.93	0.91	0.89

Since these calculations are all carried out with the same feedwater flow, the same number of vessels and RO membranes and the same operating pressure, the energy consumption and operating costs are essentially the same for all cases. However the potable water production is increasing significantly with increasing temperature. Hence operation at the higher temperatures results in a reduction in the energy consumption per cubic meter of potable water produced, with a corresponding reduction in the unit cost of potable water production.

A preliminary design concept for the floating nuclear desalination complex has been developed by OKBM and was described by them at an IAEA Advisory Group Meeting on "Floating Nuclear Power Plants for Seawater Desalination" held in Obninsk, Russia, in May 1995[16]. Preliminary peformance analysis for the desalination system were presented[13] at that same meeting. Development has being carried forward as a joint Canada-Russia project, with the FPU based on the KLT-40 shipboard reactor plant and the desalination plant based on the CANDESAL application of reverse osmosis seawater desalination. The two barge concept as it is currently envisaged is illustrated in Figure 5.



1. Reactor
2. Primary circuit circulation pump
3. Steam generator
4. Turbo-generator
5. Seawater intake
6. Condenser
7. Secondary circuit electric pump
8. Medium pressure pump
9. Recirculation pump
10. UltraFiltration membranes
11. Energy recovery system
12. High pressure pump
13. RO membranes
14. Brine discharge
15. Potable water pump
16. Potable water storage tank
17. Anti-scalant injection system
18. Clarified water tank
19. Prefilter

Figure 5
Principle Flow Diagram of the
Floating Nuclear Desalination/Cogeneration Complex

4.6 Conceptual Barge Design

A conceptual design layout for the desalination barge is shown in Figures 6 and 7. The proposed barge design is 96 m long by 28 m wide. The design includes UF capacitance tanks and RO permeate storage tanks below the UF/RO deck. Appropriate baffles and pumping arrangements will be required to restrict free water movement while the barge is under tow. Accommodations, crew spaces and the control room are located on the upper deck.

5. CONCLUSIONS

The use of nuclear power as a source of energy for potable water production is both technically viable and economically competitive. CANDESAL's system integration and design optimization techniques provide significant improvements in the efficiency of energy use and the economics of water production. These features will allow nuclear desalination to play an important role in the solution to the growing global demand for water and electricity.

The unique CANDESAL approach can be applied in a floating desalination/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 technology 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 few 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. Finally, the use of floating platforms for the system allows for easy redeployment and hence maximum flexibility for potable water production in regions where population centres are widely scattered and where the water needs vary widely from area to area.

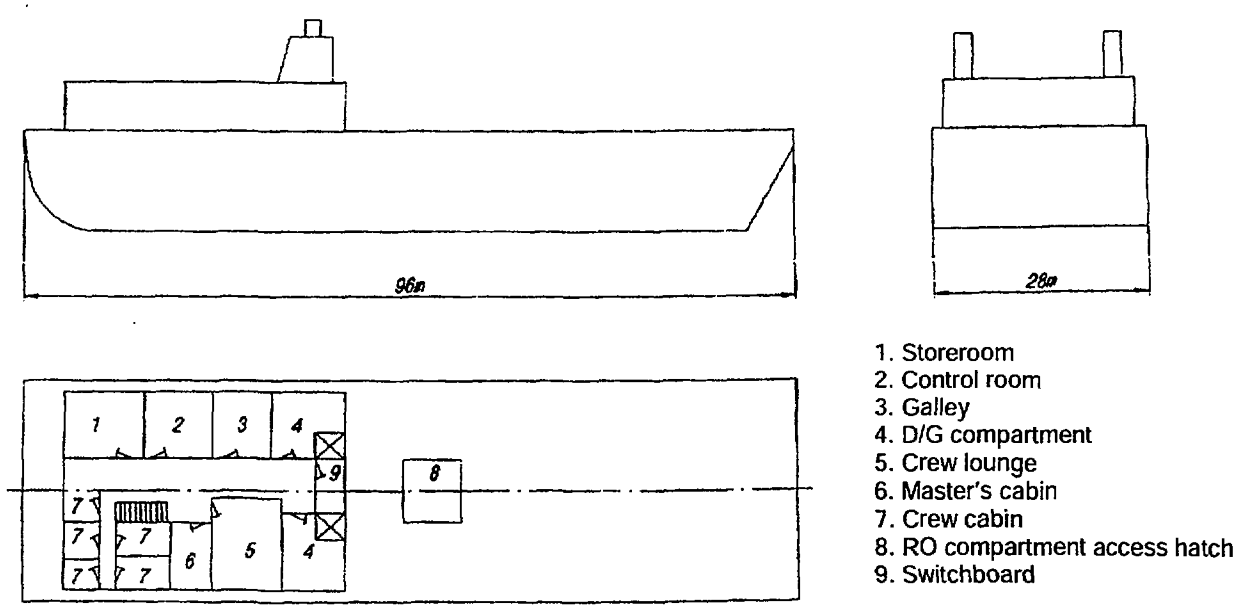


Figure 6
Reverse Osmosis Desalination Barge

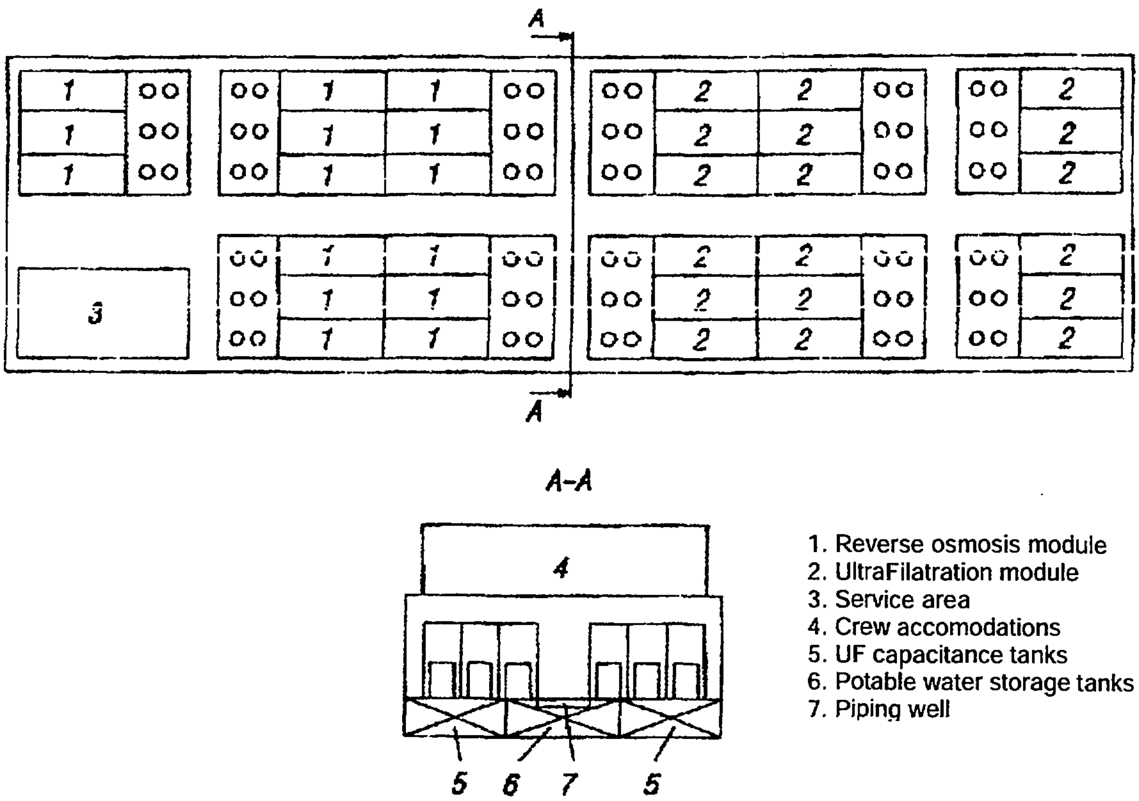


Figure 7
Desalination Barge
Desalination Plant Layout

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