A Technical And Economic Evaluation Of Reverse Osmosis Nuclear Desalination As Applied At The Muria Site In Indonesia

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Abstract

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. This is particularly true in Indonesia where there is an increasing reliance on bottled water due to shortage of safe, fresh drinking water. To mitigate the stress being placed on water resources, additional fresh water production capability must be developed. Because of Indonesia's long coastline, seawater desalination is a good 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.

In addition to providing a means of meeting regional electricity demand, the CANDU nuclear reactor can also serve as an energy source for a reverse osmosis (RO) seawater desalination plant. In conjunction with the use of electrical energy, waste heat from the reactor is used in the desalination plant to improve the efficiency of the RO process. This is done by using condenser cooling water being discharged from the CANDU reactor as a source of preheated feedwater for the RO system. The system design also makes use of advanced feedwater pretreatment and sophisticated design optimization analyses. The net result is improved efficiency of energy utilization, increased potable water production capability, reduced product water cost and reduced environmental burden. This approach to the integration of a seawater desalination plant with a CANDU nuclear reactor has the advantage of maximizing the benefits of system integration while at the same time minimizing the impacts of physical interaction between the two systems. Consequently, transients in one plant do not necessarily have adverse effects on the other.

In co-operation with BPPT of Indonesia, CANDESAL and AECL have performed an evaluation of this nuclear desalination concept to establish the design, performance and economic characteristics of a large scale reverse osmosis seawater desalination plant coupled with a CANDU reactor, operating under conditions appropriate to the Muria site in Indonesia. The results of the evaluation are discussed herein.

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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.[1,2] 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 both new sources of electrical power and improvements in the efficiency of energy utilization in the desalination process. Because of the proven capability of nuclear power for large scale energy generation, and at the request of its Member States, the International Atomic Energy Agency (IAEA) initiated a program in 1990 aimed at evaluating the use of nuclear power as an energy source for seawater desalination.[3,4]

Canada has played an active role in the IAEA's nuclear desalination program. Over the past five years CANDESAL Enterprises Ltd., with the cooperation and assistance of Atomic Energy of Canada Limited (AECL), has been working on the development of an innovative approach to the application of reverse osmosis (RO) for seawater desalination. The CANDESAL system integrates a CANDU 6 nuclear generating station with a reverse osmosis (RO) desalination facility, capturing the waste heat from the electrical generation process to improve the efficiency of the RO process. By also using advanced feed water pretreatment and sophisticated system design integration and optimization techniques, a substantial improvement in the efficiency of energy usage, economics, and environmental impact can be realized

Indonesia has also been an active participant in the IAEA nuclear desalination program. Although it is located in a tropical zone, the high population concentration in certain locations and the uneven distribution of natural water resources leaves some portions of the country with severe shortages of safe drinking water. One of the worst is the Jakarta region, which has a per capita annual availability of fresh water that is among the lowest in the world.[5]

Indonesia has an active nuclear program, with a strong interest in the application of nuclear power for both electrical generation and seawater desalination. Canadian nuclear desalination technology matches well with that interest because of its superior design characteristics, ease of technology transfer, and the proven record of outstanding performance of the CANDU reactors. The unique approach taken to coupling the RO plant with the reactor allows the need for fresh water production to be satisfied without compromising either the CANDU design or its performance as an electrical generating facility.

This paper reports the results of a preliminary design evaluation study that has been carried out to examine the technical, performance and economic characteristics of a large scale RO seawater desalination plant coupled with a CANDU 6 nuclear power plant, operating under conditions typical of the Muria site in Indonesia.

2. THE CANDESAL® NUCLEAR DESALINATION/COGENERATION SYSTEM

2.1 Development Of A Canadian Nuclear Desalination Technology

Canada began participating actively in the IAEA's potable water program in late 1993. The focus of the early design concept development work was on the determination of an appropriate seawater desalination technology for coupling to the CANDU reactor. With no prior commitment to any particular technology, all options were open for consideration. The only prerequisite was that commercially available, well-proven desalination technologies be considered.

Initial investigations indicated that with this prerequisite as a constraint, only two technologies warranted further consideration. These were multi-effect distillation (MED) and reverse osmosis. More detailed preliminary studies showed that in order to match the required thermal conditions for MED, changes were required to the reactor's balance of plant design that were both expensive to implement and led to reduced electrical generating efficiency. Moreover, the loss in electrical generating capability was such that the overall water and electrical production capacity was not as great as that which could be achieved using RO combined with the standard CANDU design.

Accordingly, it was concluded at that time that further development work would proceed on the basis of coupling the CANDU reactor with RO seawater desalination.

2.2 The CANDESAL® Design Concept

Having selected the RO process, work was then begun to address two of the most critical issues facing nuclear desalination as a commercially viable technology – energy utilization and the cost of water production. It was 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, thereby increasing potable water production for a given plant size and energy consumption, with a corresponding reduction in the unit cost of water production. As the development work progressed, it was also found that further improvements could be achieved through improved RO system feedwater pretreatment and by taking a system approach to optimizing the design.

The use of ultrafiltration (UF) pretreatment provides high quality feed water to the RO process. This serves to protect the RO membranes and enhance their performance, thereby reducing the total number of RO membranes required and increasing their lifetime. The result is reduced plant capital cost and a reduced requirement for membrane maintenance and replacement.

The RO process depends on a set of complex relationships between a variety of operating parameters including the preheated feedwater temperature, feedwater analysis, RO system operating pressure, membrane feed flow rate, recovery, permeate quality and flow rate, and brine concentration and flow rate. A comprehensive design optimization based on integrated system performance analyses is carried out to establish the best balance of design features and performance characteristics to achieve specified performance objectives and reduced water production costs.

This approach to the coupling 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. 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 concept has evolved, it has developed in a direction which allows use of a standardized off-the-shelf CANDU reactor without modification, while at the same time accruing significant benefits from the systems integration due to improved performance characteristics and energy utilization.

3. MURIA SITE DESIGN SPECIFICATIONS

The first step in performing a systematic and comprehensive design evaluation is to stipulate the requirements that must be satisfied in achieving a well-balanced system design. The following data have been used for this RO system design evaluation. To the maximum extent possible, data has been specified for the Muria site, the location at which the first nuclear desalination facility is most likely to be sited in Indonesia. Where site specific data could not be obtained, "typical" characteristics have been assumed.

- Average annual sea water temperature — 29°C
- Minimum and maximum sea water temperature — 28-30°C
- Variation in sea water temperature over the year — Negligible
- Average Total Dissolved Solids (TDS) of sea water — 40,000 ppm
- Required potable water production capacity — 240,000 m^3/day
- Required potable water quality — 500 ppm
- Allowable variation in potable water quality — Not to exceed 500 ppm
- Cooling water temperature rise across the condenser — 10°C
- Reactor power production — 660 MWe
- Cost of financing the capital investment (interest rate) — 8% and 10%
- Amortization period (plant economic lifetime) — 20 years and 30 years
- Cost of purchased electrical power — 0.05 $(US)/kW-hr
- Cost of generated electrical power — 0.04 $(US)/kW-hr
- Labour costs for RO plant staff — Used default values from IAEA economic model
- Cost of chemicals — Used default values from IAEA economic model

4. REFERENCE DESIGN FOR THE MURIA SITE

4.1 The Design Optimization Process

Based on the Muria site design specification data, a preliminary design evaluation was carried out to establish the design features and optimized performance characteristics for a nuclear desalination facility coupling a CANDU 6 reactor with an RO desalination plant.

Initially, focus was given to the RO vessels and their contained RO membrane elements. The RO vessel is the smallest water desalination unit in the system, and represents the basic unit from which the desalination modules are built. RO vessels are typically configured with either 6 or 7 membrane elements per vessel for seawater desalination, although more recently vessels capable of holding 8 membrane elements have been introduced. Changing the number of membrane elements in a vessel affects the performance characteristics of that vessel, and hence the number of vessels required. Considerations such as potable water production capacity, quality, operating limitations on the RO membrane elements, effect of feedwater preheat, and effect of feedwater pretreatment were taken into account in arriving at an appropriately balanced design. The Reverse Osmosis System Analysis (ROSA) computer code from Dow FILMTEC® was used to calculate steady state performance characteristics for each case considered.

Next, overall system considerations were taken into account. Various operating conditions and configurations of vessels and elements/vessel were evaluated. Factors that were considered include:

- An appropriate balance between energy consumption and plant size,
- Economic balance between plant capital cost and water production cost,
- Modular arrangement of vessels and membranes to facilitate fabrication and assembly.

A detailed parametric assessment of performance characteristics for a wide range of operating conditions was carried out. The results, described in more detail below, are illustrated in Figures 1-4.

4.2 Reference Design

Of particular interest in the selection of a reference design is the operating pressure. Previous CANDESAL design studies have indicated that operation at the highest pressure allowed by the membrane manufacturer's specifications (69 bar) results in the best performance and economic characteristics. Nevertheless, it was considered important to reconfirm that conclusion for the Muria site in view of the high seawater TDS. Cases were run at 62.1 bar (900 psi) and 69 bar (1000 psi) over the full temperature range of 25-45°C. Data from theses cases was used to calculate the relative energy consumption per unit water production. Figure 5, which presents the results of this analysis, shows quite clearly that in spite of the higher pumping power required to reach 69 bar, the improved water production efficiency at higher pressure results in an overall decrease in the energy required to produce a single cubic meter of water.

Having established 69 bar as the optimum operating pressure, a large number of cases was run to evaluate the effect of various combinations of vessels and membranes per vessel. The best overall balance, considering the factors described above, was found to be a configuration consisting of 10 identical trains with each train comprised of 285 RO vessels (7 RO membrane elements per vessel). Figure 6 shows an illustrative schematic of the RO system.

4.3 The Effect of RO Feedwater Preheat

Although simple in concept and in accordance with well known principles of spiral wound RO membrane performance, the use of preheated feedwater as a means to improve performance characteristics has not been applied in contemporary desalination plants. Nevertheless, the enhanced performance characteristics are shown by analysis using the ROSA code mentioned above, under conditions that are well within the limitations of both the code itself and of the membranes as specified by the manufacturer.

An evaluation of the Muria reference design configuration over the temperature range from 25-45°C was a part of the design optimization. Included in the set of cases were the minimum, average and maximum seawater temperatures and the minimum, average and maximum RO feedwater temperatures that result from the 10°C temperature rise across the condenser for each of those seawater temperatures. Figure 7 presents the results of these calculations. A more detailed summary of the analysis results is presented in Table 1. The relative water production rate as a function of temperature displays the improved system performance characteristics that result from the use of preheated RO feedwater and a properly optimized design configuration.

Table 1
Effect of RO Feedwater Temperature on RO System Performance Characteristics

Temperature, °C	Permeate Flow, m3/d	Permeate TDS, ppm	Brine TDS, ppm	Recovery, %
25	20713	352	60716	34.3
28	21497	375	61920	35.6
29	21785	383	62376	36.1
30	22038	391	62780	36.5
35	23179	437	64667	38.4
38	23827	467	65786	39.5
39	24018	478	66123	39.8
40	24221	489	66485	40.1
45	25118	548	68123	41.6

5. Reference Design Parametric Sensitivity Analyses

As part of the desalination system design optimization, the performance of the reference design under various postulated "transient" conditions was evaluated. It is expected that during the operating life of the desalination plant, certain operating parameters such as feed water temperature or feed water salt concentration will vary thereby causing the permeate production capacity and the permeate salt concentration to fluctuate. Variations in the operating parameters can be attributed to a number of factors such as abnormal/upset conditions in the plant, or gradual degradation in the membrane effectiveness due to continual exposures to low quality feed water or high feed water pressure. On this basis, the analysis provides an overview of the system performance characteristics in terms of the extent of the permeate flow and permeate salt concentration being affected by other variable parameters. This ensures that the optimum conditions are identified without compromising any design or performance criteria.

Four key variable parameters were identified as having the most influence on the performance of a reverse osmosis process. They include: a) pressure, b) temperature, c) recovery, and d) feed water salt concentration. Other key factors such as maintenance, operation, and proper pretreatment, that indirectly influence the system performance are not included in the parametric sensitivity analysis. Instead, they are considered along with other 'parameters' (system complexity, costs, etc.) in the process of defining the optimum reference design.

5.1 Basis and Methodology

Since all trains of reverse osmosis membrane modules are identical and operating in parallel, only one train was analyzed on the basis that the performance characteristics of all trains are similar. In each analysis case, the feed flow supplied by the high pressure pump to a train of membrane modules is maintained constant at 2,515 m^3/hour (60,360 m^3/day) while varying one of the four key variable parameters. The following ranges of variation were chosen to reflect the anticipated environmental conditions at the Muria site, the availability of the condenser, and the design of the Dow FILMTEC® membrane elements:

- Feed water pressure 55-87 bars
- Feed water temperature 25-45°C
- Recovery factor 34-42%
- Feed water salt concentration 38,000-42,000 ppm

The parametric sensitivity analysis is performed using the ROSA software. The software simulates the operation of a reverse osmosis water treatment plant that uses FILMTEC® membrane elements. It requires a series of inputs on the reference system configuration such as water analysis, feed water temperature to project the performance of the proposed configuration during steady state operation.

5.2 Results and Discussion

200 simulation cases were performed using different combinations of feed water pressure, feed water temperature, recovery factor (by varying feed water pressure), and feed water salt concentration. Details of the analysis results are presented in Reference [6]. Representative samples of the results are shown in Figure 1 to 4.

5.2.1 Effects of Feed Water Pressure

Based on the review of the analysis results, the system performance characteristics generally agree with the principles of reverse osmosis membranes.[7,8] In all figures, it can be seen that high feed water pressure helps to maintain high permeate flow and low permeate salt concentration, both of which are desirable. The extent to which the feed water pressure can be increased however is limited by the design of the FILMTEC® sea water membrane which is currently set at 69 bars, and the economic factor associated with the feed water pump power consumption. At the reference conditions of 40,000 ppm feed water salt concentration and 39°C feed water temperature, a train of the system operating at 69 bars feed water pressure would provide a permeate flow of 24,018 m^3/day and the permeate salt concentration would be 478 ppm.

5.2.2 Effects of Feed Water Temperature

The effects of feed water temperature on system performance are illustrated in Figure 1 and 2. Here, it can be seen that high feed water temperature helps to maintain high permeate flow at the expense of higher permeate salt concentration. One extreme case of changes in feed water temperature is the combination of condenser unavailability and minimum sea water temperature. At these conditions, the feed water temperature can be as low as 28°C. The other extreme case of changes in feed water temperature is the combination of condenser availability and maximum sea water temperature which can increase the feed water temperature to as high as 40°C. At this feed water temperature range, for the reference case of 40,000 ppm feed water salt concentration and 69 bars feed water pressure, the permeate flow from each train would vary from 21,497 m^3/day to 24,221 m^3/day; and the permeate salt concentration would be in the range of 375 ppm to 489 ppm. This indicates that for the Muria site, high feed water temperature would increase the potable water production capacity while still meeting the maximum allowable limit of 500 ppm for permeate salt concentration.

5.2.3 Effects of Feed Water Salt Concentration

The effects of feed water salt concentration on system performance are illustrated in Figure 3 and 4. The negative effects of high feed water salt concentration on system performance is apparent with a reduction in the permeate flow and an increase in the permeate salt concentration. Variations in the feed water salt concentration can be the result of seasonal changes in the sea water conditions. Based on the assumption that feed water salt concentrations at the Muria site can range from 38,000 ppm to 42,000 ppm, the permeate flow from a train operating at the reference conditions of 39°C feed water temperature and 69 bars feed water pressure was estimated to vary from 25,668 m^3/day to 22,480 m^3/day; and the permeate salt concentration would be in the range of 439 ppm to 521 ppm.

5.2.4 Combined Effects of Feed Water Temperature and Salt Concentration

It is worth noting that the analysis so far has only examined the effects of one variable parameter on the system performance while the other parameters are assumed to remain constant at the reference conditions. An attempt was made to analyze the combined effects of varying both the feed water temperature and salt concentration on a system operating at the optimum feed water pressure of 69 bars.

In terms of permeate flow, two extreme cases of combined inlet conditions were identified. In one extreme case, the feed water inlet condition is at 28°C and has a salt concentration of 42,000 ppm. In the other extreme case, the feed water inlet condition is at 40°C and has a salt concentration of 38,000 ppm. For the reference design operating at 69 bars feed water pressure, the two extreme cases would cause the permeate flow from each train to vary from 20,099 m^3/day to 25,850 m^3/day.

In terms of permeate salt concentration, two extreme cases of combined inlet conditions were identified. In one extreme case, the feed water inlet condition is at 28°C and has a salt concentration of 38,000 ppm. In the other extreme case, the feed water inlet condition is at 40°C and has a salt concentration of 42,000 ppm. For the reference design operating at 69 bars feed water pressure, the two extreme cases would cause the permeate salt concentration to vary from 321 ppm to 533 ppm.

6. ECONOMIC ASSESSMENT

6.1 The IAEA Economic Model

The IAEA has developed an economic assessment model that can be used to compare the cost of water production from various desalination alternatives, including both fossil fueled and nuclear.[9] Their Cogeneration/Desalination Economic Evaluation (CDEE) methodology uses simplified models (built into an Excel spreadsheet) of several types of nuclear and fossil power plants, and both distillation and membrane desalination plants. Typical cost and performance data representative of currently operating stations has been included in the CDEE model so that the spreadsheet can be adapted to other cases. Output of the spreadsheet includes the levelized cost of water and power, energy consumption and net saleable power for each option. The IAEA model contains two different options for reverse osmosis desalination. One has been called stand alone RO (SA-RO) and the other contiguous RO (C-RO). Stand-alone RO considers a situation in which the power plant and the RO plant are not physically co-located. Contiguous RO assumes the RO plant and the power plant to be located on the same site, and to take advantage of whatever shared facilities and resources are available, including common seawater intake and discharge structures. The IAEA acknowledges the CANDESAL approach to using condenser cooling water as preheated feedwater to the RO system in an RO plant, but have not included it in their economic modeling due to the "complexity of providing a general purpose algorithm for such preheating option in the spreadsheet..."

6.2 Site Specific Economic Assessment of the Muria Design Configuration

The economic assessment of an RO desalination plant using the CANDU 6 reactor as its energy source for the Muria site differed in two key respects from the standard IAEA CDEE analysis. First, as a site-specific assessment, the input characteristics differed from the standard values included in the IAEA code.

The second, of course, is the introduction of preheated RO system feedwater. Hence, as a first step in carrying out an economic assessment for the Muria reference design configuration it was necessary to modify CDEE specifically for this purpose. This required a number of detailed changes to the spreadsheet, including the addition of a new section to carry out the calculations for RO systems with feedwater preheat (RO-PH). A new section was added rather than modifying the existing calculations so that a direct comparison could be made of the effect of moving from a stand-alone system to contiguous system to an integrated desalination/cogeneration system incorporating preheated RO feedwater.

Having modified the CDEE to include the effects of preheated RO feedwater temperature, economic analyses were performed for several cases. In each analysis case water costs are given for three plant configurations: a stand alone RO system; a contiguous RO system co-located with the CANDU 6 nuclear generating station; and a CANDESAL system in which the RO feedwater is drawn from the CANDU condenser cooling water discharge stream and is therefore preheated 10°C above ambient seawater temperature. The results are presented in Table 2 and depicted graphically in Figure 8.

Table 2
Muria Site Specific Economic Evaluation Results

Case	Description	Water Cost, US$/m^3		
		SA-RO	C-RO	RO-PH
M1	Calculation using CDEE modified to include effect of preheated feedwater to RO system, with built-in algorithms for recovery, inlet and outlet osmotic pressures, and discharge brine concentration	0.74	0.71	0.65
M2	Calculation using CDEE modified to include effect of preheated feedwater to RO system, with actual Muria design configuration values for recovery, inlet and outlet osmotic pressures, and discharge brine concentration	0.74	0.71	0.63
M3	Same as Case M2, except using 10% discount rate and IDC (interest during construction) for financial calculations	0.84	0.80	0.72
M4	Same as Case M2, except using 20 year "economic lifetime"	0.81	0.77	0.69
M5	Combined effect of 10% discount/IDC and 20 year "economic lifetime"	0.91	0.86	0.77
M6	Same as Case M5, except that 10% discount/IDC and 20 year "economic life" is assumed to apply **only** to the water plant; levelized power cost calculated using CDEE methodology	0.82	0.78	0.70
M7	Same as Case M5 except that cost of purchased power is assumed to be $0.05/kW-hr and cost of generated power is assumed to be $0.04/kW-hr	0.79	0.74	0.67

In Case M1 the effects of feedwater preheat are taken into account, but the specific performance characteristics of the Muria reference design configuration are not. The algorithms contained in the CDEE are used to estimate system recovery, inlet and outlet osmotic pressure and discharge brine concentration. Since these algorithms remain unchanged from the basic CDEE model, this case provides a very good example based on the IAEA methodology of the cost benefit of preheating the RO system feedwater. As can be seen from the table, the cost of producing potable water from a stand alone RO plant (the only kind currently in use) under these site specific conditions is 13.8% higher than the cost of water from a plant designed to take advantage of feedwater preheating.

While the algorithms used in the CDEE model provide a reasonable representation of typical RO system performance characteristics, they are developed based on the characteristics of existing designs, and are therefore representative of the traditional approach to RO system design. One of the features of the CANDESAL approach described above is a careful design optimization aimed at achieving minimum water production costs. In Case M2 the specific performance characteristics for the Muria reference design configuration have been used in the economic evaluation, replacing the generic characteristics used in Case M1. As can be seen from the results, the use of site-specific design characteristics as the basis for an optimized design has led to a further reduction in water costs. From this result it can be observed that the cost of producing potable water from a stand alone RO plant under these specific conditions is 17.5% higher than the cost of water from a plant designed to take advantage of feedwater preheating and system design optimization. Case M2, incorporating the effects of both feedwater preheat and design optimization, becomes the reference design case for further economic comparisons. Cases M3-M7 illustrate the effect on water production costs of changes in various economic parameters.

6.3 Plant Capital Cost

Total water plant construction cost (sometimes called "overnight cost" as it does not include the cost impact of interest during construction) is also calculated by the CDEE spreadsheet. Using Case M2 as our standard of comparison, CDEE calculates the total construction cost for a stand-alone RO plant given the Muria site specific seawater conditions to be US$264 million. The corresponding capital cost for the CANDESAL system, incorporating preheated RO feedwater and an optimized design, is calculated to be US$236 million. This represents a reduction in plant capital cost of about 11%.

7. CONCLUSIONS

This paper reports the results of a preliminary design evaluation study that has been carried out to examine the technical, performance and economic characteristics of a large scale RO seawater desalination plant coupled with a CANDU 6 nuclear power plant, operating under conditions typical of a site in Indonesia. Based on site characteristics for the Muria site supplied by participants in the study from Indonesia, a reference design configuration has been developed and described for a reverse osmosis nuclear desalination system that meets those conditions.

The Muria reference design consists of ten identical RO trains operating in parallel. Each train is capable of producing slightly more than 24,000 m^3/d at a 29°C reference seawater temperature. The total water production capacity of the plant is thus in excess of 240,000 m^3/d, with potable water quality consistent with World Health Organization standards, having a total dissolved solids content of less than 500 ppm.

The estimated capital cost of the plant is on the order of US$236 million, with a cost of water production of about US$0.63/$m^3$ based on standard economic assumptions used by the IAEA in their economic analyses. The cost of water from a stand-alone RO plant under these same conditions is about US$0.74, or about 17% higher, illustrating the significant economic benefit of the CANDESAL approach.

To cater for the anticipated changes in seawater conditions, the current system configuration includes a number of features to achieve a robust design:

- Uses preheated feed water (39°C) and high salt rejection reverse osmosis membranes to ensure high permeate production capacity at low permeate salt concentration.
- Provides high feed water pressure (69 bars). The power cost to reach this pressure is more than offset by the improved membrane efficiency.

- Uses sufficient margin in the system design capacity to accommodate variations in feed water temperatures and/or feed water salt concentrations.
- Equipment trains are modularized to allow room for changes in design production capacity if needed.

However, the importance of having a comprehensive knowledge of the seawater conditions at the Muria site cannot be overemphasized. For instance, one area that may need to be investigated further is the selection of the feed water salt concentration of 40,000 ppm as a reference condition for the system design. From the analysis, it appears that if the system is operating at the reference temperature and pressure conditions (39°C feed water temperature and 69 bars feed water pressure), and the feed water salt concentration exceeds 40,000 ppm, the maximum allowable limit of 500 ppm for permeate salt concentration would not be met. A knowledge of the seawater conditions at the Muria site would allow further optimization of the RO system design to ensure appropriate performance.

Based on the results of this work it can be concluded that a nuclear desalination facility based on the integration of the CANDU 6 reactor with a reverse osmosis desalination plant can be configured to operate effectively and efficiently even under the high seawater salinity and temperature conditions prevailing in Indonesia. Such a plant can provide for the cogeneration of water and electricity, using waste heat from the electrical generation process to improve the efficiency of the water generation process. Such a plant is based on currently available, proven technologies and could be implemented on request. The innovative approach taken to the application of RO technology leads to performance and economic advantages that represent significant improvements over other alternatives currently available.

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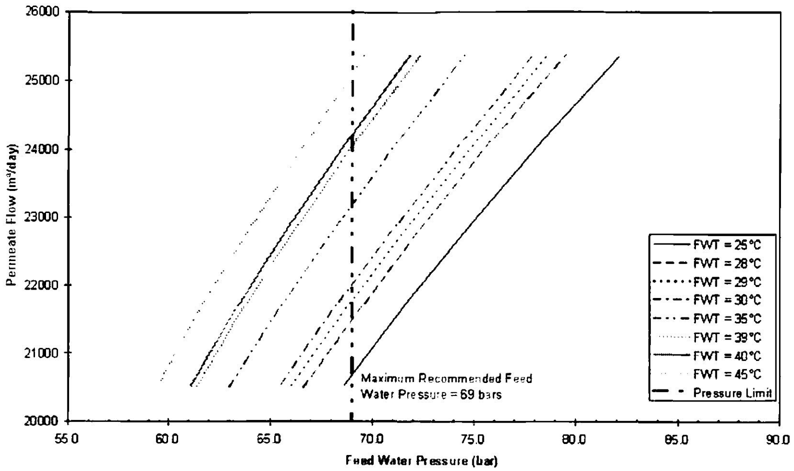
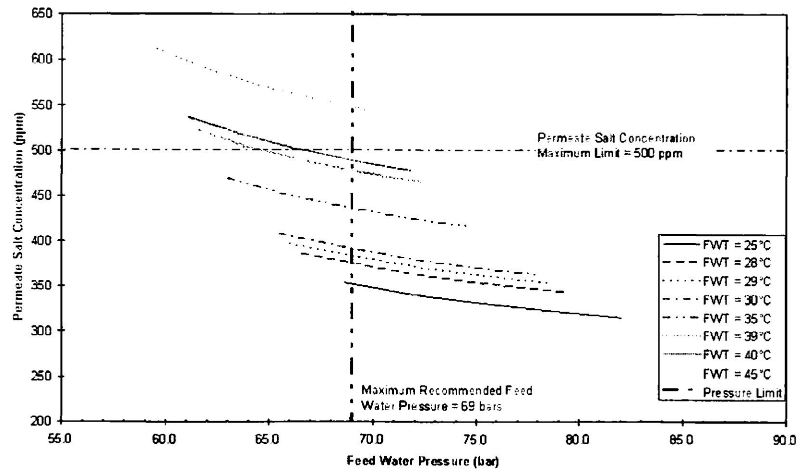


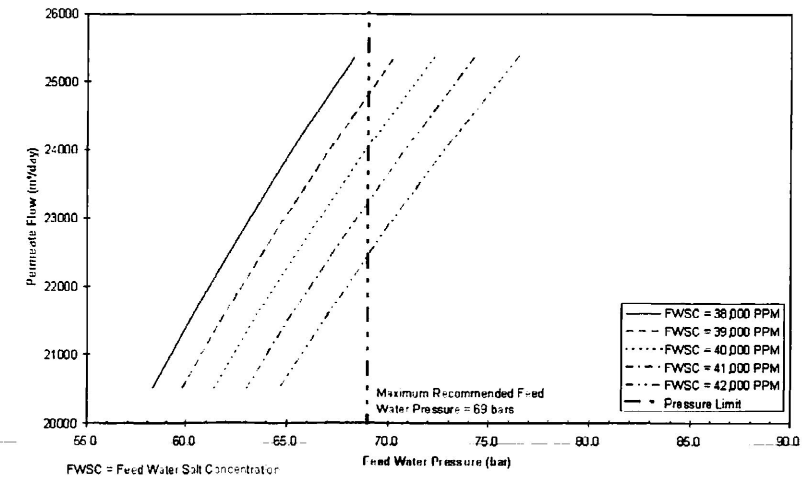
FWT = Feed Water Temperature

Figure 1: Permeate Flow at Feed Water Salt Concentration of 40,000 ppm



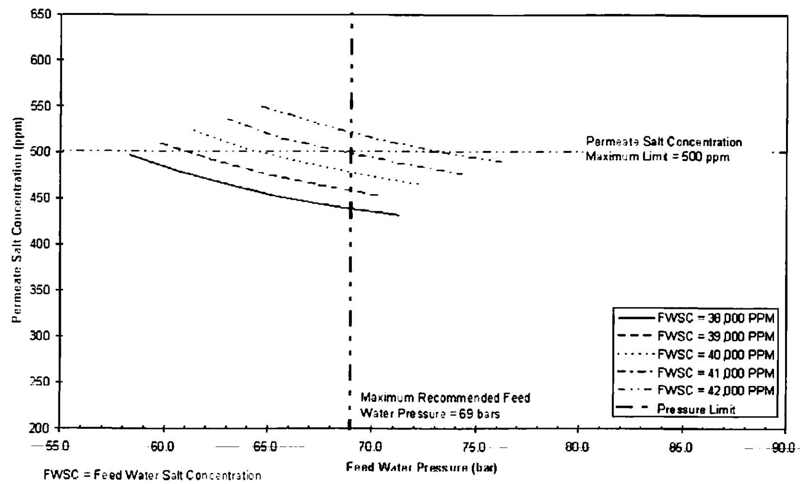
FWT = Feed Water Temperature

Figure 2: Permeate Salt Concentration at Feed Water Salt Concentration of 40,000 ppm



FWSC = Feed Water Salt Concentration

Figure 3: Permeate Flow at Feed Water Temperature of 39°C



FWSC = Feed Water Salt Concentration

Figure 4: Permeate Salt Concentration at Feed Water Temperature of 39°C

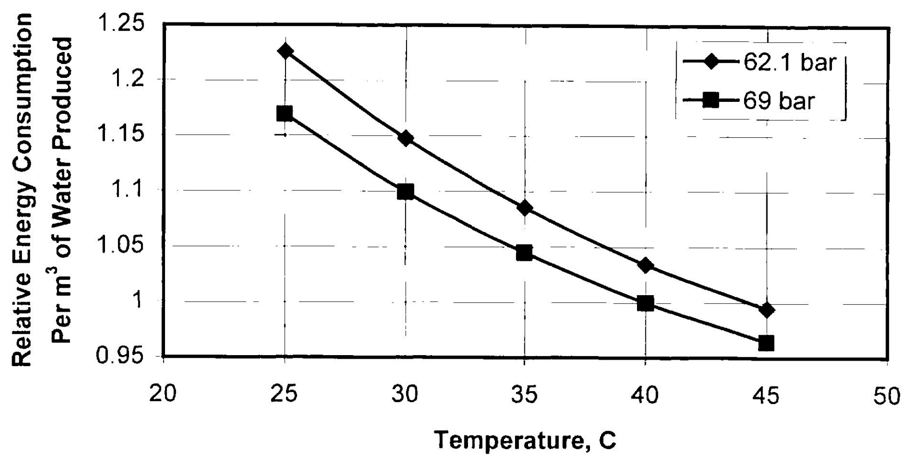


Figure 5: Effect of RO Feedwater Temperature and Pressure on Energy Consumption

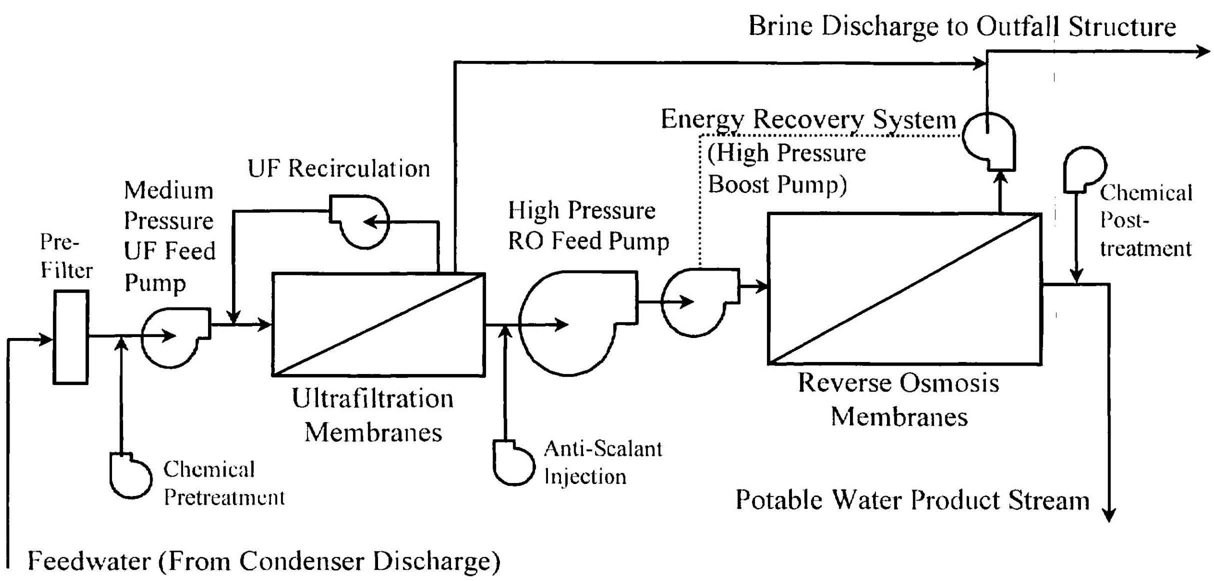


Figure 6: Simplified Schematic Diagram of RO Seawater Desalination System

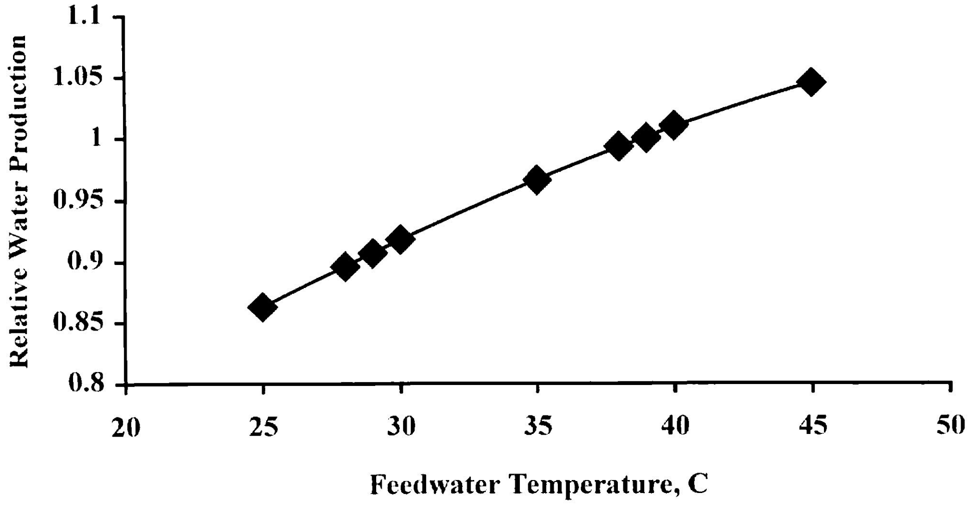


Figure 7: Effect of RO Feedwater Preheat for the Muria Reference Design Configuration

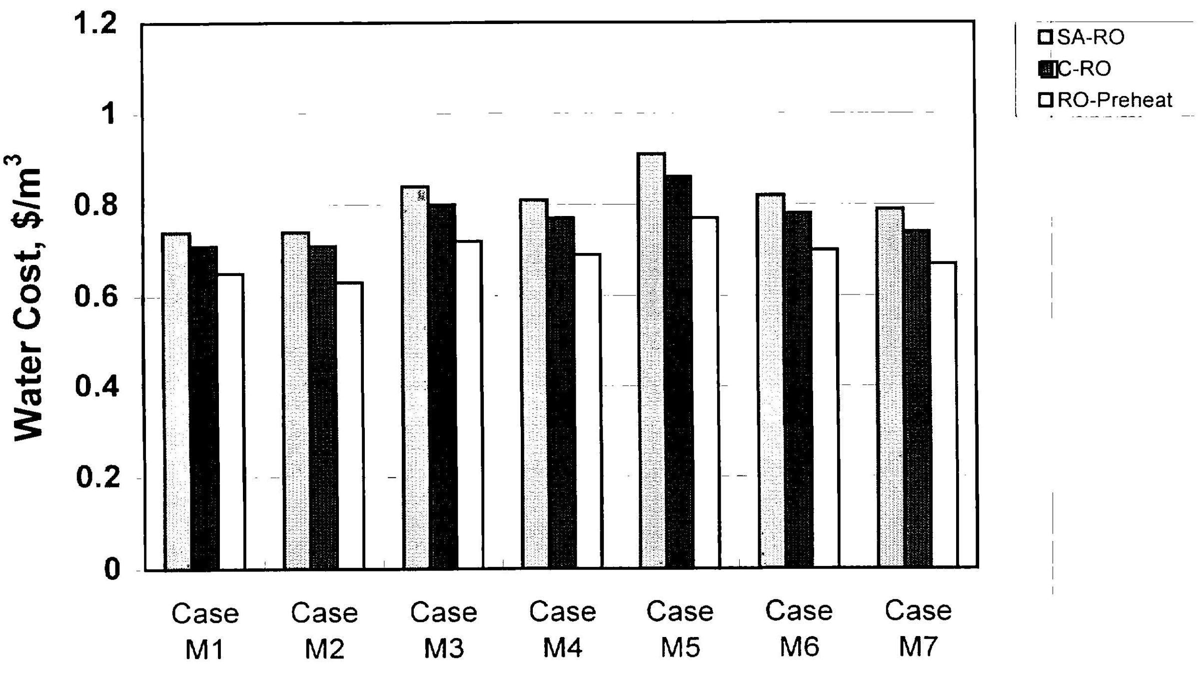


Figure 8: Potable Water Production Costs for Muria Site Specific Economic Assumptions