DESIGN GUIDELINES FOR A REVERSE OSMOSIS DESALINATION PLANT

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Acknowledgements

For it is God which worketh in you both to will and to do of his good pleasure.

- Phi 2:13

And after these things I heard a great voice of much people in heaven, saying, Alleluia; Salvation, and glory, and honour, and power, unto the Lord our God:

- Rev 19:1

Secondly I would like to thank my father and mother, Izak and Sylvia Hoffman, for their love and guidance during my entire life. Also to my bothers, sisters and friends, thank you for all the support and encouragement.

Last but not least, Dr. Barend Botha. Thank you for your guidance throughout this project. You are an excellent engineer and I have learned many things under your supervision that I could not have done elsewhere.

May God bless you all, through Jesus Christ our Savior.

Abstract

There are two basic needs globally and that is the control and supply of reliable electricity and clean water. However, one of the biggest challenges the world is facing today is the lack of fresh water resources. Lower rainfall, together with population and industry growth, are only a few factors contributing to the fast increasing strain on existing water supplies around the world. This fast increasing need therefore necessitates the investigation into finding alternative sources. One such option is that of desalination. In the last 50 years desalination technologies have been applied to produce high quality fresh water from brackish and seawater resources. In the 1980's a break-through was made with the introduction of the membrane desalination technology, known as the reverse osmosis (RO) process.

Today newly developed technologies are improving the competitiveness of the reverse osmosis process against the traditional distillation processes. There are a number of options to increase the efficiency of a reverse osmosis plant and one option is to use warm industrial waste water as the feed water to the desalination plant. It is known that the viscosity of water is inversely proportional to its temperature. Therefore, if the feed water temperature of a reverse osmosis plant is increased the membranes will become more permeable. This will result in a higher production volume or in a lower energy demand. South Africa is on the edge of building the first fourth generation nuclear power plant, called the Pebble Bed Modular Reactor (PBMR) at Koeberg. The PBMR will produce a cooling water outlet temperature of 40°C which can be used as feed water to a reverse osmosis plant.

In this study design guidelines of a reverse osmosis plant are given in nine steps. These steps were then used during a basic component design of a reverse osmosis plant coupled to the waste water stream of a PBMR nuclear power plant. Furthermore design software programs were used to simulate the coupling scheme in order to validate the outcome of the design guidelines. The results of the two design approaches compared well to one another. It furthermore showed that by using the waste water from the PBMR nuclear power plant the efficiency of the RO plant is increased and the operating cost is decreased. Fresh water can be produced at a cost of R 5.64/m^3 with a specific electricity consumption of 2.53 kWh/m^3.

Keywords:

Desalination, Osmosis, Reverse osmosis, Nuclear desalination, PBMR

Uittreksel

Daar is twee basiese behoeftes in die moderne wêreld en dit is die beheer en voorsiening van elektrisiteit en skoon water. 'n Baie groot uitdaging wat die wêreld in die gesig staar is die feit dat vars water bronne skaars is. Lae reënval tesame met gekonsentreerde populasie en industriële groei is maar enkele redes vir die toename in druk op bestaande vars water bronne regoor die wêreld. Omdat die behoefte so drasties toeneem, word die belangrikheid vir alternatiewe waterbronne beklemtoon. Een opsie wat as 'n alternatief beskou kan word is seewater ontsouting. In die afgelope 50 jaar is verskillende waterontsoutingsmetodes gebruik om hoë kwaliteit vars water te produseer vanuit brak- en seewaterbronne. In die 1980's is daar egter 'n nuwe membraan tegnologie, beter bekend as omgekeerde osmose, aan die ontsoutingsmark bekend gestel.

Die proses van omgekeerde osmose word deurlopend verbeter deur nuwe tegnologiese ontwikkelinge en kompeteer dus al hoe beter met die tradisionele distillasie prosesse. Daar is verskeie opsies wat oorweeg kan word om die effektiwiteit van die omgekeerde osmose proses te verbeter. Een opsie is om verhitte, industriële water te gebruik as voerwater na die ontsoutingsaanleg. Dit verhoog die effektiwiteit van die omgekeerde osmose proses, aangesien die viskositeit van water omgekeerd eweredig is aan die temperatuur. Suid-Afrika is op die drumpel om die eerste vierde generasie kernkrag aanleg, genaamd die *Pebble Bed Modular Reactor* (PBMR), by Koeberg te bou. Die verkoelingswater van die PBMR sal 'n maksimum uitlaattemperatuur van 40°C hê wat dan as voerwater vir 'n omgekeerde osmose aanleg gebruik kan word.

In hierdie verhandeling word basiese ontwerpsriglyne gegee om 'n omgekeerde osmose aanleg te ontwerp. Verder word hierdie stappe gebruik tydens 'n basiese komponent ontwerp van 'n omgekeerde osmose proses wat gebruik maak van die verkoelingswater van 'n toekomstige PBMR aanleg. Om hierdie ontwerp riglyne te evalueer is bestaande sagteware gebruik om die koppeling tussen die ontsoutingsaanleg en die PBMR te simuleer. Die resultate van die ontwerpsriglyne kompeteer goed met die resultate van die sagteware programme. Tydens die studie is waargeneem dat die effektiwiteit van die omgekeerde osmose toeneem met die gebruik van die warm voerwater. Die uitkoms is dat vars water vervaardig kan word teen 'n koste van R 5.64/m^3 met 'n spesifieke elektrisiteit verbruik van 2.53 kWh/m^3.

Sleutel woorde:

Ontsouting, Omgekeerde osmose, Osmose, Kern ontsouting, PBMR

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English Symbols

I	van't Hoff factor
M	Morality
R	Gas constant
T	Thermodynamic temperature
J	Volumetric flux
ΔP	Transmembrane pressure drop
R_f	Fouling resistance
R_m	Membrane resistance
Q_{Total}	Total amount of product water to be produced by membranes
$Q_{Requirement}$	Requirement of customer
RR	Maximum recovery ratio
Alk	Feed alkalinity
$Area_{Total}$	Total membrane area required
$Area_{Membrane}$	Membrane area of an element
Z	Number of passes
T	Temperature
$Q_{Total(Feed)}$	Total amount feed water
E_{Desal}	Estimated desalination energy requirement
$P_{f(T)}$	Feed pressure
$P_{Pre/Post}$	Estimated pressure requirement for the Pre- and Post-treatment plants
E_{Total}	Total energy consumption of the RO plant
E_{Extra}	Additional energy requirements
$E_{Specific}$	Specific energy consumption
C	Capital cost
K	Correction factor for the Pre-treatment complexity
CR	Cost of capital repayment

r	Monthly interest rate
n	Redemption period
SC	Specific cost of the redemption
SC_{Energy}	Specific energy cost per volume product water
$D_{Electric}$	Electricity cost
$E_{Specific}$	Specific energy consumption per volume product water
$SC_{Membranes}$	Specific membrane replacement cost
$Cost_{Mem}$	Cost of one membrane element
$SC_{Main/Labour}$	Specific membrane replacement cost
Z	Number of membranes

Greek Symbols

$\Delta\pi$	Osmotic pressure difference [Pa]
μ	Dynamic viscosity [Pa.s]
φ_1	First pass membrane flux [L /m^2.d]
φ_2	Second pass membrane flux [L /m^2.d]
$\pi.(TDS)_F$	Osmotic pressure multiply by the TDS value of feed water
φ	Membrane flux [L /m^2.h]
ψ	Membrane flux per driving pressure [L / (m^2.h.bar)]
ξ	Water fraction required at pre-treatment (Normally between 3 - 15 %)
η_{Pump}	Pump efficiency
$\eta_{Recovery}$	Pressure recovery efficiency
η_{Pump}	Pump efficiency
δ	Membrane depreciation per year
υ	Availability fraction

Subscripts

$CaCO_3$	Calcium Carbonate
Ca	Calcium
$CaCO_4$	Calcium Sulphate
CaF_2	Calcium Fluoride
F	Fluorine
SiO_2	Silicon Dioxide
$BaSO_4$	Barium Sulfate
$SrSO_4$	Strontium Sulfate
Ba	Barium
Sr	Strontium
Desal & pre	Desalination and pre-treatment system
Enviro	Environment

List of Abbreviations

BOD	Biological Oxygen Demand
CA	Cellulose Acetate
DPP	Demonstration Power Plant
ED	Electro-dialysis
EDR	Electro-dialysis Reversal
FO	Forward Osmosis
MD	Membrane Distillation
MED	Multi-Effective Distillation
MHSS	Main Heat Sink System
MSF	Multi Stage Flash
NF	Nanofiltration
NOM	Natural Organic Matter
PA	Polyamide
PBMR	Pebble Bed Modular Reactor
PWR	Pressure Water Reactor
RO	Reverse Osmosis
RR	Recovery Ratio
SDI	Silt Density Index
TDS	Total Dissolved Solids
TS	Total Solids
TSS	Total Suspended Solids
TFC	Thin Film Membrane
TOC	Total Organic Carbon
UPW	Ultra Pure Water
VC	Vapour Compression Evaporation

1 Chapter

INTRODUCTION

1.1 *Introduction*

There are two basic needs in every country around the world and that is the control and supply of water and electricity. One of the biggest challenges we are facing today is the lack of fresh water resources. In some countries they have already moved into a critical state where resolutions are needed for future supply and survival. There are several effects contributing to the scarcity of water such as the development in the economic sector and growth in the population of communities. Global warming is also a future concern which can influence the rainfall for the better or worse. Although the earth is covered with more than three quarters of water this is not an answer to the increasing demand. Only 2.5% of the water in the world can be used for domestic, agriculture and industrial purposes, and less than 1% of water in the world is suitable and safe to use for drinking water. The remaining 97.5% water on earth lies in the sea with a very high salt concentration (Colak, 2005:427).

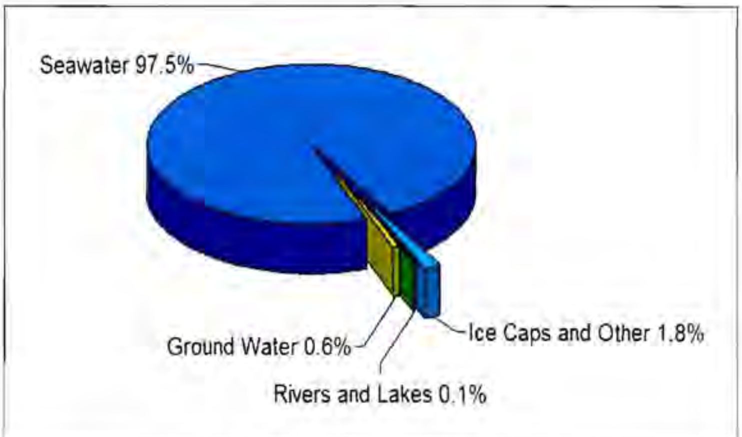

Figure 1: Water resources on earth.

The World Water Council has developed a water stress indicator to indicate the human usage compared to the amount available from the water resources (Refer to Figure 2). Water available to human use is calculated by subtracting the environmental demand from the total amount of water available in the region. A lack of water to the environment could have a significant negative impact on the ecosystem's existence. In Figure 2 a stress indicator higher than 0.8 is considered to be high stressed regions.

The United Nations Environment Program (UNEP) has compiled a Global Environment Outlook (GEO) document which state that some countries will be subjected to water scarcity and water stress in 2025. In Figure 3 some countries in Africa are highlighted showing water scarcity by 2025. *According* to the UNEP almost two thirds of the world population would be without sufficient water supply by 2025 (UNEP, 1999a:6). "One in every six people (1.1 billion) doesn't have access to daily basic needs. Everyday 3800 children die from diseases associated with lack of safe drinking water and proper sanitation" (Health24). Furthermore, the UNEP has conducted a survey among 200 scientists in 50 countries which revealed that the most important issue to be addressed is global warming. The second issue is freshwater scarcity and thirdly freshwater pollution. Note that global warming can have a large impact on water resources. Therefore we can conclude that water is going to be one of the most important factors to be addressed in the next 10 to 20 years.

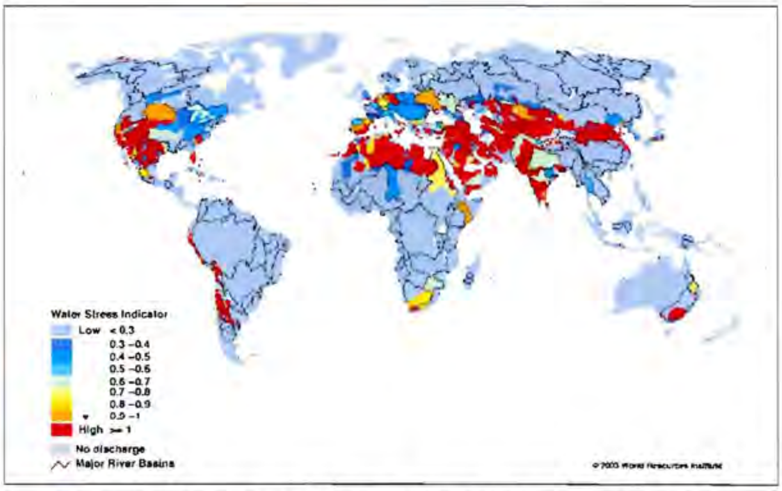

Figure 2: Water stress indicator (World Water Council, 2007)

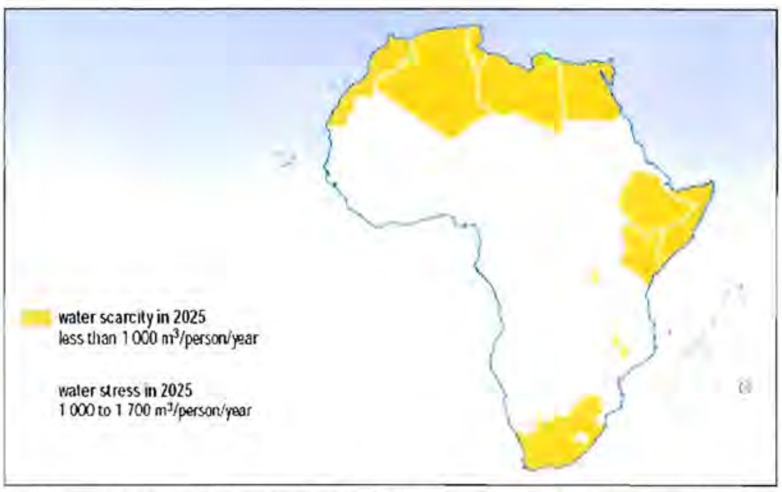

Figure 3: Water stress in Africa by 2025 (United Nations Environment Program, 1999)

Clearly the world must recognize that responsible people need to take action, not only to sustain future fresh water availability, but to increase the quantity and quality for a healthier lifestyle for the human race and also to conserve the ecosystem. It has been recognized and proven that seawater desalination is a good alternative for producing safe drinking water. There are four major reasons increasing the interest in the use of sea water to aid in reducing the scarcity expected. These are:

- Most of the countries with a water scarcity lie close to the sea.
- Desalination technology has improved dramatically resulting in a decrease of the water production cost.
- By-products from desalination plants can be used to increase the salt production rate at salt factories, for example.
- Desalination technology can benefit from industrial waste heat such as with a nuclear power plant that dissipates huge amounts of waste heat into the environment. Waste heat is practically for free and can decrease the operating cost or increase the performance of a desalination process radically.

1.2 *Nuclear Desalination Technology*

"Nuclear desalination is defined to be the production of potable water from seawater in a facility in which a nuclear reactor is used as the source of energy for the desalination process. Electrical and/or thermal energy as an alternative may be used in the desalination process. The facility may be dedicated solely to the production of potable water, or may be used for the generation of electricity and production of potable water, in which case only a portion of the total energy output of the reactor is used for water production" (International Atomic Energy Agency, 2007:5).

According to the IAEA report published in 2007, 30 countries make use of nuclear power to generate more than 16 % of their electricity. In addition it stated that more than ten thousand nuclear reactor-years of operation experience were accumulated in the last five decades. The nuclear desalination technology has more than 176 years of plant operation experience (International Atomic Energy Agency, 2007:5).

Nuclear desalination is becoming a very good option for the production of drinking water from seawater. There are several advantages in using nuclear power for desalination purposes and one of them is the utilization of the waste heat that is normally dissipated into the environment. The rejected waste heat is then practically free and can reduce electricity consumption (in case of RO) or can replace old fashioned thermal driven processes (such as MED plants where heat is normally generated via the burning of oil, coal etc.).

1.3 *Problem Statement*

The renewed attention to desalination for supplying clean water raises the question whether the current efficiency can be raised even further in order to improve the potential of the technology. One option is to connect the process to a waste heat source of another process, such as a nuclear power plant, utilizing the almost "free energy" in the waste heat. For this a good understanding of the basic principles of the RO process is required before options of "free energy" can be investigated. The need was therefore identified for a set of guidelines for designing a RO plant for connection with a waste heat source. However, in order to investigate new potential the question was raised whether connecting a RO plant to a new generation high-temperature reactor would offer a viable option.

1.4 *Objective*

The primary objective of this study is to develop a set of suitable design guidelines and associated economic aspects for conceptually designing a reverse osmosis plant. These guidelines are then to be verified against existing RO design software and tested in a case study connecting a RO plant to a new generation high-temperature nuclear power plant.

1.5 *Methodology*

A thorough literature study will be preformed to identify previous work done on the reverse osmosis process. From the literature study, suitable reverse osmosis design guidelines can be identified. These guidelines will then be verified against existing design software programs such as CSMPRO, ROSA and DEEP. Finally the applicability of the guidelines will be evaluated in a case study connecting the RO plant to a new generation nuclear power plant. For this the case study will focus on the PBMR nuclear plant that will be built at Koeberg in the Western Cape. Finally, suggestions will be discussed for further work on expanding the guidelines to improve the accuracy of the conceptual design vs. a detailed design.

1.6 *Conclusion*

The project is a small step for the North West University to gain knowledge in the potential of the reverse osmosis process to contribute to water desalination as a source of clean water in the future. By using waste heat from nuclear power plants, such as the PBMR, the desalination industry can improve its efficiencies and reduce the cost of water resulting in a bright future for water production across the globe.

2 Chapter

LITERATURE SURVEY

2.1 *Introduction*

In this chapter a swift overview will be given on the major desalination processes available on the market today. A component breakdown of the reverse osmosis process is presented and each component is discussed in detail. Furthermore, basic water terminology is presented to give the reader a broader background on water chemistry.

2.2 *Desalination Technology*

Desalination processes are relatively new with development only starting around the 1950's. The first seawater desalination demonstration plant was built in the United States at Freeport in Texas. President John F. Kennedy officially opened the plant on June 21, 1961. A water production rate of 3800 m^3/day was achieved. In his speech he said "No water resources program is of greater long-range importance than our efforts to convert water from the world's greatest and cheapest natural resources – our oceans – into water fit for our homes and industry. Such a break-through would end bitter struggles between neighbors, states and nations" (Krishna 2004:1). The statement was made 40 years ago and is still true today.

Today there is a large variety of desalination processes available to produce any quality and quantity of water to consumers in different water markets. Figure 4 shows a breakdown of the most popular processes in two main categories namely the membrane and thermal distillation processes.

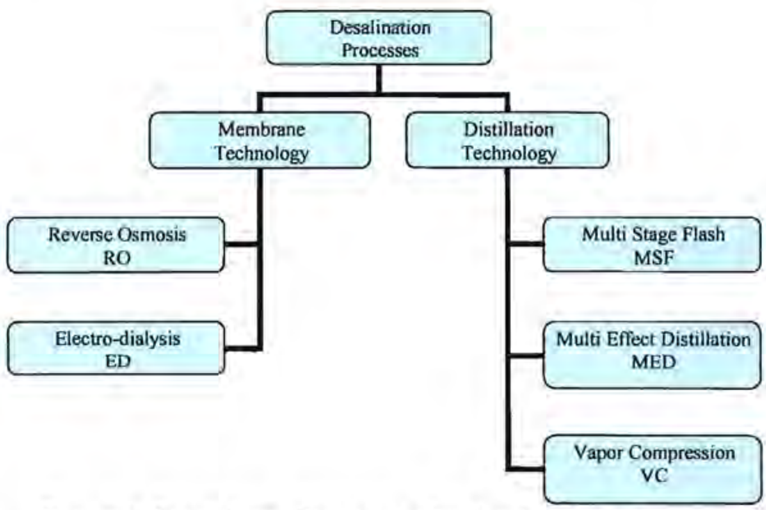

Figure 4: Breakdown of most popular desalination processes.

2.2.1 Membrane Technology

Distillation processes were dominating the market in the early phase of water desalination. In 1959 the membrane technology was introduced and it took a few more years to become economical comparable to the distillation processes. Today, market shares of membrane technology are growing at a high rate due to lower operating costs and lower energy consumptions. The growth is supported with continued efforts to increase the process efficiency with new technology. Major membrane processes leading the market are:

- Reverse Osmosis (RO)
- Electro-dialysis Reversal (EDR)
- Nanofiltration (NF)

Other membrane processes also being used are:

- Forward Osmosis (FO)
- Membrane Distillation (MD)

2.2.1.1 Reverse Osmosis (RO)

Osmosis is a natural way for water to move through a semi permeable membrane from a low concentration solute to a high concentrate solute. In nature trees make use of osmosis to absorb water from the ground by creating a concentration gradient over the membrane. The pressure difference associated with osmosis is called osmotic pressure. In the reverse osmosis process, high pressure pumps are used to overcome the osmotic pressure difference. Subsequently the water flows in the opposite direction through the membrane resulting in a high salt concentration brine stream and high quality product water. Figure 5 shows the principle of a typical reverse osmosis plant and its main components. Compared to the other desalination processes, reverse osmosis is the most promising technology due to the fact that its product cost is the lowest. A disadvantage of the RO process is the fact that the product water is not as clean compared to the distillation processes.

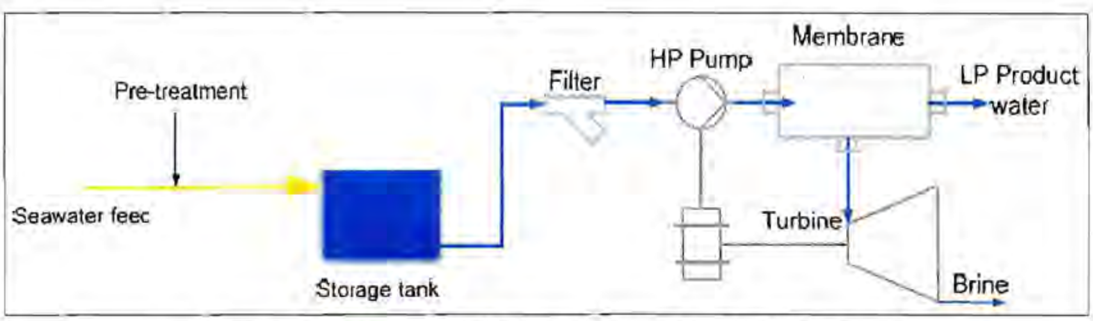

Figure 5: The principle of Reverse Osmosis (RO) desalination.

2.2.1.2 Electro-dialysis (ED)

Electro-dialysis is a membrane driven process which makes use of an electro dialysis-cell (Lenntech Water treatment & Air purification, 2009). In Figure 6 a cell is shown to illustrate the flow of ions. Two different membranes are used, namely an anion and cation membrane. The cation membrane is negatively charged and rejects negative ions in the feed water that allows positive ions to flow through it. The opposite applies to the anion membrane. Particles that do not consist of a charge cannot be removed from the feed water. As with reverse osmosis some pre-treatment is necessary before ED can be applied. Suspended solids must be removed to ensure that membrane fouling does not occur. Particles exceeding 10 micrometers are normally filtered out of the feed water. ED has some advantage over other membrane processes. One of them is that the concentration of the feed water decreases downstream and therefore a higher feed recovery can be achieved.

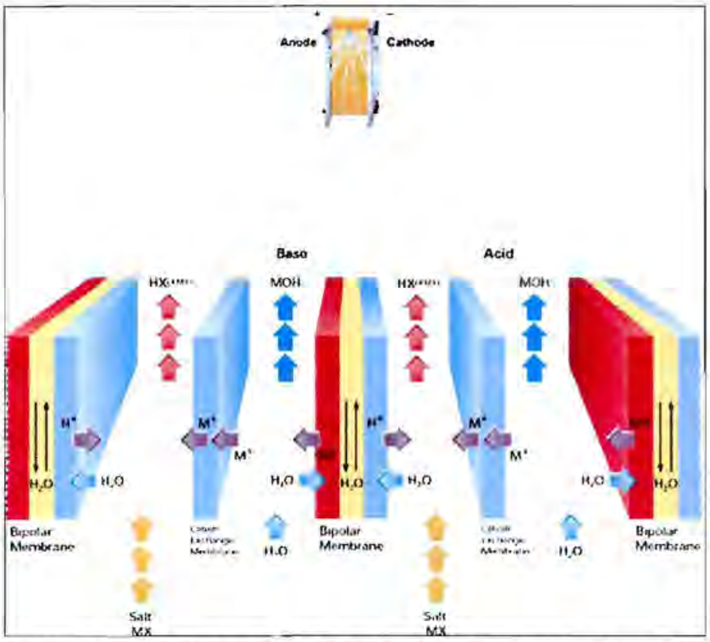

Figure 6: The principle of Electro Dialysis (ED) desalination (Amerida, 2008).

2.2.2 Distillation Technology

The distillation process was the first commercial process used to produce fresh water from brackish water. Today there are three major distillation cycles available on the market, namely:

- Multi Stage Flash (MSF)
- Multi-Effect Distillation (MED)
- Vapor Compression Evaporation (VC)

A disadvantage of the distillation process is that large amounts of thermal energy are necessary to drive the process. The energy sources differ between oil, fossil fuel and etc. which are not clean sources of energy. Nuclear is also used as an energy source and is definitely the future option for clean, cost-effective water production. One example of a nuclear distillation plant is the one situated in Kazakhstan. The BN-350 fast nuclear reactor at Aktau was designed to produce 1000 MWt energy, but never operated more than 750 MWt. A Multi-Effect Distillation (MED) plant was coupled to the nuclear reactor and only 60 % of the reactor energy was used to produce 80 000 m^3/day of drinkable water (World Nuclear Association, 2008). Nuclear desalination is becoming a highly preferred option for clean, cost effective water production.

2.2.2.1 Multi Stage Flash (MSF)

The MSF process is the world's largest installed thermal evaporation process which was invented and patented by Weirs of Cathcart in 1957 (Halcrow Water Services, 2008). It is a straightforward design and the process has proven its reliability over the years. In Figure 7 a typical MSF process is shown where the feed water enters the plant (top right) in the last stage. The feed water is used to condensate the vapour that is being flashed out of the bottom bulk liquid to produce the product water. As the feed water flows through the stages the temperature increases until it reaches the ultimate brine heater. Oil, coal and nuclear etc. are used to generate thermal power to drive the brine heater. The pressure in each stage is below the saturated vapour pressure of the particular stage.

One of the largest MSF plants in the world is situated in Shuweihat in the United Arab Emirates. The plant distills seawater and produces approximately 378,000 m^3 of fresh water per day (Water-technology.net, 2009b). Irrespective of its reliability, operation simplicity and proven performance, the MSF is starting to lose market shares due to new technology that achieve higher efficiencies and are less expensive.

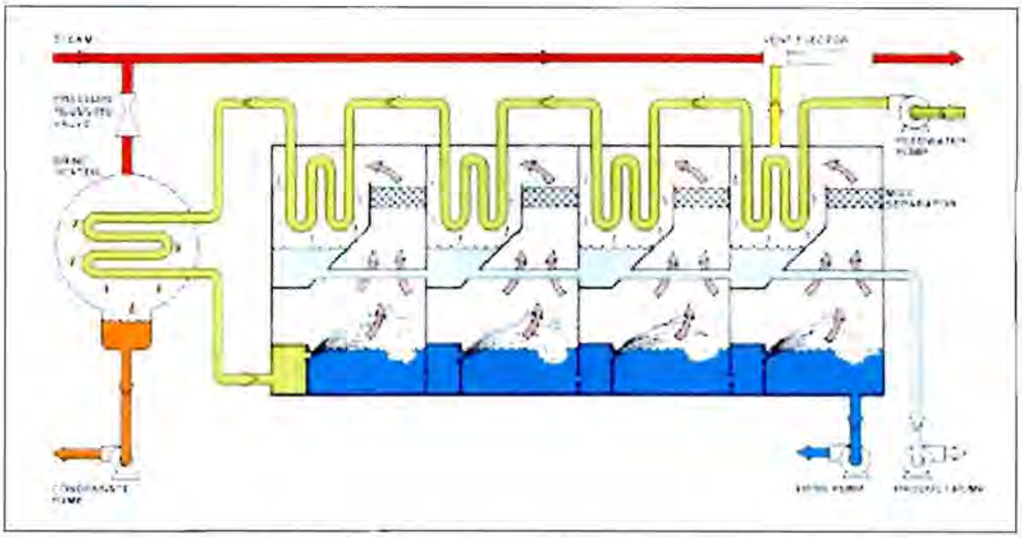

Figure 7: The principle of Multi Stage Flash (MSF) distillation (AcwaSasakure, 2008)

2.2.2.2 Multi-Effective Distillation (MED)

The Multi-Effect Distillation (MED) process was initially used to evaporate juice or salty water for the production of sugar and salt respectively (Desalination, 2009). The MED process was also used to distill water, but on a much smaller scale. During the 1980's the MED process emerged extremely fast after related distillation problems were addressed. The process is designed to make use of the heat energy in steam to evaporate water. There are a number of boiling vessels in series, each held at a lower pressure than the previous effect (stage). If the pressure decreases, the energy required to evaporate the water is also reduced. Therefore, the steam in the previous effect can be used as a heat source in the next effect to evaporate water from the feed stream. Only the first effect needs energy from a power source such as from nuclear, coal or fossil fuel. The plant size depends on the number of effects used and can vary between 8 and 16 effects in series. A higher amount of effects will increase the plant efficiency, but will increase the capital cost as well. The main disadvantage of the MED process is that it cannot produce high amounts of product water, relative to the MSF process.

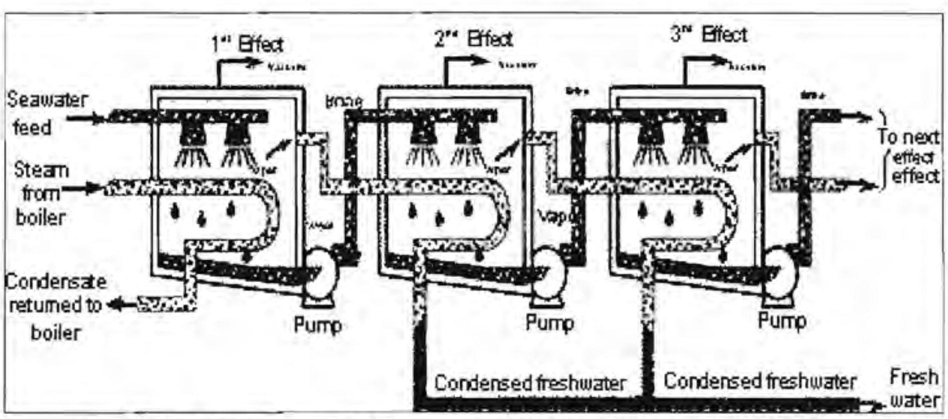

Figure 8: The principle of Multi-effect distillation (MED) (UNEP, 2008b).

2.2.2.3 Vapour Compression (VC)

The Vapor Compression process differs from the previous distillation processes in the sense that a mechanical compressor is used for the main energy input to the cycle (Aqua Technology, 2008). In Figure 9 the feed water is preheated by the outgoing product water and brine. The feed water is then heated by the hot steam coming from the compressor. Additional heater elements can be implemented if necessary. The hot steam is condensed while transferring the heat to the brine. Non condensing gasses are normally removed via a vent pump. To condense the pure liquid, a lower temperature below the boiling temperature of the brine water (at the same pressure) is required. Therefore it is necessary to increase the pressure of the vapour in order to condense. Large compressors are used and are normally driven with electric or thermal power. The VC process is a straightforward and reliable distillation process. Compared to the other distillation processes, the VC process can only produce a small amount of product water (In the order of 3000 m^3/day).

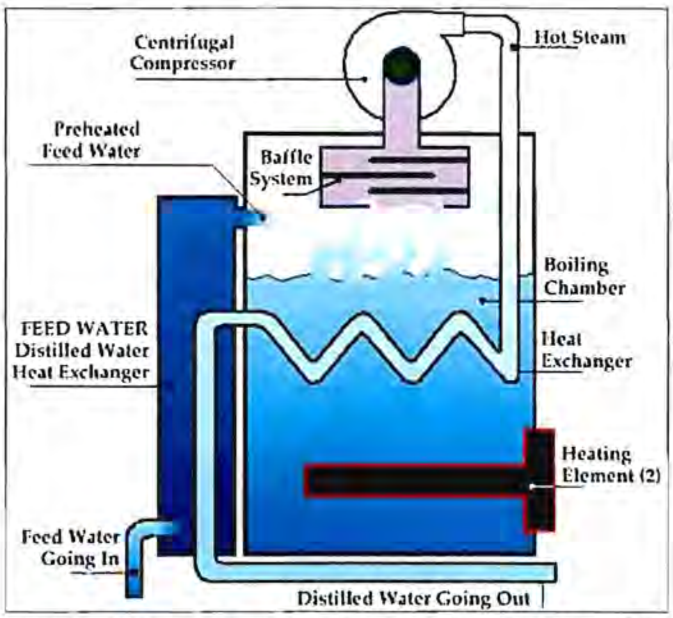

Figure 9: The principle of Vapour Compression (VC) distillation (Aqua Technology, *2008)*

2.3 *Desalination Market*

According to the Global Water Intelligence (GWI) group, the world's installed capacity of desalination plants is producing water at approximately 35 million m^3/day and is growing in the order of 7 % per annum (GWI, 2005). Figure 10 gives the history of the world's installed capacity over 50 years. The dotted line shows the cumulative installed capacities. The total desalination market can be divided into the main technologies available. Figure 11 gives a breakdown of all the main processes used in the desalination market worldwide.

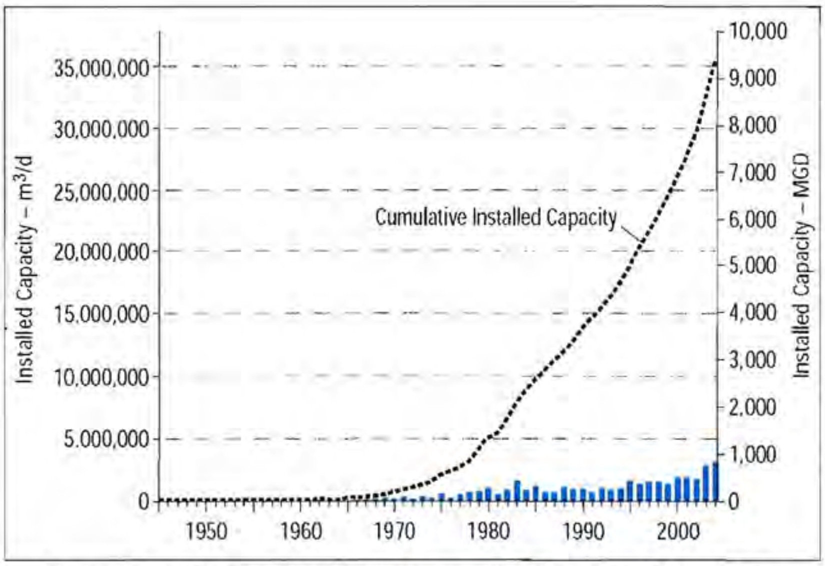

Figure 10: History of desalination capacities installed (GWI, 2005).

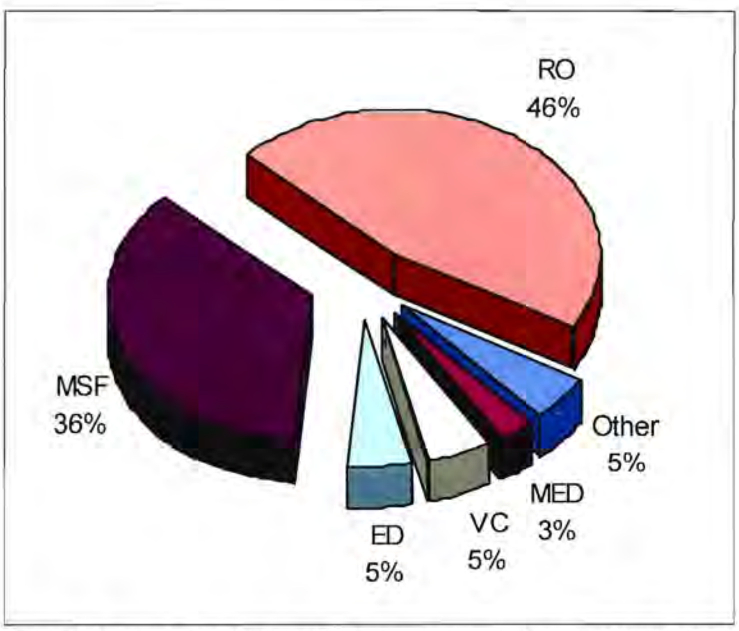

Figure 11: Installed desalination processes worldwide (GWI, 2005).

2.4 *Reverse Osmosis*

2.4.1 Historical Background

The United States wanted to supply the navy ships with clean water for months at a time resulting in the need for large tanks. In large ships this problem was acceptable, but in a submarine little space was available for water supplies. A compact method was needed to produce drinking water from seawater and this lead to the development of reverse osmosis technology. In 1959 a breakthrough was made with the first experiment and demonstration of the reverse osmosis process. At the same time a synthetic reverse osmosis membrane was developed from a cellilose acetate polymer with relative good performance. The first commercial RO plant was built in the town Coalinga in California. It was the first trial for the new membranes and it produced almost 23 cubic meter of pure water from brackish groundwater. From here the next pilot plant was built in La Jolla, California (UCLA Engineering, 2009a). The plant was built mainly to evaluate the performance of the RO membranes while desalinating seawater. During the space race, NASA also invested in reverse osmosis technology for the production of fresh water from astronauts' urine. This decreased the weight of the spacecrafts which was an additional benefit.

The reverse osmosis discovery had a huge impact on the world and this technology started to spread into many different areas and applications.

2.4.2 System Components

The reverse osmosis process consists of numerous stages and sub-systems that are designed to integrate with each other. Each component has an important function and a detailed design should be made to achieve the highest efficiency. For instance, if the pre-treatment system should under perform, it will have a negative impact on the RO membranes that will lower the quantity and quality of the product water. Figure 12 gives a breakdown structure of the main reverse osmosis components. A brief discussion of each component will follow.

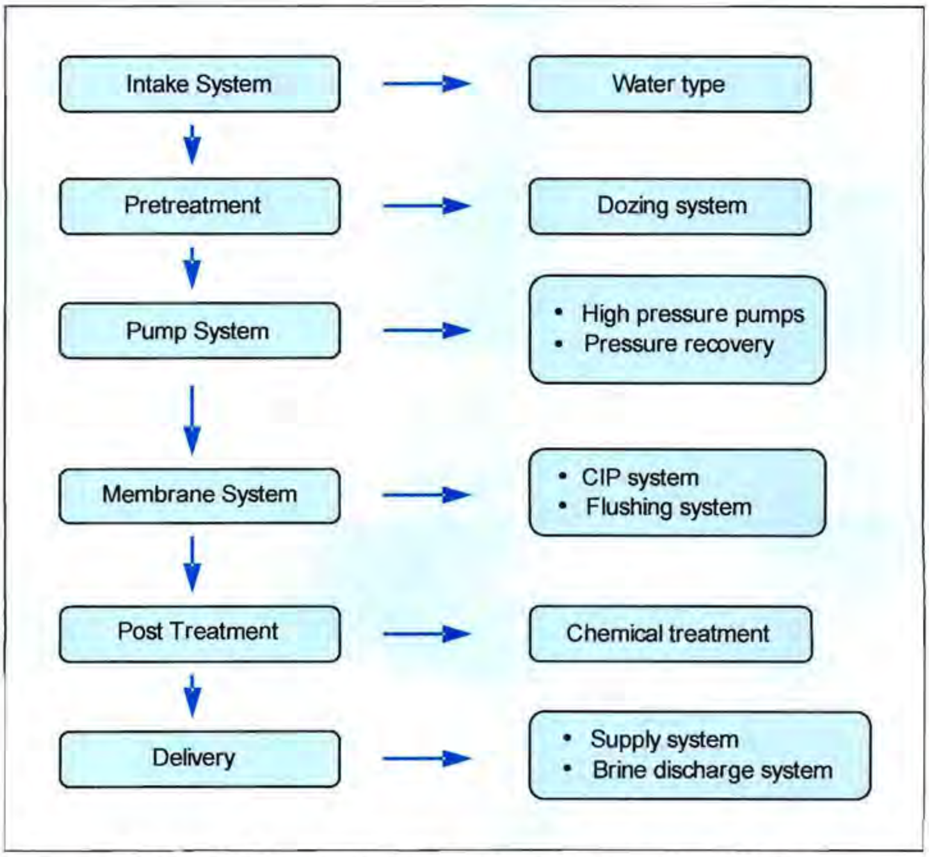

Figure 12: Reverse osmosis system component breakdown

2.4.2.1 Intake and Outfall System

There are different types of intake and outfall systems and each system must be designed according to the desalination plant size, type of feed water, feed water quality, environmental impact of the brine and legislation. For seawater desalination plants, there are mainly four different types of intake systems, namely:

- Conventional open intake system.

  The system consists of long pipe lines that lie on top of the seabed and make use of either active or passive screens. This method has a large impact on the marine environment and thorough investigations should be performed to minimize the negative effects on the environment. Furthermore, this method requires large and expensive pre-treatment systems in order to clean the water before it enters the reverse osmosis system. (Thomas, P. & Domenec, 581)

- Indirect intake system with a beach-well.

  A beach-well intake system is a famous indirect method used for the extraction of seawater from below the seabed near a shore. A large collector pipe runs and collects seawater from beneath the sea bed. The sea sand acts as a filter and reduce the effect of marine biological and other pollution dilemmas. Higher quality feed water is attained and a smaller, less expensive, pre-treatment plant can be installed before the RO membranes. (Thomas, P. & Domenec, 581)

- Indirect system with seabed filtration technology.

  This system requires a pipeline installed in the seabed. Consequently, a narrow piece in the seabed needs to be excavated in order to install the pipe. The pipe is then covered with several layers of material such as crushed stones, gravel, replaced sand and lastly a layer of original sand. Due to the installation process this system will have a huge impact on the marine life and the surrounding environment, including the beach. Another issue to be considered is that the layer of material (sand & rock) needs to be replaced after a few years of operation. Figure 13 gives an excellent illustration of the design of such a system. (Thomas, P. & Domenec, 581)

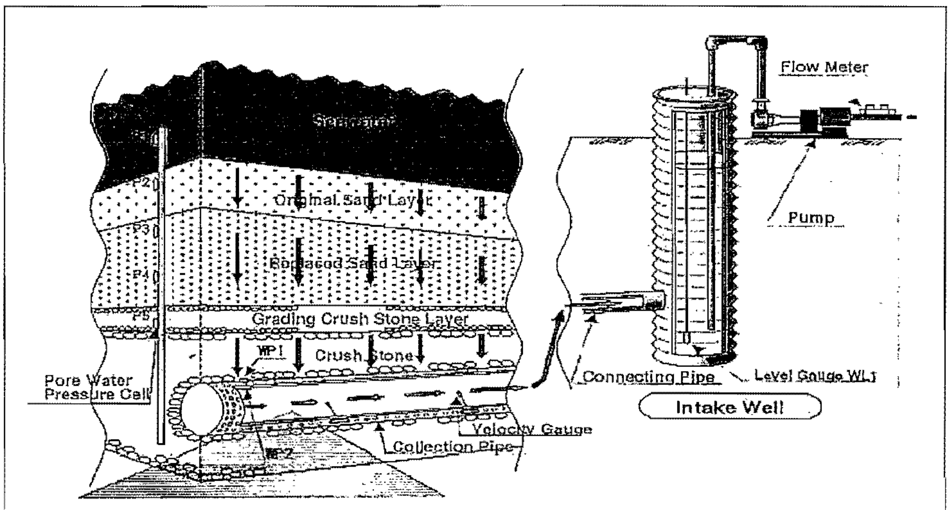

Figure 13: Indirect seawater intake system (Thomas, P. & Domenec, 581)

• Indirect HDD-based Neodren intake system.

  This process makes use of horizontal pipes that are installed underneath the seabed with a special drilling method. Drilling takes place from behind the seashore. Special drilling material is used due to technical issues and for the protection of the environment. The pipes can be several hundred meters long and are installed only a few meters underneath the seabed. Patented pipes made with a special material are used to collect the seawater at an extremely low flow rate. The advantage of the low flow rate is that no impact is made on the flora and fauna of the environment. Figure 14 gives an excellent illustration on the design of such a system. (Thomas, P. & Domenec, 581)

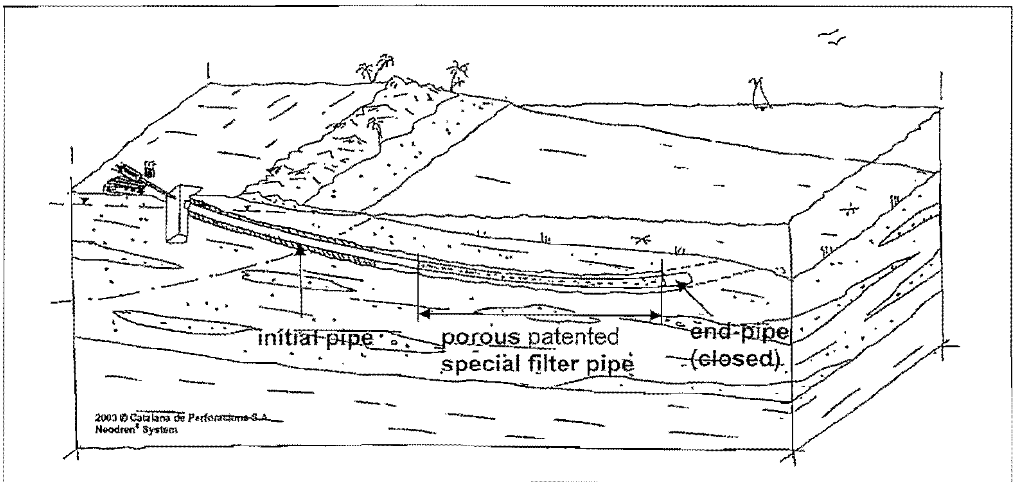

Figure 14: Neodren intake system (Thomas, P. & Domenec, 581)

The intake system is important, not only for the desalination plant effectiveness, but also for the conservation of the environment. Therefore the industry has conducted a lot of research on all types of intake systems over the years and today the intake systems are well established.

2.4.2.2 Pre-Treatment

One of the most important components in a reverse osmosis plant is the pre-treatment system. The performance of the pre-treatment system will have a huge impact on the efficiency and life time of the RO membranes. If a pre-treatment plant is designed accordingly, membrane fouling can be minimized, scaling and degradation will be less and a higher product recovery can be achieved. This will decrease the operating cost of the plant.

Membrane fouling is associated with the entrapment of particles such as inorganic (clay, silica, iron and silt) and organic (organic polymers and micro-organisms) colloids on the membranes. Scaling on the other hand is a deposit of salt onto the membranes, normally associated with calcium carbonate, calcium sulfate and barium sulfate. Therefore, specialists need to analyze the feed water before a proper pre-treatment system can be designed. Figure 15 gives a summary of different pre-treatment options for prohibiting possible scaling and fouling issues (The DOW Chemical Company, 2007:69). The figure gives a quick reference to "possible" and "very effective" techniques. Note that an arrangement of possible methods can also be effective.

Pretreatment	$CaCO_3$	$CaSO_4$	$BaSO_4$	$SrSO_4$	CaF_2	SiO_2	SDI	Fe	Al	Bacteria	Oxid. agents	Org. matter
Acid addition	•							o				
Scale inhibitor antifoulant	o	•	•	•	•	o		o				
Softening with IX	•	•	•	•	•							
Dealkalization with IX	o	o	o	o	o							
Lime softening	o	o	o	o	o	o	o	o				o
Preventive cleaning	o					o	o	o	o	o		o
Adjustment of operation parameter	o	o	o	o	o	•						
Media filtration						o	o	o	o			
Oxidation filtration							o	•				
In-line coagulation							o	o	o			o
Coagulation-flocculation						o	•	o	o			•
Microfiltration/Ultrafiltration						•	•	o	o	o		•
Cartridge filtration						o	o	o	o	o		
Chlorination										•		
Dechlorination											•	
Shock treatment										o		
Preventive biocidal treatment										o		
GAC filtration										o	•	•

o Possible • Very effective

Figure 15: Summary of the different pre-treatment options (The DOW Chemical Company, 2007:69).

2.4.2.3 Pump System

Seawater reverse osmosis requires high pressure to overcome the osmotic pressure of the feed water. High pressure pumps with special design, functions, materials and diverse efficiencies are used to produce the right amount of pressure and volume flow for RO plants. On the other hand these pumps are responsible for the high running cost of the RO process and many different techniques have been applied to reduce the high energy demand. A major breakthrough was made in the pressure recovery technology.

2.4.2.3.1 High Pressure Pumps

There are many different pumps available for the RO process, but only two types are normally used, namely the centrifugal and positive displacement pumps. The positive displacement pump has an advantage over the centrifugal pump when it comes to efficiencies. A typical efficiency range for the positive displacement pump is between 80 % and 90%. However, the flow rate of a positive displacement pump can not be controlled compared to a centrifugal pump. The centrifugal series has a lower efficiency range of between 30% and 60%, but with pressure recovery systems one can have maximum return on investment. Further more, high grade materials are used to withstand corrosion and abrasion from seawater, increasing the costs. Other techniques, such as plasma coating, can be used to decrease deterioration of the pump components, but the process is expensive and a sensitivity analysis should be preformed to determine if it is economically feasible.

One of the leading companies (established in 1834 in Winterthur, Switzerland) that produces high quality pumps and equipment in more than 120 locations worldwide, is Sulzer (Sulzer, 2008). Sulzer have supplied pumps for major RO projects around the globe including the world's largest RO plant built in Ashkelon. Sulzer installed 8 large pumps and 47 smaller pumps at the Ashkelon plant. The eight large pumps (MSD-14x14x19) are driven by electric motors, each with a power output of 5.5 MW. The Ashkelon plant was designed to produce 320 000 cubic meter of water per day!

Figure 16: High-pressure pump from Sulzer (Sulzer, 2008)

2.4.2.3.2 Pressure Recovery

After the membrane process, there are two water streams, namely the product water and the brine (waste) stream. The brine stream contains a large amount of energy in the form of pressure which can be re-used with a pressure recovery system. Pressure recovery systems make use of the energy in the brine stream to pressurize a portion of the incoming feed water. Consequently it reduces the initial energy demand of the RO process. Over the years the pressure recovery system was applied, but with small effect until recent positive displacement technology was established. Positive displacement pressure recovery systems have very high efficiencies of approximately 95%. Positive displacement has reduced the energy demand of the RO process considerably and gave RO a new level of competitiveness in the desalination market. Today it is possible to desalinate seawater for less than 2 kWh/m^3 (MACHARG 2005:53). To elaborate on these systems, we will look at the working principle of a DWEER pressure recovery system.

DWEER Pressure Recovery System

DWEER is a product from a privately owned company, CALDER AG, based in Switzerland (Calder AG, 2008). The company was established in 1981 and is a world leader in the manufacture and supply of pressure recovery systems. Figure 17 gives an illustration of the working principle of a DWEER pressure recovery system. There are 2 main pipes (A & B) each with a piston that can move to the left or right, separating the two fluids in the pipe (feed water and brine water). The valves on both sides of the pipes are used to regulate the flow direction. In this case the valves are set with the intention that Piston A is moving to the right and B to the left. Therefore Pipe A is being reloaded with feed water and B is still exchanging pressure from the brine fluid to the feed water.

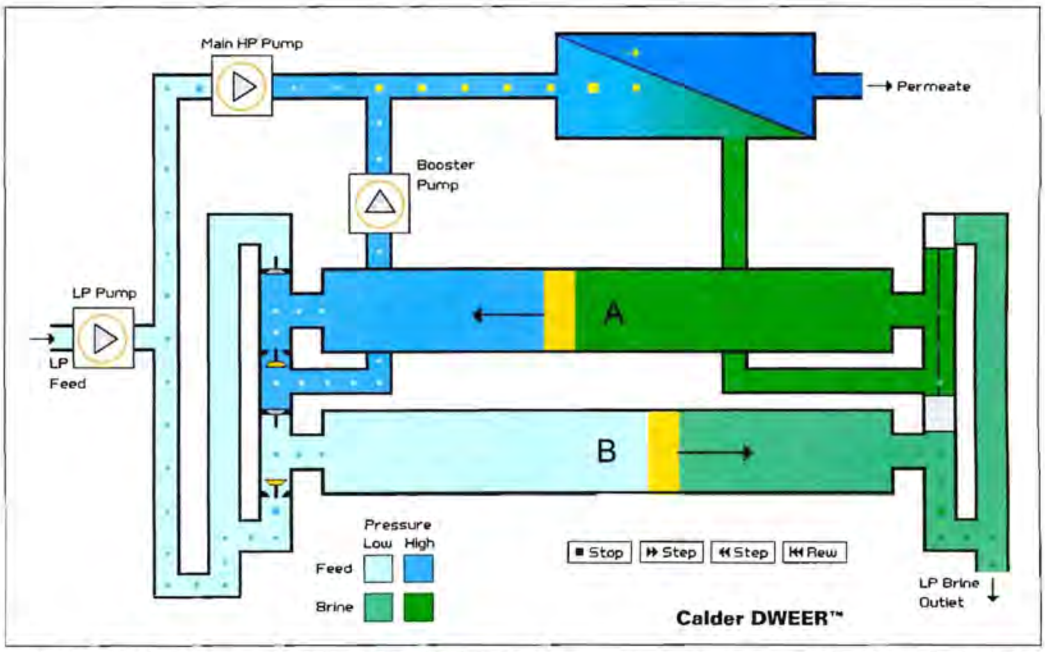

Figure 17: Working principle of the DWEER pressure recovery system (Calder AG, 2008)

2.4.2.4 Reverse Osmosis Flow Configuration[1]

In reverse osmosis technology there is a variety of flow configurations, each with a special purpose and performance. Some experience is required to select the right flow configuration and therefore specialists are normally contracted to analyze the clients' requirements, feed water characteristics, etc. Today there are many software programs on the market that can assist a designer during a RO design. These programs can simulate complex flow configurations with the help of iterations to calculate the performance of the design. The following flow configurations are standard in the RO market and further information on each can be found in Appendix C:

- Continuous Process
- Batch Process
- Single Element System
- Single Array Multi Element System
- Multi Array System

2.4.2.5 Reverse Osmosis Membranes

There are mainly two types of reverse osmosis membranes available on the market, namely the Asymmetric membrane, also called Cellulose Acetate (CA) polymer membrane, and the Thin Film Composite (TFC) membrane.

Asymmetric Membrane – Cellulose Acetate (CA)

The first reverse osmosis membrane was developed by the UCLA Engineering department in California. Sidney Loeb and Srinivasa Sourirajan were two students working under Professor Samuel Yuster when they successfully developed the first reverse osmosis membrane in 1959 (UCLA Engineering, 2008b). The membrane was cast from an acetone based solution of cellulose acetate polymer and was patented in 1960. The first thin layer ensures the salt rejection and the second layer supplies the mechanical support to the membrane.

Thin Film Composite Membrane (TFC) – Polyamide (PA)

TFC membranes were developed much later than CA membranes and were first used commercially in 1981. These types of membranes have a thin dense layer that is deposited on the support layer made from polysulfone. This is a porous layer through which water and salt can move freely. The thin dense layer is made by an interfacial polymerization reaction between a poly-functional amine and a poly-functional acid chloride. This layer ensures the separation of salts and water molecules. The major advantage of the TFC membrane is that it has a higher flux rate and also rejects more salt than cellulose acetate membranes.

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[1] Obtained from THE DOW CHEMICAL COMPANY. 2007. Dow Liquid Separations, Filmtec Reverse Osmosis Membranes, Technical Manual - From No. 609-00071-0705. Page 75-80

A comparison between the CA and the TFC membranes

A designer must choose between these two membranes to meet his application purposes. The designer must realize that the TFC (PA) membrane has some advantages over the CA membrane, namely:

- Higher salt rejection capability
- Higher flux through the membranes
- Lower working pressures
- Stable in a wide pH range

Table 1: Comparison between a PA and CA membrane (Saehan Industries, Inc. 2006:18).

Parameter	PA Membrane	CA Membrane
Operating pH range	2 - 12	4 - 6
Operating Pressure Kg/cm^2)	15	30
Salt Rejection % - TDS	99+	98
Salt Rejection % - Silica (SiO_2)	99+	<95
Salt Rejection after 3 years	99% - 98.7%	98% - 96%
Chlorine Tolerance	< 0.1 ppm	1 ppm
Membrane Fouling	High	Low

2.4.2.6 Element Construction

There are four different forms of reverse osmosis membranes, namely:

- Spiral membrane
- Tubular membrane
- Capillary membrane
- Flat sheet membrane

The most popular membrane for large scale desalination plants is the spiral membrane. This type of membrane can be replaced during a plant operation, increasing the plant availability and lowering operation costs. Furthermore the initial design of the plant can simply be changed and expanded according to future water demands.

One of the leading reverse osmosis membrane manufactures is the FILMTEC group. FILMTEC works in collaboration with the DOW Chemical Company and they specialize in spiral membranes (The DOW Chemical Company, 2007:9). The construction and installation procedure of a FILMTEC membrane is showed schematically in the Figure 18. One spiral element contains between 1 and 30 leafs, depending on the membrane type and application. During the manufacturing, two membrane leafs are glued back-to-back against each other with a permeate spacer in-between. This acts in the same way as a plastic bag closed at all sides except at the top. Between a pair of leafs a feed water spacer is inserted to increase the turbulence of the feed water flow over the membrane surfaces. During the operation, the feed water enters the face of the element through the feed spacer channels and exit at the opposite side with an increase in the salt concentration. This concentrate is then used for the feed water for the next element. The raise in salt concentration has to be taken into account during the design of a RO plant. Leafs are rolled to form a spiral membrane element which then allow the permeate water to flow in a spiral direction to the center tube. Each membrane element recovers between 10% and 20 % of water from the feed water stream leaving the element through the center tube at the end. The center tube is connected to the next element tube and the combined permeate water in total exits the pressure vessel at one side. The number of elements in the pressure vessel depends on the design performance of the plant.

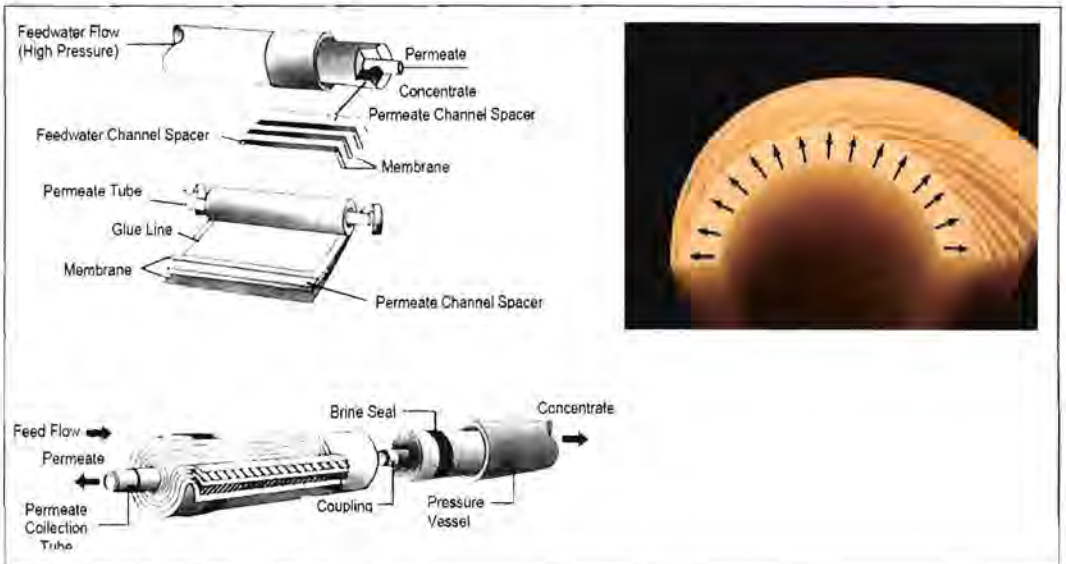

Figure 18: Comparison between PA and CA membranes (The DOW Chemical Company, 2007:18)

2.4.2.7 Post Treatment and Brine Discharge

Both the product and brine water need to be treated before it can be used or discharged back into the sea.

Product Water Treatment:

The product water needs to be stabilized and disinfected before it can be used. For disinfection purposes chlorine is normally added together with an ultraviolet light. It is mainly done for the prevention of biological growth in the pipe lines and reservoirs. Furthermore, a desalination plant can easily remove the carbonate, calcium and magnesium from the water which makes it corrosive. Therefore the product water needs to be stabilized before it can be used as drinking water.

Brine Discharge:

Depending on the size of the desalination plant, the brine water can either be pumped into evaporation ponds or returned to the feed water source (e.g. the sea). Seawater desalination plants normally dispense the brine water together with an industrial plants cooling water to dilute the brine water as quickly as possible. Sometimes submarine pipes are used to dilute the brine over a large distance on the sea floor. Both methods dilute the brine water to a legislated concentration that will not damage the environment at all. However, detailed studies have to be made to determine the discharge method's performance, for the maximum protection of the environment.

2.4.3 Reverse osmosis design software

In the 20^{th} century the computer has become part of every day life in most engineering fields. Major suppliers of reverse osmosis systems have developed design software programs that can simulate and optimize complex RO designs. A few of these programs can also conduct economic calculations. The following 3 programs where obtained from leading RO companies.

- Customer Satisfaction Membrane PRO (CSM-PRO)
- Desalination Economic Evaluation Programme (DEEP)
- Energy Recovery INC. (ERI)

For detailed information on each, please refer to Appendix B.

2.5 *Water Chemistry*

2.5.1 Introduction

Before a detailed design of a reverse osmosis plant is carried out, the feed water must be analyzed according to proper measurements to determine the composition of the feed water. This will have a large influence on the membrane layout, recovery ratio and pre-treatment design of the RO plant. Pre-treatment is one of the most important components in a RO process. With an improper pre-treatment design, the plant will have a lower efficiency due to membrane fouling, scaling and degradation. The key factor is to balance all components of the plant to achieve optimum product flow, recovery ratio and keeping the operating and maintenance costs as low as possible.

2.5.2 Physical Characteristics of Water

The following part will address some important water terminology.

- Turbidity

According to Wikipedia the definition for turbidity is "the cloudiness or haziness of a fluid caused by individual particles (suspended solids) that are generally invisible to the naked eye, similar to smoke in air" (Wikipedia, 2008a). Turbidity is measured in Nephelometric Turbidity Units (NTU). If particles increase in water, like sand, the water clearness decreases, resulting in a higher turbidity value.

- Total Solids (TS)

Total solids are sometimes called the total residue in the water. The total residue consists of the total solids plus the dissolved minerals. Total Solids are measured with the following technique: a water sample is evaporated and the remaining residue is then weighted. The value is given in mg/liter.

- Total Suspended Solids (TSS)

Total suspended solids were once called non-filterable residue (NFR). NFR was defined as the dry-weight of particles that was trapped by a filter. Note that the filter had a specific pore size. Due to some definition problems the term was changed to Total Suspended Solids (TSS). Measuring the TSS consists of water being filtered through a specified membrane. The particles that are trapped on the membrane are then dried and weighed. TSS are also given in mg/liter (Wikipedia, 2008b).

- Total Dissolved Solids (TDS).

According to Wikipedia the definition for TDS is "an expression for the combined content of all inorganic and organic substances contained in a liquid which are present in a molecular, ionized or micro-granular (colloidal sol) suspended form" (Wikipedia, 2008c). The measuring value is given in mg/liter.

- Silt Density Index (SDI)

The silt density index gives a fouling potential to the feed water in a reverse osmosis process. If the feed water contains an SDI value of 5 and less, it will have a low fouling probability. A complicated test is done to determine the SDI of the feed water. According to Wikipedia the test is defined by a specific procedure (ASTM D-4189) which was updated on July 2007 (Wikipedia, 2008d). In a reverse osmosis process the feed water must be tested on a daily basis to ensure that the SDI is maintained below the design figure.

- Total Organic Carbon (TOC)

The TOC is the inorganic carbon subtracted from the total carbon reading or is the organic multipart in the water and also gives a quantity on the purity of the water.

2.5.3 Feed Water Type

As stated before, more than 97% of the earth's water is captured in the sea. This is making the sea more and more attractive as a source for future drinking water. However, a desalination plant that extracts water from the sea must be designed in such a way that the plant will not harm the environment in any way. Therefore, a good environmental study must be conducted together with a detailed feed water analysis to maximize the efficiency and lifespan of the desalination plant. A detailed analysis of the feed water must also include measurements of sea currents, marine life, the inflow of large rivers, human waste etc. On the microscopic level, measurements such as the colloidal, organic and biological amounts are important. There are many water sources around the world with different constituents. According to Dow Liquid Separations there are 5 key categories of water types which are listed in Table 2. Figure 19 shows the major water types being treated by reverse osmosis and nano filtration.

Table 2: Major water types treated by RO and NF (The DOW Chemical Company 2007:22).

Salinity	Quality	TDS	Source
Very Low Salinity	High Purity Water (HPW)	< 50 mg/L	- First RO System/Stage - From Polishing Stage in Ultra pure Water (UPW)
Low Salinity	Below World Standard	< 500 mg/L	Tap Water
Medium Salinity	High Organic Matter (NOM)	< 5000 mg/L	Groundwater
Medium Salinity Brackish Water	-	< 5000 mg/L	Groundwater
Medium Salinity Tertiary Effluent	High TOC and Biological Oxygen Demand (BOD)	< 5000 mg/L	Groundwater
High Salinity Brackish Water	Area depended	< 50 000 mg/L	Seawater

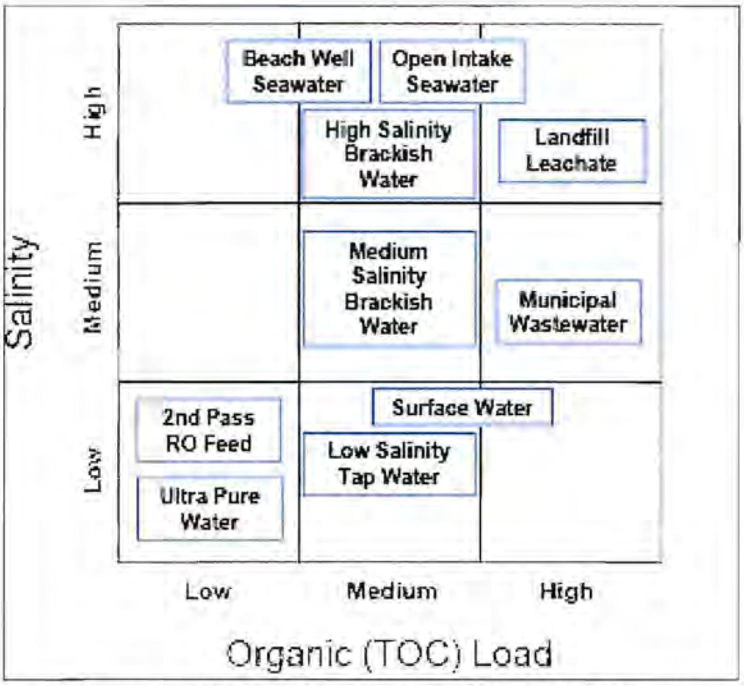

Figure 19: Major water types treated by RO/NF (The DOW Chemical Company, 2007:22).

Seawater characteristics differs from region to region depending on the fresh water inflow, for example; the average TDS of the Baltic Sea is less than 20,000 mg/liter and in some regions it can reach values as low as 6,000 mg/liter due to a large inflow of fresh water from inland rivers. However, in the Middle East the condition is different where TDS readings of more than 45,000 mg/liter can be achieved. According to Dow Liquid Separations, the standard seawater composition is given in Table 3.

Table 3: Standard seawater composition (The DOW Chemical Company, 2007:23).

ION	CONCENTRATION (mg/L)
Calcium	410
Barium	0.05
Bicarbonate	152
Boron	05-Apr
Bromide	65
Chloride	19700
Fluoride	1.4
Iron	<0.02
Magnesium	1310
Manganese	<0.01
Nitrate	<0.7
Potassium	390
Silica	0.04 - 0.08
Sodium	10900
Strontium	13
Sulfate	2740
TDS	35 000
pH	8.1

2.5.4 Feed Water Analysis

A detailed analysis should not only be carried out during the design phase, but also throughout the RO plant's life time. Regular measurements must be taken to adjust pre-treatment and plant operation for maximum efficiency. One important factor is the temperature at which this measurement is taken. If the temperature varies, it will have a large impact on the scaling rate of the membranes. The American Society for Testing and Materials (ASTM) has developed standard techniques for the analysis of both RO and NF systems. DOW Liquid Separations has set up Table 4 which is a list of the relevant ASTM procedures and *Standard Methods for the Examination of Water and Wastewater* (The DOW Chemical Company, 2007:26).

Table 4: Standard procedures applicable to water analysis for RO and NF applications (The DOW Chemical Company, 2007:26).

	ASTM	Standard Methods /1/
Calcium and magnesium	D 511	3500-Ca, Mg
Chloride	D 512	4500-Chloride
Carbon dioxide, bicarbonate, carbonate	D 513	4500-Carbon dioxide, 2320
Phosphorus	D 515	4500-P
Sulfate	D 516	4500-Sulfate
Aluminum	D 857	3500-Al
Manganese	D 858	3500-Mn
Silica	D 859	4500-Silica
Dissolved oxygen	D 888	4500-O
Iron	D 1068	3500-Fe
Fluoride	D 1179	4500-Fluoride
COD	D 1252, D 6697	5220
Residual chlorine	D 1253	4500-Cl
pH	D 1293	4500-pH value
Lithium, potassium, sodium	D 1428, D 3561	3500-Li, Na, K
Ammonia nitrogen	D 1426	45—NH_3
Particulate and dissolved matter	D 1888	2560
Turbidity	D 1889	2130
Total organic carbon (TOC)	D 2579, D 4129, D 4839, D 5904	5310
Arsenic	D 2972	3500-As
Boron	D 3082	4500-B
Strontium	D 3352	3500-Sr
Practices for sampling water	D 3370	1060
Nitrite - nitrate	D 3867	4500-Nitrogen
Silt density index	D 4189	—
Barium	D 4382	3500-Ba
Microbiological contaminants in water	F 60	......
Oxidation-reduction potential (ORP)	D 1498	2580
BOD	—	5210
AOC	—	9217

2.6 *Conclusion*

Based on the need identified in Chapter 1, this chapter looks at the major desalination processes available on the market and gave some background on each. The world market share of these desalination processes is also given. The main focus of this chapter is the reverse osmosis technology which provides the reader with a component breakdown of the process. Furthermore, some water chemistry terms and issues are also addressed.

3 Chapter

DESIGN GUIDELINES FOR A REVERSE OSMOSIS PLANT

3.1 *Introduction*

In this chapter the design guidelines of a reverse osmosis plant are given in nine easy steps which also include steps for an economic evaluation. The main issue during a design is to minimize the cost of a plant while improving the quantity and quality of the product. In the reverse osmosis process there are numerous possibilities that can reduce the capital and operating costs. For example, the main component responsible for the high electricity consumption is the high pressure pump. By reducing the feed pressure the energy demand will decrease and the cost will be reduced. However, this will also influence the performance of the membranes and reduce the quantity and quality of the product water. To balance a complicated reverse osmosis system, software programs are normally used to solve complex equations by iteration methods.

3.2 *Theory of Reverse Osmosis*

Osmosis is a very important phenomenon used in nature by most living creatures. For example, trees make use of the osmosis process to extract water from the ground. During the process of osmosis energy is released and work can be done, for example, when a root of a tree breaks a rock for further growth. Osmosis is the movement of water from a region of a less concentrated solution through a semi permeable membrane towards a region of a higher solute concentration (See Figure 20). The osmotic event can be opposed by applying pressure to the side of the high solute region. When no water is flowing across the membrane, the system has reached its equilibrium. The pressure applied is called the osmotic pressure for the system and its conditions. If the pressure is raised above the osmotic pressure, the water will flow in the opposite direction. This is called reverse osmosis. The following equation can be used to calculate the osmotic pressure (π) of a dilute solution:

$$\pi = I \times M \times R \times T \qquad \text{[Equation 1]}$$

where

I - van't Hoff factor
M - Morality
R - Gas constant
T - Thermodynamic temperature

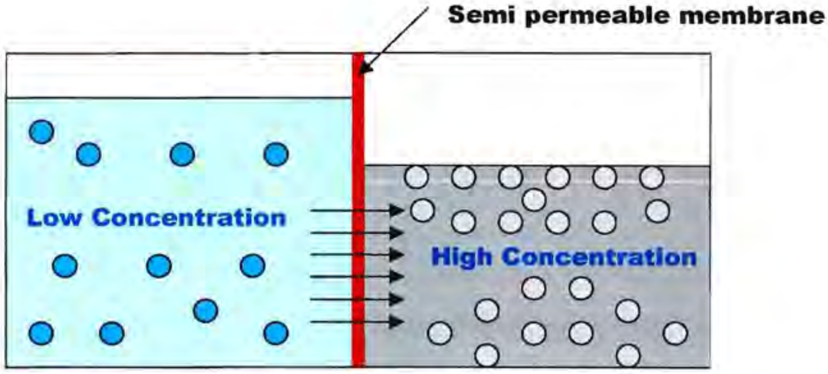

Figure 20: The principle of osmosis

Reverse osmosis makes use of high pressure to overcome the osmotic pressure of a saline medium. Consequently the water molecules flow from the region of high saline concentration through a semi permeable membrane to the region of a low saline concentration (See Figure 21). There are many different reverse osmosis membranes available on the market, each with a unique flux rate. A typical seawater membrane has a flux rate of between 11 and 20 liter/m^{2}h.

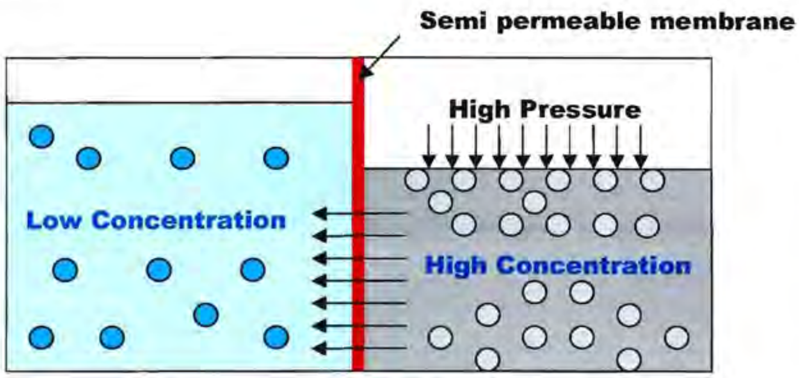

Figure 21: The principle of reverse osmosis

Membrane flux is proportional to the difference between the applied hydraulic pressure and the osmotic pressure. It is also proportional to the membrane's permeability. To calculate the volumetric flux (J) trough a membrane the following equation is applied.

$$J = \frac{\Delta P - \Delta \pi}{\mu (R_f + R_m)} \quad \text{[Equation 2]}$$

where

J - Volumetric flux [m^3/m^2.s]

ΔP - Transmembrane pressure drop [Pa]

$\Delta \pi$ - Osmotic pressure difference [Pa]

μ - Dynamic viscosity [Pa.s]

R_f - Fouling resistance

R_m - Membrane resistance

The performance of an RO membrane can be influenced by a number of effects such as the feed water temperature, system recovery ratio, applied pressure and the feed water concentration. The following figures show what effects above parameters have on the system performance. Figure 22 gives the relationship between the permeate flux and salt rejection according to the applied pressure. If the pressure is increased, the flux and salt concentration of the permeate increases. Note that all RO membranes have a pressure limit due to the mechanical integrity of the materials used.

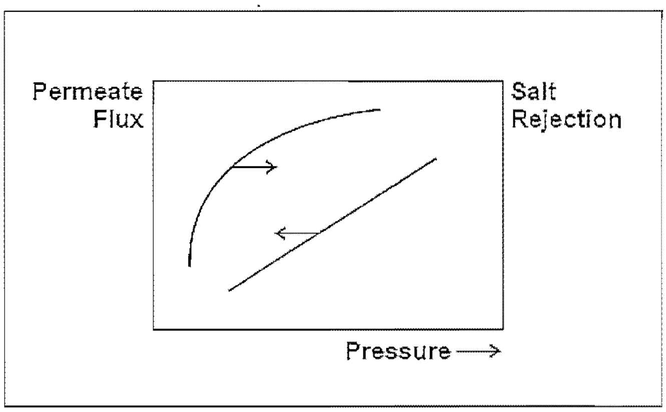

Figure 22: System performance vs. feed pressure
(The DOW Chemical Company, 2007:14).

One of the major advantages for future RO plants is the coupling scheme between the RO process and a nuclear power plant such as the PBMR. By using the cooling water from the PBMR the efficiency of both systems can be increased. Figure 23 shows the relationship between the flux rate, salt rejection and temperature of the feed water. Usually a reverse osmosis membrane has a maximum operating temperature of 45°C due to limitations of the adhesive used in the construction. If the maximum temperate range is exceeded the membranes will most definitely be damage and this must be avoided at all times.

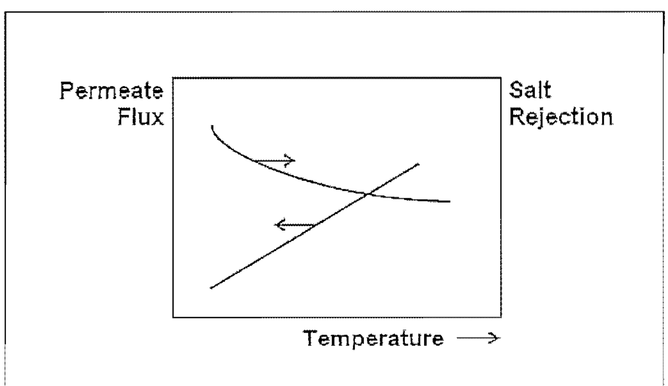

Figure 23: System performance vs. feed water temperature
(The DOW Chemical Company, 2007:14).

If the recovery ratio is increased the salt rejection will also decrease together with the permeate flux rate. This can be seen in Figure 24. Figure 25 illustrates the effect of the feed water quality. It the feed water concentration is increased, the salt rejection and permeate flux rate will decrease.

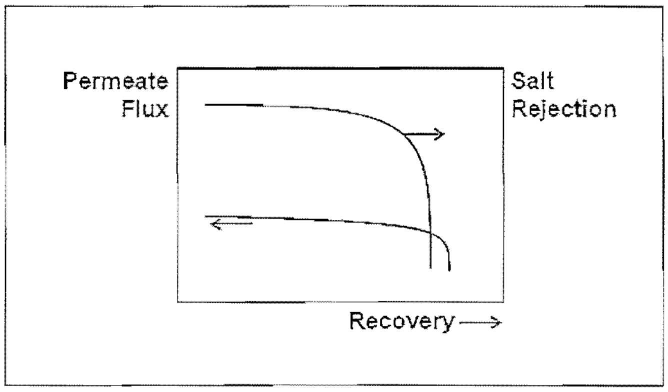

Figure 24: System performance vs. recovery ratio (The DOW Chemical Company, 2007:14).

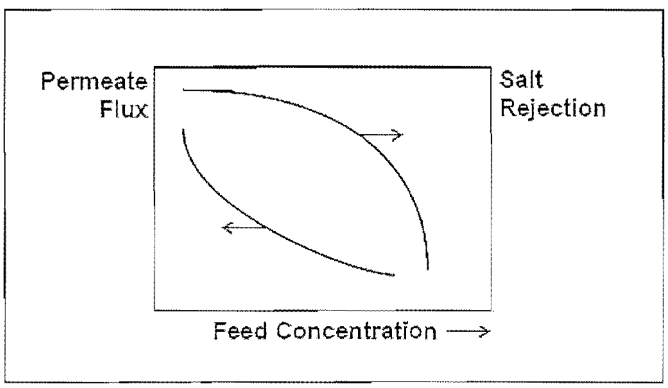

Figure 25: System performance vs. feed water salt concentration (The DOW Chemical Company, 2007:14).

3.3 *Design Guidelines for a Reverse Osmosis plant*

In the following paragraph the fundamental principles of the design process will be given. Note that most of the guidelines were obtained from the *Department of Water Affairs and Forestry*. In 2006 the department published a document named: "*A Desalination Guide for South African Municipal Engineers*". The following steps are guidelines to design a reverse osmosis plant. These steps will be used during the concept design of the RO plant coupled to the cooling system of the PBMR nuclear power plant. The steps are:

- Step 1: Determine the product volume requirement.
- Step 2: Determine the characteristics of the feed water.
- Step 3: Calculate the number of membranes required
- Step 4: Calculate the feed pressure requirement
- Step 5: Calculate pre-treatment supply requirements
- Step 6: Estimate the energy requirements of the RO plant
- Step 7: Consider discharge of brine water
- Step 8: Estimate the capital cost of the RO plant
- Step 9: Economic evaluation of the RO plant

Step 1: Determine the product volume requirement.[2]

First of all, a good evaluation should be carried out to determine the customer's water requirements. Some customers, for instance a municipality, experience an increase in water demand due to economic growth. These facts need to be incorporated together with existing water supply programs to optimize the total water supply. Plant downtime should also be taken into account and Equation 3 gives the actual plant production rate.

$$Q_{Total} = \frac{Q_{Requirement}}{\upsilon} \qquad \text{[Equation 3]}$$

Q_{Total} – Total amount of product water to be produced by membranes [m^3/d]

$Q_{Requirement}$ – Requirement of customer [m^3/d]

υ – Availability fraction

[2] Obtained from the Department of Water Affairs and Forestry published in 2006. "A Desalination Guide for South African Municipal Engineers". Page 38-43

Step 2: Determine the characteristics of the feed water[3]

The quality of the feed water gives an estimation of the maximum recovery ratio (RR) a RO plant can achieve. Membrane fouling is the limiting factor for the recovery ratio due to scaling. At the critical recovery ratio crystal formation in the brine stream would appear due to the saturation point of the salt. RO plants should never be operated above this critical recovery ratio. The following gives some guidance to the recovery ratio of seawater and ground water.

- Seawater – 30 % < RR > 50 %
- Groundwater – 60 % < RR > 90 %

Estimation of the maximum recovery ratio:

According to the Department of Water Affairs and Forestry the following calculation gives an estimation of the maximum recovery ratio in the presence of an appropriate anti-scaling medium. A wide spectrum of anti-scaling products is available on the market and professionals should be contracted to conduct a complete investigation and propose the best anti-scaling medium for the RO plant.

Calcium Salts:

The recovery ratio is highly limited by the presence of calcium salts if it is not removed by softening. Three different calcium salts will be addressed and equations given to calculate each maximum recovery ratio before membrane fouling can accrue.

- Calcium Carbonate ($CaCO_3$)

This is one of the most general salts found in feed water. In the presence of an anti-scaling medium the fouling possibility can be controlled by lowering the pH of the feed water. The following equitation gives an estimated recovery ratio in the presence of calcium carbonate:

$$RR_{CaCO_3} \approx 1 - \frac{\sqrt{Alk.C_{Ca}}}{2000} \qquad \text{[Equation 4]}$$

RR_{CaCO_3} – Maximum recovery ratio allowed

Alk – Feed alkalinity CaCO3 in mg/L

C_{Ca} – Feed water concentration of Ca in mg/L

[3] Obtained from the Department of Water Affairs and Forestry published in 2006. "A Desalination Guide for South African Municipal Engineers". Page 38-43

- Calcium Sulphate ($CaCO_4$)

Changing the pH of the feed water will not have an effect on the scaling possibility of Calcium Sulphate. Using a softener, limiting the concentration factor and controlling the feed water temperature will reduce the possibility of membrane fouling. The following equitation gives an estimated recovery ratio:

$$RR_{CaCO_4} \approx 1 - \frac{\sqrt{C_{SO_4}.C_{Ca}}}{2500} \qquad \text{[Equation 5]}$$

RR_{CaCO_4} – Maximum recovery ratio allowed

C_{SO_4} – Feed water concentration of SO_4 in mg/L

C_{Ca} – Feed water concentration of Ca in mg/L

- Calcium Fluoride (CaF_2)

Limiting the concentration factor, or by removing the calcium with a softener, the maximum recovery can be achieved before membrane fouling. The following equation gives the maximum recovery ratio achievable, in the presence of an anti scaling medium.

$$RR_{CaF_2} \approx 1 - \frac{\left[(C_F)^2.(C_{Ca})\right]^{0.33}}{40} \qquad \text{[Equation 6]}$$

RR_{CaF_2} – Maximum recovery ratio allowed

C_F – Feed water concentration of F in mg/L

C_{Ca} – Feed water concentration of Ca in mg/L

- Silicates (SiO_2)

In a mixture with calcium and magnesium, silica may polymerise or precipitate. The maximum recovery ratio in an anti scaling medium for SiO_2 is given by the following formula:

$$RR_{SiO_2} \approx 1 - \frac{C_{SiO_2}}{200} \qquad \text{[Equation 7]}$$

RR_{SiO_2} – Maximum recovery ratio allowed

C_{SiO_2} – Feed water concentration of SiO_2 in mg/L

- Oxides and hydroxides of iron, manganese and aluminum (Fe, Mn, Al)

Fe, Mn and Al are metals that need to be kept below a certain concentration in the brine stream to prevent membrane fouling. Again, the manufacturers and experts needs to be contacted. The maximum recovery ratio in an anti scaling medium for SiO_2 is given by the following formula:

$$RR_{Fe} \approx 1 - \frac{C_{Fe}}{3}$$ [Equation 8]

RR_{Fe} – Maximum recovery ratio allowed

C_{Fe} – Feed water concentration of Fe in mg/L

- Salts with barium and strontium (Ba, Sr)

The dissolve capability of Barium is very low and the following formula gives the maximum recovery ratio in an anti scaling medium for $BaSO_4$:

$$RR_{BaSO_4} \approx 1 - \frac{\sqrt{C_{SO_4} . C_{Ba}}}{30}$$ [Equation 9]

RR_{BaSO_4} – Maximum recovery ratio allowed

C_{SO_4} – Feed water concentration of SO_4 in mg/L

C_{Ba} – Feed water concentration of Ba in mg/L

The maximum recovery ratio in an anti scaling medium for $SrSO_4$ is given by the following formula:

$$RR_{SrSO_4} \approx 1 - \frac{\sqrt{C_{SO_4} . C_{Sr}}}{400}$$ [Equation 10]

RR_{SrSO_4} – Maximum recovery ratio allowed

C_{SO_4} – Feed water concentration of SO_4 in mg/L

C_{Sr} – Feed water concentration of Ba in mg/L

Step 3: Calculate the Number of Membranes Required

In this step the designer must identify a RO supplier from whom to obtain information regarding the performance of the membranes. Today, there are a number of excellent RO specialists around the world which can supply advice and service on any RO products. On request they can provide detailed information and the designer can use the data for a preliminary design. Some companies have developed their own design software programs that can help the designer to simulate an RO plant by using different types of membranes. These programs can simulate complicated RO designs that need iterations to solve RO equations. A number of design software programs are discussed in Appendix C.

In this step the total membrane area needs to be estimated. Furthermore, Equation 12 estimates the number of membrane modules required.

Estimate the total membrane area required[4]:

By using the flux rate of a membrane the total membrane area can be calculated with Equation 11. Note that the flux-rate is subjective to many parameters such as the feed water temperature, water quality, supply pressure and etc. Furthermore, the membrane area is used as a guideline to estimate the physical size of a RO plant, which again is a guideline to the capital cost. The calculation of the capital cost is covered in Step 9.

$$Area_{Total} \approx \left(\frac{1000.Q_{Total}}{\varphi_1} \right) + Z.\left(\frac{1000.Q_{Total}}{\varphi_2} \right) \quad \text{[Equation 11]}$$

$Area_{Total}$ – Total membrane area required [m^2]

Q_{Total} – Total amount of product water, obtained from Equation 3 [m^3/d]

φ_1 – First pass membrane flux [$L/m^2.d$]

φ_2 – Second pass membrane flux [$L/m^2.d$]

Z – Number of passes (Z = 0 if one passes and Z = 1 if 2 passes)

[4] Obtained from the DEPARTMENT OF WATER AFFAIRS AND FORESTRY, 2006. A Desalination Guide for South Africa Municipal Engineers. Page 43-44

Estimate number of membrane modules:

To calculate the number of membrane elements required, the applicable membrane area has to be known. Solving Equation 12 and rounding up to the highest integer will give an estimated amount of membranes required.

$$Number_{Elements} \approx \frac{Area_{Total}}{Area_{Membrane}} \qquad \text{[Equation 12]}$$

$Number_{Elements}$ – Total membrane elements required

$Area_{Total}$ – Total membrane area required [m²]

$Area_{Membrane}$ – Membrane area of an element [m²]

Step 4: Calculate the Feed Pressure Requirement[5]

Overpressure can damage membranes permanently and therefore the general feed pressure is limited at approximately 80 bar. For further protection some manufacturers decrease this limit to 70 bar.

To calculate the feed pressure requirement for a specific permeate flow, Equation 13 can be used. Note that a higher feed water temperature will decrease the feed pressure requirement. On the other hand a higher flux rate and recovery ratio will increase the feed pressure. Note that for a second pass the variables must be changed to the characteristics of the second feed water stream. For example, the TDS value of the second pass can be estimated as 1% of the first stream value.

$$P_{f(T)} \approx \frac{\pi.(TDS)_F}{1-RR} + \left(\frac{\varphi}{\psi} + 5\right).1.034^{(25-T)} \qquad \text{[Equation 13]}$$

$\pi.(TDS)_F$ – Osmotic pressure multiply by the TDS value of feed water

RR – Maximum recovery ratio allowed, obtained from Step 2

φ – Membrane flux [L /m².h]

ψ – Membrane flux per driving pressure [L / (m².h.bar)]

T – Feed water temperature [°C]

[5] Obtained from the DEPARTMENT OF WATER AFFAIRS AND FORESTRY, 2006. A Desalination Guide for South Africa Municipal Engineers.

Step 5: Calculate Pre-treatment Supply Requirements[6]

A pre-treatment system requires additional water for maintenance purposes such as backwash, CIP, etc. Therefore the feed pumps must supply an additional volume of water for the pre-treatment system and not only for the RO membranes. Solving Equation 14 will give the total water supply per day (to be provided by the feed pumps).

$$Q_{Total(Feed)} \approx \frac{Q_{Total}}{RR \cdot (1-\xi)} \qquad \text{[Equation 14]}$$

$Q_{Total(Feed)}$ – Total amount to be supplied [m³/d]

Q_{Total} – Total amount of product water obtained from Equation 3 [m³/d]

RR – Maximum recovery ratio allowed, obtained from Step 2

ξ – Water fraction required at pre-treatment (Normally between 3 - 15 %)

Step 6: Estimate the Energy Requirements of the RO Plant[6]

In Step 5 it was mentioned that seawater RO membranes require pressures up to 70 bars. High pressure pumps are used to achieve this high feed pressure. However, this results in high energy demands for the RO process. Equation 15 gives an estimation of the desalination energy consumption.

$$E_{Desal} \approx \left[\frac{Q_{Total} \cdot \mathrm{P}_{f(T)}}{36 \cdot RR \cdot \eta_{Pump}}\right] - S \cdot \left[\frac{Q_{Total} \cdot (\mathrm{P}_{f(T)} - 5) \cdot (1-RR)}{36 \cdot RR \cdot \eta_{\mathrm{Recovery}}}\right] \qquad \text{[Equation 15]}$$

E_{Desal} – Estimated desalination energy requirement [kW]

Q_{Total} – Total amount of product water obtained from Equation 3 [m³/d]

$\mathrm{P}_{f(T)}$ – Feed pressure obtained from Equation 13 [Bar]

RR – Maximum recovery ratio allowed, obtained from Step 2

η_{Pump} – Pump efficiency

S – 0 if no pressure recovery is installed and 1 if a pressure recovery is installed

η_{Recovery} – Pressure recovery efficiency (New positive exchangers can reach 96% efficiency)

[6] Obtained from the DEPARTMENT OF WATER AFFAIRS AND FORESTRY, 2006. A Desalination Guide for South Africa Municipal Engineers.

Additional systems energy requirements:

Apart from the desalination energy the RO plant needs basic electricity for auxiliary systems, lighting, etc. By using a slight over-estimated pressure for the pre- and post-treatment ($P_{Pre/Post}$), depending on the design, Equation 16 will give an estimated energy requirement for these systems.

$$E_{Extra} \approx \left[\frac{Q_{Total(Feed)} \cdot P_{Pre/Post}}{36 \cdot \eta_{Pump}} \right] \qquad \text{[Equation 16]}$$

E_{Extra} – Additional energy requirements [kW]

$Q_{Total(Feed)}$ – Total amount to be supplied, obtained from Equation 14 [m^3/d]

$P_{Pre/Post}$ – Estimated pressure requirement for the Pre- and Post-treatment plants [bar]

η_{Pump} – Pump efficiency

The total RO plant energy consumption can be calculated as follows:

$$E_{Total} \approx E_{Desal} + E_{Extra} \qquad \text{[Equation 17]}$$

E_{Total} – Total energy consumption of the RO plant [kW]

E_{Desal} – Total amount to be supplied [kW]

E_{Extra} – Additional energy requirements [kW]

The specific energy consumption for the production of water can be calculated with Equation 18.

$$E_{Specific} = \frac{E_{Total}}{Q_{Total}} \qquad \text{[Equation 18]}$$

$E_{Specific}$ – Specific energy consumption per volume product water [kWh/m^3]

E_{Total} – Total energy consumption of the RO plant, obtained from Equation 17 [kW]

Q_{Total} – Total amount of product water, obtained from Equation 3 [m^3/d]

Step 7: Consider Discharge of Brine Water

In this step the designer must understand that discharge of high saline brine water to the environment can have a significant negative impact on the fauna and flora. Again, experts need to address this important issue and assess the discharge method. There are mainly two options for the discharging method, namely to use an evaporation pond or to discharge the brine back into the feed water source (e.g. the sea). Evaporation ponds can only be used in small RO applications, but will have an extra cost. In the case where the brine water is returned to the feed water source (i.e. the sea), currents, marine life, inflow of large rivers, etc. must be considered during the design. On the microscopic level measurements such as the colloidal, organic and biological amounts are important and must be monitored by specialists.

Another option is to extract components from the brine water. In Eliat a salt company has produced 30 % more salt from using 20 % brine water from a desalination plant with 80 % seawater. One advantage is that the salt production cost is decreased. (Ravizky & Nadav, 2007:374)

Step 8: Estimate the Capital Cost of the RO Plant[7]

Desalination installation cost:

The desalination cost is classified as the cost of mechanical, civil and electrical systems together with the RO membrane systems. The membrane area has a direct influence on all above installations. Consequently, the installation cost of the desalination division can be obtained by a correlated calculation from the required membrane area. According to the Department of Water Affairs and Forestry (2006), Figure 26 to Figure 28 gives the relationship between the installation cost and installed membrane area. Due to inflation, the correlation must be adjusted with approximately 10 % per year. Therefore the cost was increased with 30 % to relate with the financial year of 2008.

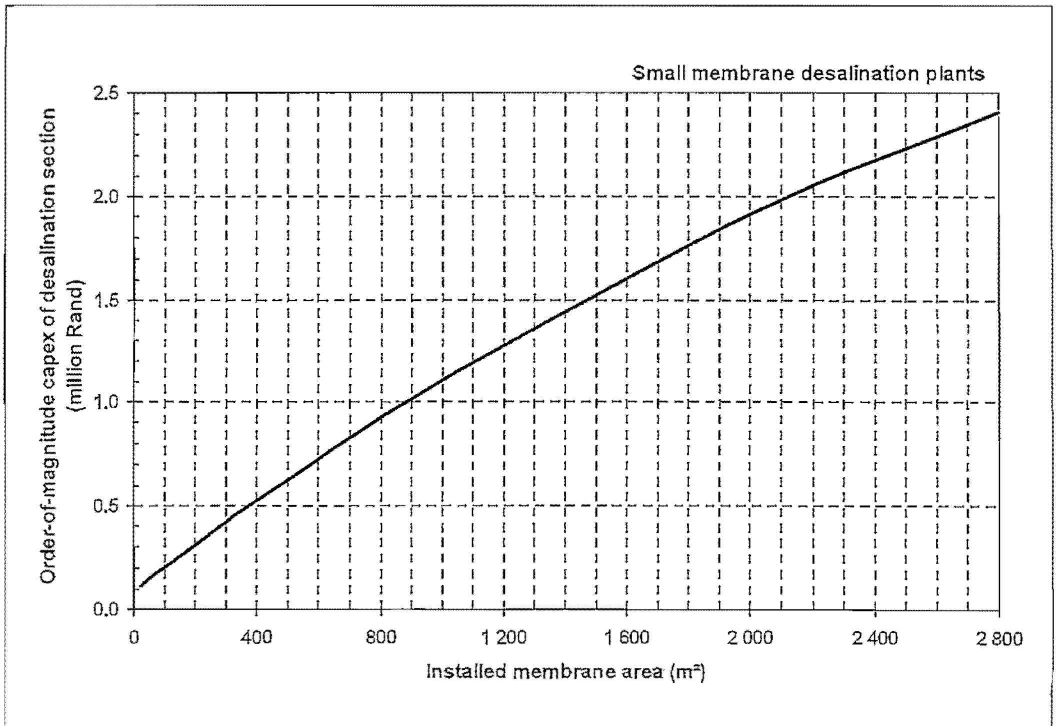

Figure 26: Installation cost prediction of desalination section (Small RO plant)

[7] Obtained from the DEPARTMENT OF WATER AFFAIRS AND FORESTRY, 2006. A Desalination Guide for South Africa Municipal Engineers. Page 52-57

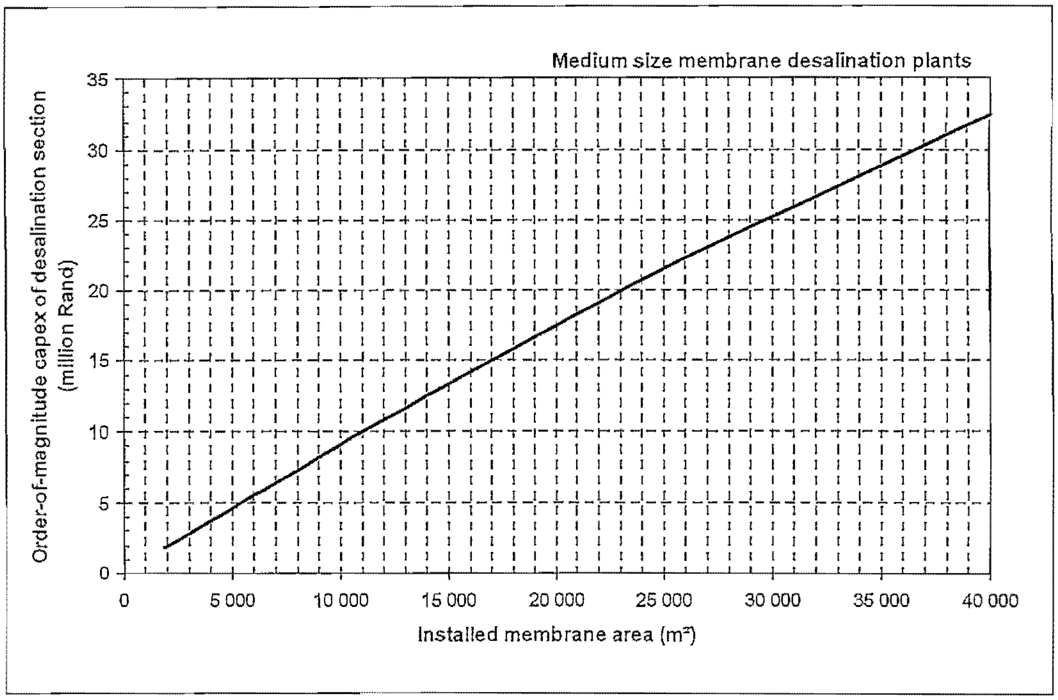

Figure 27: Installation cost prediction of desalination section (Medium RO plant)

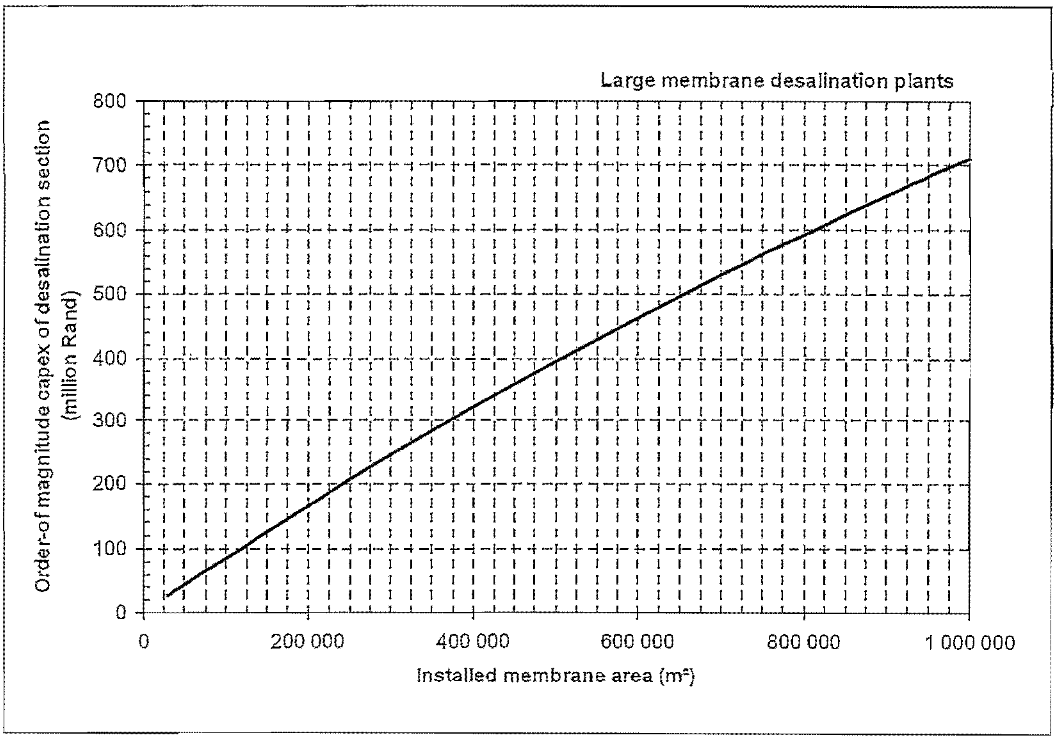

Figure 28: Installation cost prediction of desalination section (Large RO plant)

Pre-treatment installation cost:

The pre-treatment system is an extremely important and complicated process. If this system is designed ineffectively, the membrane lifetime can be reduced tremendously due to scaling. This will increase the plant running cost and can easily drive the plant over budget. Therefore a detailed study and design must be conducted by specialists to determine the most effective pre-treatment system for the applicable feed water.

Figure 29 and 30 gives estimated correlations between the installation cost of the pre-treatment system and the total feed flow.

$$C_{\mathrm{Pre}} \approx CC_{Pre} \cdot K \qquad \text{[Equation 19]}$$

C_{Pre} – Estimated installation cost of the pre-treatment system [R]

CC_{Pre} – Cost obtained from Figure 29 or Figure 30 [R]

K – Correction factor for the Pre-treatment complexity

- K = 0.7 typical for seawater desalination plant with high flow rates and double media filtration necessary.
- K = 1.5 typical for desalination plants with ultra-filtration systems installed.
- K = 2 for complex pre-treatment systems.

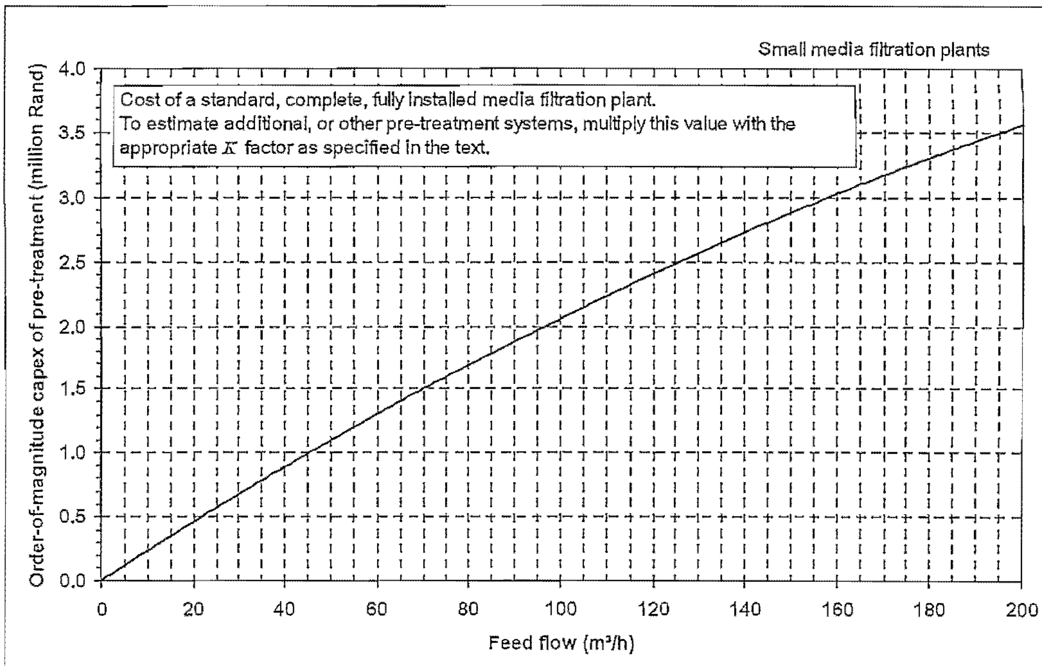

Figure 29: Installation cost prediction of pre-treatment plant (Small/Medium RO plant)

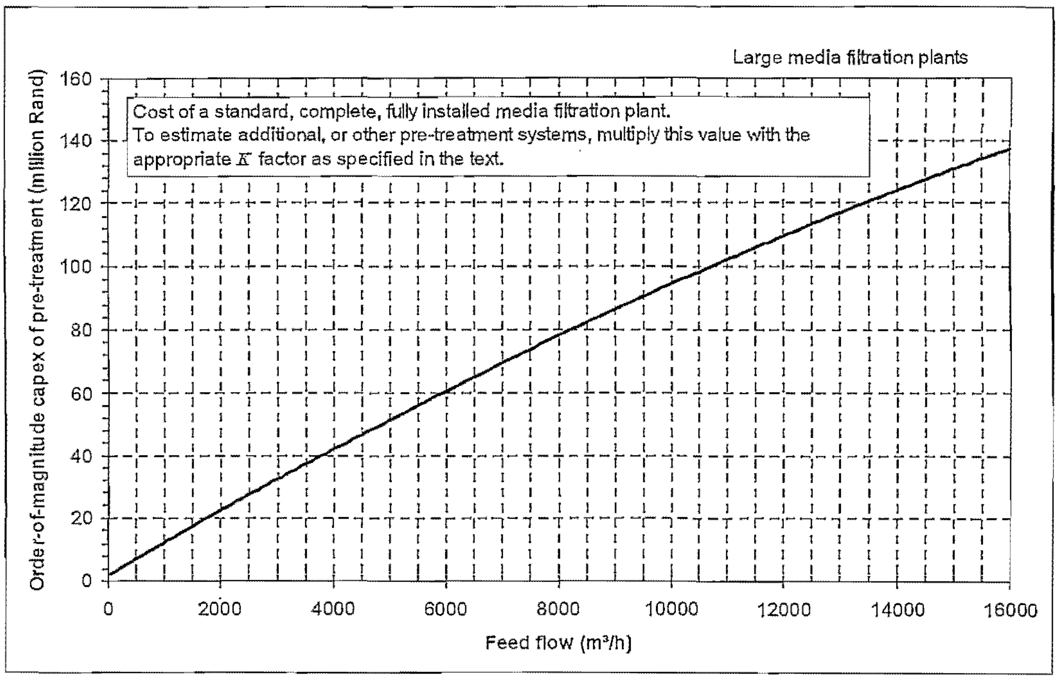

Figure 30: Installation cost prediction of pre-treatment plant (Medium/Large RO plant)

Estimation of the intake, outfall and post-treatment installation cost:

These costs include pipe lengths, intake systems, etc. Equation 20 and 21 estimates the cost for the intake, outfall and post-treatment systems of a seawater- and inland-brackish-water-desalination-plant respectively.

$$C_{Pipe/post} \approx C_{Desal\&pre} \cdot P \qquad \text{[Equation 20]}$$

$C_{Pipe/post}$ – Estimated installation cost of the intake, outfall and post-treatment system of an seawater desalination plant [R]

$C_{Desal\&pre}$ – Total cost of pre-treatment and desalination system [R]

P – Estimate between 15% and 30% for the complexity of the system (Department of Water Affairs and Forestry, 2006:56)

$$C_{Pipe/post} \approx C_{Desal\&pre} \cdot P \qquad \text{[Equation 21]}$$

C_{Enviro} – Estimated installation cost of the intake, outfall and post-treatment system of an inland brackish water desalination plant [R]

$C_{Contract}$ – Total contract cost [R]

P – Estimate between 2% and 10% for the complexity of the system (Department of Water Affairs and Forestry, 2006:56)

Estimation of the environmental evaluation and contract costs:

In the 20th century a designer must know that the environment is the most important issue to be addressed during the design. Experts should be contracted to analyze the feed water and in the case of seawater desalination, the sea currents, marine life, inflow of large rivers, etc. On the microscopic level measurements such as the colloidal, organic and biological amounts are important. Furthermore, mitigation and licensing cost need to be taken into account and Equation 22 gives an estimated cost.

$$C_{Enviro} \approx C_{Contract} \cdot P \qquad \text{[Equation 22]}$$

C_{Enviro} – Estimated installation cost of the environment evaluation and liable costs [R]

$C_{Contract}$ – Total contract cost [R]

P – Estimate between 0.05% and 5 % for the complexity of the system (Department of Water Affairs and Forestry, 2006:57)

Step 9: Economic evaluation of the RO plant

In this step an economic calculation is preformed to calculate the specific cost of one cubic meter of product water. The specific cost of each expense before and during the operation of the plant is considered.

Specific cost of capital redemption: [8]

Firstly the capital cost repayment needs to be calculated.

$$CR = \frac{C \cdot r \cdot (1+r)^n}{(1+r)^n - 1} \qquad \text{[Equation 23]}$$

CR – Cost of capital repayment [R/month]
C – Capital cost, obtained from Step 9 [R]
r – Monthly interests rate
n – Redemption period

The specific cost of the capital redemption can now be calculated.

$$SC_{Cap} \approx \frac{CR}{30 \cdot Q_{Total}} \qquad \text{[Equation 24]}$$

SC_{Cap} – Specific cost of the redemption [R/m^3]

CR – Cost of capital repayment, obtained from Equation 23 [R/month]

Q_{Total} – Total amount of product water obtained from Equation 3 [m^3/d]

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[8] Obtained from the DEPARTMENT OF WATER AFFAIRS AND FORESTRY, 2006. A Desalination Guide for South Africa Municipal Engineers.

Specific cost of energy: [9]

$$SC_{Energy} \approx D_{Electric} \cdot E_{Specific} \qquad \text{[Equation 25]}$$

SC_{Energy} – Specific energy cost per volume product water [R/m^3]

$D_{Electric}$ – Electricity cost [R/kWh]

$E_{Specific}$ – Specific energy consumption per volume product water, obtained from Equation 18 [kWh/m^3]

Specific cost of membrane replacements:

$$SC_{Membranes} \approx \frac{Number_{Elements} \cdot Cost_{Mem} \cdot \delta}{Q_{Total}} \qquad \text{[Equation 26]}$$

$SC_{Membranes}$ – Specific membrane replacement cost per volume product water [R/m^3]

$Number_{Elements}$ – Number of membranes as calculated in Equation 12

$Cost_{Mem}$ – Cost of one membrane element (Obtain from supplier) [R]

δ – Membrane depreciation per year

Q_{Total} – Total amount of product water obtained from Equation 3 [m^3/d]

Cost of chemicals and consumables: [9]

This is a difficult cost prediction and has to be calculated carefully during the design phases of the RO plant. The reason is that for every source of feed water the water characteristics can vary so much that different chemicals and consumables must be used for the protection of the RO membranes. The following equations give some guidance to the specific cost of chemicals and consumables for RO plant.

- For brackish feed water with an pH adjustment system, disinfection and anti-scalant agents together with a sensible post-treatment system, the cost is estimated at:

$$SC_{Chemicals} \approx 0.3 \text{ [R/m}^3\text{]} \qquad \text{[Equation 27]}$$

- Seawater with the necessary chlorine-, acid-, coagulant and anti-scalant-agent treatment. Also with a de-chlorination system and a sensible post-treatment system, the cost is estimated at:

$$SC_{Chemicals} \approx 0.5 \text{ [R/m}^3\text{]} \qquad \text{[Equation 28]}$$

[9] Obtained from the DEPARTMENT OF WATER AFFAIRS AND FORESTRY, 2006. A Desalination Guide for South Africa Municipal Engineers.

- For brackish feed water with a full lime system, acid, chlorine, de-chlorination system and anti-scalant agents together with a sensible post-treatment system, the cost is estimated at:

$$SC_{Chemicals} \approx 1.6 \text{ [R/m}^3\text{]} \qquad \text{[Equation 29]}$$

Cost of labour and maintenance: [10]

The maintenance and labour cost of RO plants larger than 2000 m^3/day may be estimated as 5% of the capital cost (Department of Water Affairs and Forestry, 2008:61). For smaller RO plants Equation 23 can be solved to obtain the cost.

$$SC_{Main/Labour} \approx \frac{Z \cdot Cap}{366 \cdot Q_{Total}} \qquad \text{[Equation 30]}$$

$SC_{Main/Labour}$ – Specific membrane replacement cost for one cubic meter water [R/m^3]
Z – Number of membranes as calculated in Equation 12
Cap – Capital cost
Q_{Total} – Total amount of product water, obtained from Equation 3 [m^3/d]

Total cost of one cubic meter product water: [10]

The total cost of one cubic meter of product water can then be calculated:

$$SC_{Total} = SC_{Cap} + SC_{Energy} + SC_{Membranes} + SC_{Main/Labour} + SC_{Chemicals} \qquad \text{[Equation 31]}$$

Note that the following cost factors where not taken into account in above calculations:

- Storage facilities for the product water.
- Distribution system (Pumps, pipe and etc.)
- Buildings, roads and infrastructure
- Exploration of land
- Evaporation ponds

3.4 *Conclusion*

The fundamental principles of the osmosis process have been discussed. Design guidelines for a reverse osmosis plant have been given in nine steps and these steps can be implemented during a concept design for reverse osmosis desalination plant.

[10] Obtained from the DEPARTMENT OF WATER AFFAIRS AND FORESTRY, 2006.
A Desalination Guide for South Africa Municipal Engineers.

4 Chapter

CONCEPTUAL DESIGN OF A REVERSE OSMOSIS PLANT COUPLED TO A PBMR PLANT AT KOEBERG

4.1 *Introduction*

There are many industrial thermodynamic cycles that dissipate large amounts of thermal energy into the environment through cooling water. Thermal energy can be used for desalination purposes either as the main heat source (in the case of MED), or to increase the efficiency of a desalination plant (in the case of RO).

In this chapter a coupling scheme between a RO plant and a thermodynamic cycle will be discussed. Further more, a case study will be made between a RO plant and the PBMR nuclear power plant (fourth generation nuclear plant). The RO plant will benefit from the PBMR because of the use of the electricity and the waste heat from the cooling water. By using the design guidelines presented in Chapter 3, the RO plant's performance is calculated and the economic study includes a sensitivity analysis. Furthermore software programs are used to simulate the above mentioned coupling scheme and the results are compared to the design guidelines outcome.

4.2 *RO plant utilizing waste heat from a thermodynamic process*

There are a few thermodynamic cycles in the industry that makes life easier for humans, for example; the Brayton and Otto cycles are used in the transportation sector and the Rankine cycle is normally implemented in steam power plants for the generation of electricity. Most of these thermodynamic cycles use water as the main cooling medium. After the cooling phase the water is usually dissipated into the environment and large amounts of energy are lost.

Figure 31 illustrates a T-s diagram of a basic Rankine cycle. A small amount of energy is supplied to the working fluid with the pump (W_{pump}). Coal- or gas-fired boilers are then used for the main energy input to the cycle (Q_{IN}). After the boilers, the steam is expanded over a turbine that normally drives a generator for the production of electricity. Subsequently the steam needs to be condensed. A secondary water stream is normally used to cool and condense the working fluid in the primary loop. Large amounts of energy are transported from the primary loop to the secondary loop (Q_{out}). It is at this stage where the Rankine cycle's efficiency is decreased tremendously and a huge amount of energy lost to the environment.

Depending on the flow rates and amount of energy transferred to the cooling water, it can be used for desalination purposes. If the cooling water reaches temperatures above 70°C it can be used in a MED distillation plant. At lower temperatures (40°C) the water can be used as feed water to an RO desalination plant. It is known that the viscosity of water is inversely proportional to its temperature. Therefore if the feed water temperature of a reverse osmosis plant is increased the membranes will become more permeable. This will result in a higher production volume or in a lower energy demand.

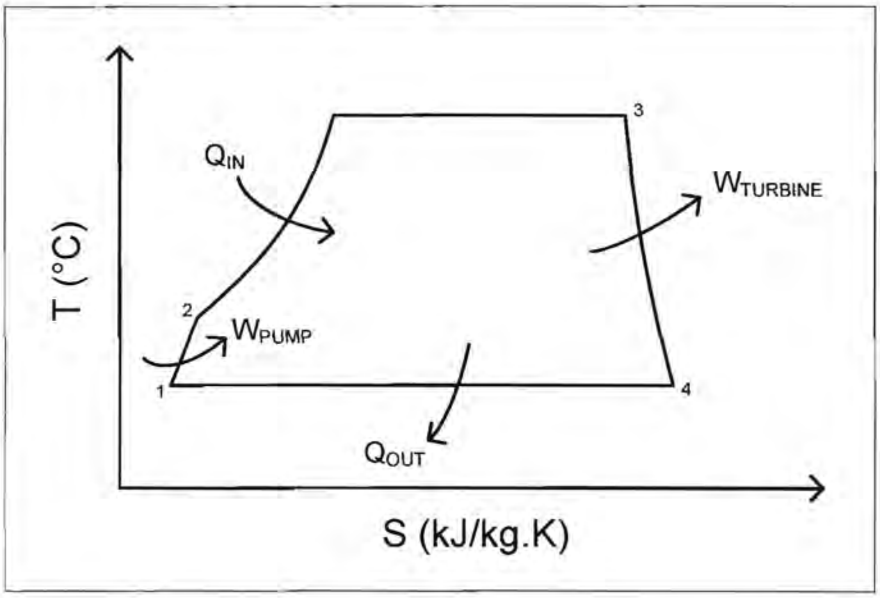

Figure 31: T-s diagram of a basic Rankine thermodynamic cycle

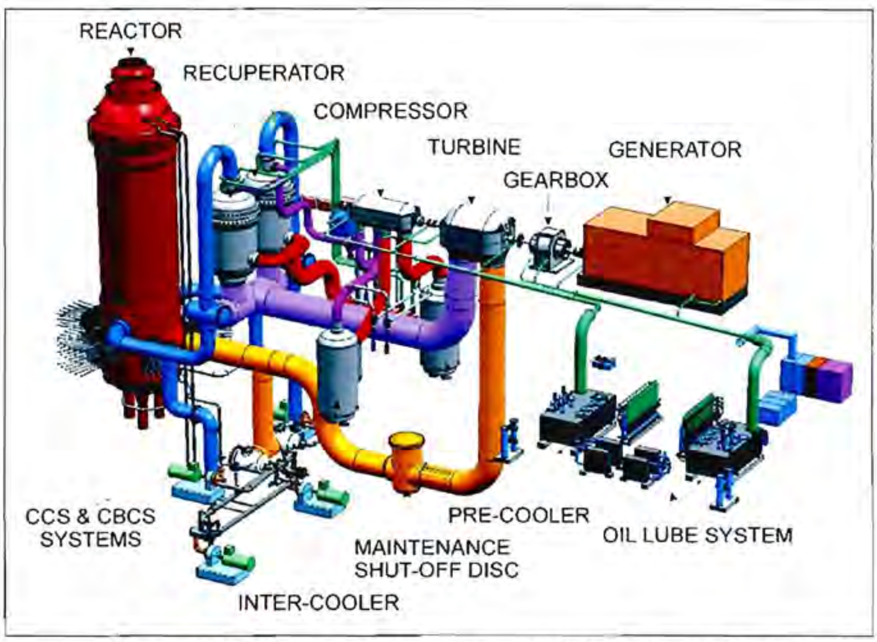

Figure 32: PBMR nuclear power plant (PBMR (Pty) Limited, 2008)

4.3 *Integration concept between an RO plant and the PBMR Main Heat Sink System (MHSS) system*

The Pebble Bed Modular Reactor (PBMR) is a fourth generation nuclear power plant currently being developed in South Africa (Figure 32). PBMR Pty. Ltd. is planning to build the demonstration power plant (DPP) at Koeberg, an existing nuclear site, before 2015. ESKOM, South Africa's power utility, is currently operating a Pressure Water Reactor (PWR) at the Koeberg site (Figure 33). The PWR was initially built by the consortium Framateg, a French company. One advantage for the PBMR is that it will make use of the existing intake and outfall water system of the PWR. If the PWR is working at full capacity, the cooling water's flow rate is an enormous 80 000 kg/s!

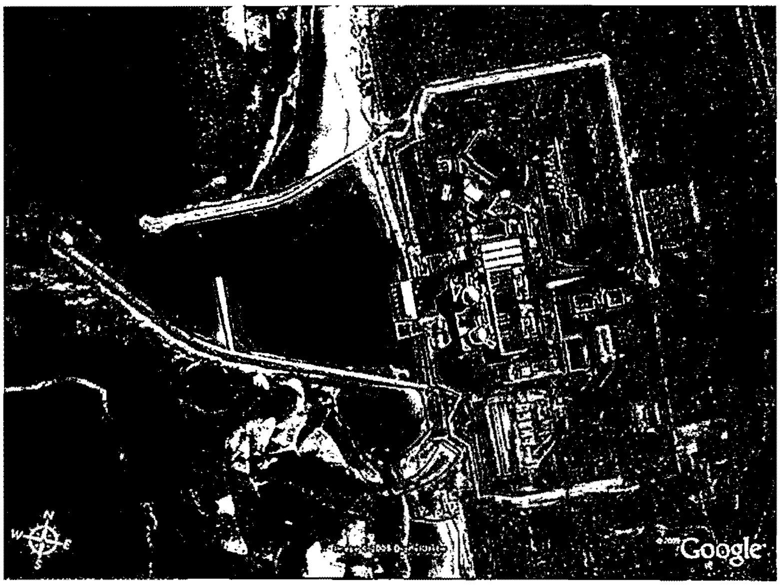

Figure 33: Koeberg nuclear site (Google Earth, 2008)

The PBMR nuclear power plant is a closed loop cycle with a high temperature reactor capable of producing a gas (helium) outlet temperature of 900 °C which will be used for the generation of electricity. The thermodynamic cycle is based on a closed loop Brayton cycle, thus the helium will drive the turbine directly (See Figure 34). After the turbine the helium passes through a recuperator to recover energy and increase the plant's efficiency. At this stage the helium temperature is approximately 140 °C. In order to increase the PBMR efficiency the helium needs to be cooled before it enters the two compressors. Large plate heat exchangers will be used to cool the helium with seawater on the secondary side. Together the heat exchangers are capable of extracting more than 220 MW of thermal energy from the gas cycle. This is wasted into the sea increasing the sea temperature. One option is to rather use this waste heat for desalination purposes, increasing the PBMR cycle efficiency, reducing cost of the desalination plant and reducing the impact on the environment.

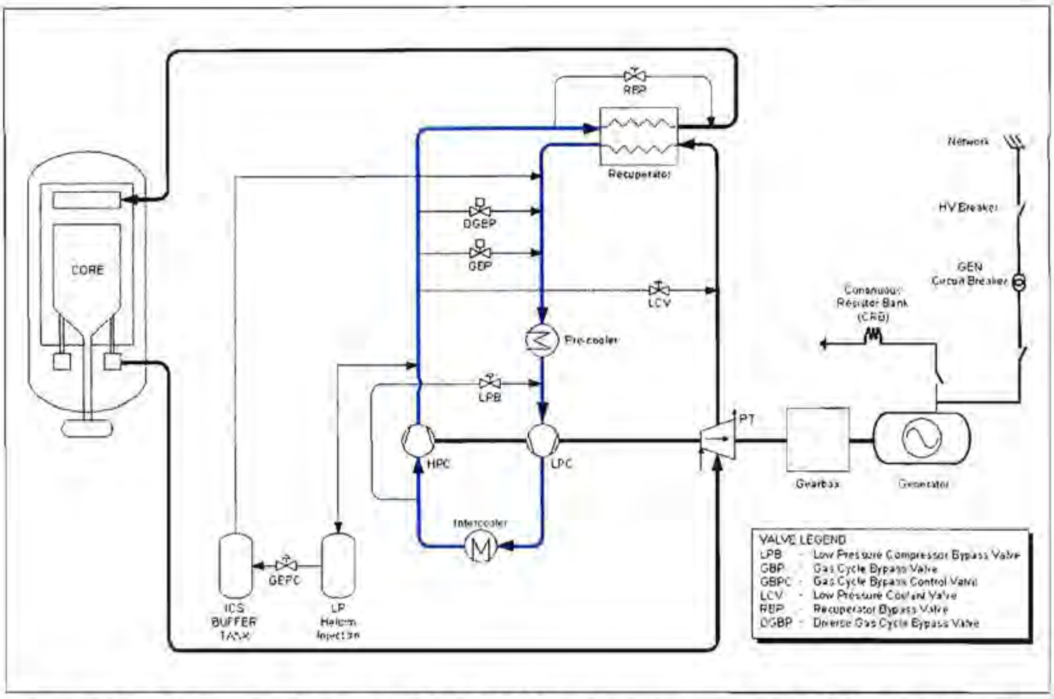

Figure 34: Schematic pipe layout of the PBMR nuclear power plant (PBMR (Pty) Limited, 2008)

The cooling water flow rate for both the heat-exchangers is approximately 2475 kg/s and the potential water outlet temperature will be around 40 ^{o}C. For a reverse osmosis plant this water temperature is beneficial to be used as feed water. A higher temperature increases the flux rate through the membranes and as a result it will decrease the energy consumption and operating cost. Furthermore, by using the waste water from the reactor, the RO plant will indirectly make use of Koeberg's existing intake and outfall system. This advantage will decrease the capital cost.

The coupling technique is an important issue for the licensing of both the RO- and nuclear-plants. In short, the RO plant must not disturb the cooling cycle of the PBMR in any way. This is possible by using a water pool (See Figure 35). The PBMR simply dumps the waste water into the pool which is at atmospheric pressure. From here the RO plant can extract the necessary amount of feed water. Additional waste water or in the case where the RO plant is shut down it can simply overflow the pool into the sea. Figure 35 illustrates the coupling scenario between the RO plant and the PBMR DPP.

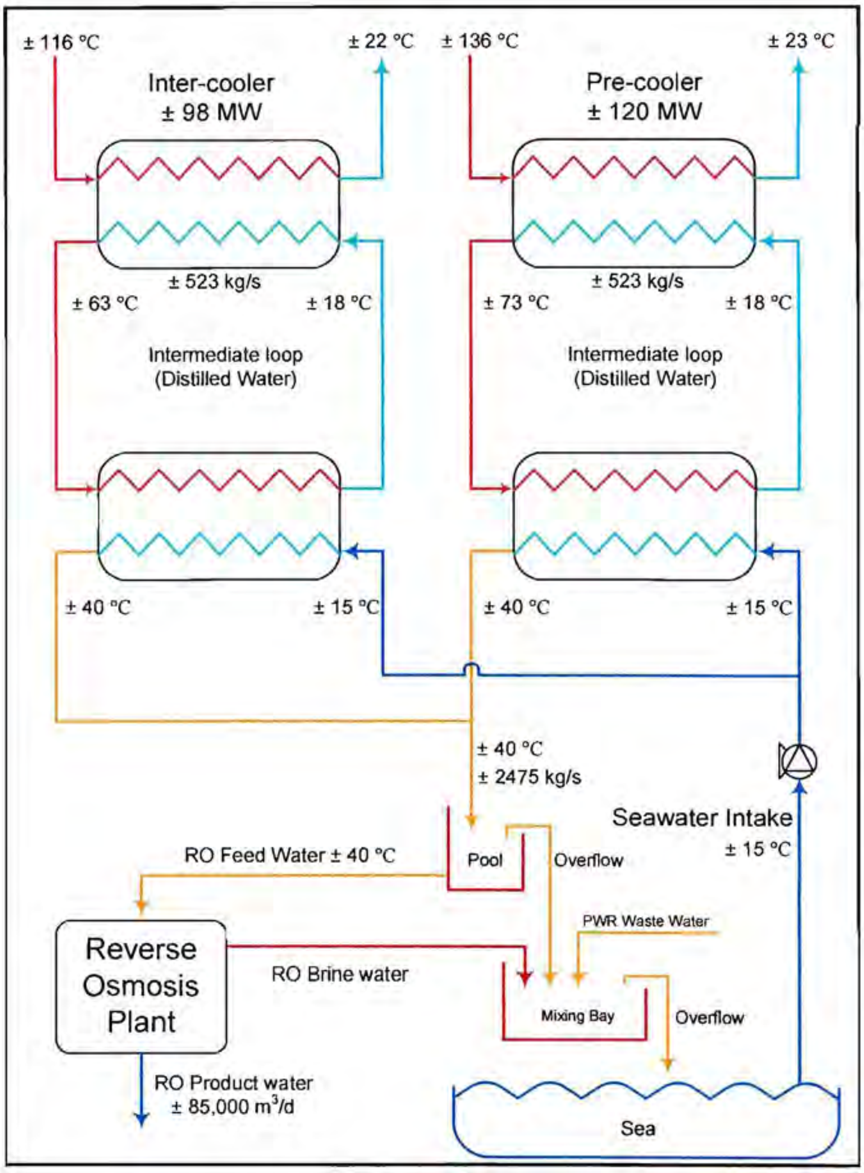

Figure 35: PBMR MHSS and couple scenario for an RO plant.

4.3.1 Design of the reverse osmosis plant using design guidelines from Chapter 3

The design of the RO plant was based on the design steps given in Chapter 3. All the assumptions and estimated parameters are explained and the results given for each step. Furthermore, a program was written to calculate the RO plants' performance and the complete excel program is given in Appendix A.

Step 1: Maximum recovery ratio achievable due to feed water characteristics

PBMR contracted Buckham Laboratories to determine the characteristics of the West Coast seawater. The results were obtained from PBMR and it was used in Equation 4 to Equation 10 (in Chapter 3). The outcome is presented in Table 5.

Table 5: Maximum recovery ratio due the composition of the feed water

Ion	Name	Max. RR (%)	Reverence
$CaCO_3$	Calcium Carbonate	86.18%	Equation 4
$CaCO_4$	Calcium Sulphate	51.03%	Equation 5
CaF_2	Calcium Fluoride	79.39%	Equation 6
Fe	Oxides/hydroxides of iron	96.67%	Equation 8
Ba	Salts with barium	47.18%	Equation 9
Sr	Salts with strontium	96.04%	Equation 10

Outcome of Step 1:

- Critical component in water is: **Barium**
- Maximum recovery ratio achievable is: **47%**

A recovery ratio of 47% compares well to existing seawater reverse osmosis plants. The typical range of a seawater reverse osmosis plant is between 40% and 50%.

Step 2: The maximum product water producible

According to PBMR the Main Heat Sink System (MHSS) will reject 2475 kg/s cooling water at an outlet temperature of 40°C. If the assumption is made that all the cooling water will be used for the desalination plant, a projected product volume can be calculated with the following assumption:

- Feed water availability of 95%
- Pre-treatment system will use 15% of the feed water for backwash and CIP purposes
- RO recovery ratio 47%
- The density of the water is estimated as 1000 kg/m^3

Outcome of Step 2:

Figure 36 shows the design flow rates of the desalination plant.

- Maximum supply to pre-treatment system: **205,200** [m^3/day]
- Maximum product water from RO plant: **87,132** [m^3/day]

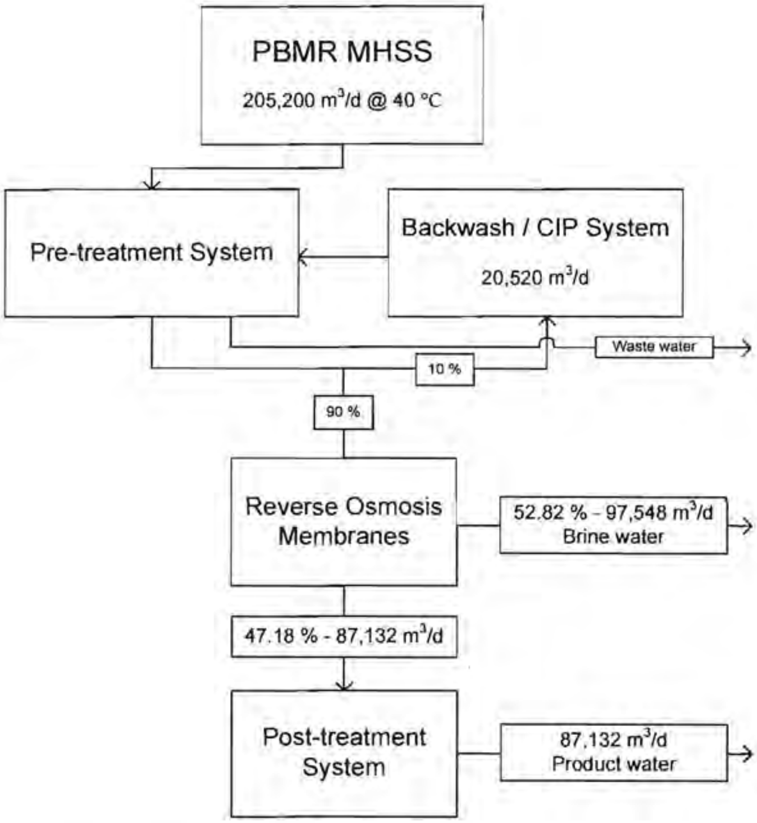

Figure 36: Flow diagram of the desalination plant

Step 3: Membrane area required and number of membranes

Membrane flow configuration:

Depending on the application, various ratios (5:2, 3:1, etc.) can be used between the membrane arrays. In this case a multi array flow configuration was chosen with a ratio of 2:1 between Array 1 and Array 2 (See Figure 37). According to the Department of Water Affairs and Forestry the feed water quality of the second stream can be estimated as 1% of the main feed stream (Department of Water Affairs and Forestry, 2006:45).

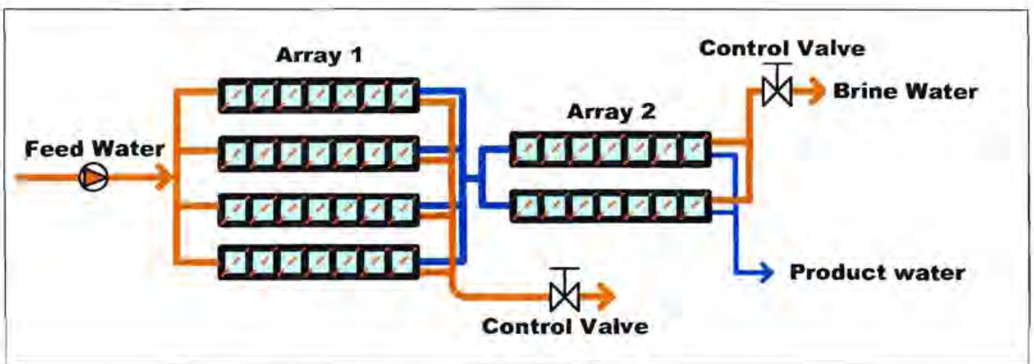

Figure 37: Flow diagram of the desalination plant

Two different membrane types are chosen for the two arrays. For the first pass seawater membranes are used and for the second pass a brackish type membrane. Table 6 provides the membrane information and in Appendix B the complete data sheets of both membranes can be found.

Table 6: Membrane specifications and performances

Pass 1 - Membrane A (Seawater type)		
Manufacture		Hydranautics
Model		SWC3-16X40
Permeate flow rate	m^3/day	80
Stabilized salt rejection	%	99.5
Effective area	m^2	120.8
Flux rate (70 % of maximum)	L / h.m^2	19.00
Pass 2 - Membrane B (Brackish water type)		
Manufacture		CSM
Model		RE 1640-BLR
Permeate flow rate	m^3/day	136.8
Stabilized salt rejection	%	99.5
Effective area	m^2	116.2
Flux rate (70 % of maximum)	L / h.m^2	34.00

Outcome of Step 3:

- The total membrane area required: **297,855 [m^2]**
- Number of membranes required: **2466**

Step 4: Calculate the feed pressure requirement

In Step 3 the flow configuration was chosen so that the product water of the first array will feed the second array membranes. For the pressure calculation of the second array the feed water quality was estimated to be 1 % of the first array's feed water. The following data was used during the calculations of the feed pressure requirements:

- Feed water temperature: 40°C
- System pressure loss: 5 bar
- Osmotic pressure: 0.00076*(TDS)
- First pass TDS value: 35,000
- Second pass TDS value: 350
- RO recovery ratio for the first pass: 47%
- RO recovery ratio for the second pass: 85%
- The flux per driving pressure of membrane A: 1 L/(m^2.h.bar)
- The flux per driving pressure of membrane B: 4.5 L/(m^2.h.bar)

Outcome of Step 4:

Equation 13 is applied and the required feed pressure for both the passes is:

- First membrane pass: **64.89 [bar]**
- Second membrane pass: **9.38 [bar]**

According to the membrane specification sheet the seawater membrane has a maximum operating pressure of 79.5 bars. The pressure for the first membrane pass is well under the maximum limit and is in range.

Step 5: Calculate Pre-treatment Supply Requirements

The pre-treatment system will process 216,000m^3/day, hence it is the total water amount from the PBMR MHSS, see Figure 35.

Step 6: Estimate the Energy Requirements of the RO Plant

The RO plant will be fitted with pressure recovery units to decrease the energy demand. During the design it was calculated that the energy consumption of the RO plant will be 4 MW higher without a proper pressure recovery system. The calculation was done with the following assumptions:

- Pressure recovery systems installed
- Pressure recovery system efficiency: 90 %
- Feed pumps efficiencies: 70 %
- Pressure inlet for feed pumps: 5 bar

Outcome of Step 6:

The total energy consumption for the desalination plant is: **9.19 [MW]**
Thus, the specific energy of one cubic meter product water is: **2.53 [kWh/m^3]**

With new technology on the market a specific energy of below 3 kWh/m^3 is achievable. An article written by John P. MacHarg stated that the electric consumption of a reverse osmosis plant has reached a staggering 2 kWH/m^3 or even less with the help of modern pressure recovery systems (MacHarg, 2005:53). However, this breakthrough is still in its experimental phases.

Step 7: Consider Discharge of Brine Water

The brine water will be released into the existing mixing bay of the Koeberg nuclear site (see Figure 35). This outfall technique should be investigated by a specialist to determine if any damage to the environment may accrue.

Step 8: Estimate the Capital Cost of the RO Plant

The installation cost of the desalination section and the pre-treatment system was determined with Figure 28 and Figure 30 respectively.

- Desalination system installation cost: **R 244,830,846**
- Pre-treatment system installation cost: **R 259,010,550**

For the intake, outfall and post treatment systems the assumption was made that it would be 5 % of the above installation cost because the desalination plant will make use of the existing intake and outfall systems.

- Intake, outfall and post-treatment installation cost : **R 25,192,070**

The cost of the environmental assessments and contractual items has been estimated at 5 % of the total installation cost. The high assumption is due to the fact that a first of a kind nuclear power plant is involved.

- Environmental assessment and contract item cost: **R 26,451,673**

Due to inflation, a 30 % increase on above costs has been added.

- Total capital investment of the desalination plant: **R 722,130,680**
- Specific capital cost of the desalination plant: **R 8,288 per m^3**
  \$ 1,105 per m^3

Table 7 provides a summery of the cost calculations.

Table 7: Installation cost of RO plant

Item	Units	Value	Reverence / Comment
Total Membrane Area Required	m^2	297,856	
Installation cost of desalination segment	R	244,830,846	
Maximum feed flow rate	m^3/h	8,550	
Correction factor for pre-treatment cost		3	3 according to Proff. A Burger
Installation cost of pretreatment system	R	259,010,550	
Cost of intake, outfall and post-treatment	R	25,192,070	5% (PBMR intake/outfall)
Cost of environmental assessments and contractual items	R	26,451,673	5% of (D5+D8+D9)
Cost increment due to inflation	%	1.3	30%
Total capital investment	**R**	**722,130,680**	
Total capital investment	**$**	**96,284,091**	
Specific capital cost	**R/m3/day**	**8,288**	
Specific capital cost	**$/m3/day**	**1,105**	R7.5 : $1

According to the GrahamTeck, specialists in RO plant manufacturing, the specific capital cost of a typical reverse osmosis plant is between 1000 and 1500 $\$/m^3/day$. Step 8 compares exceptionally well to the current market trend.

Step 9: Economic evaluation of the RO plant

The economic model of the RO plant consists of various economic parameters that will be discussed below:

- Electricity Cost
- Specific Energy Consumption
- Membrane Replacement Cost per Year
- Specific Chemical Cost
- Specific Labour and Maintenance cost
- Capital cost
- Cost of the capital (Interest rate)

Electricity cost:

ESKOM will supply the electricity to the DPP and therefore will sell the electricity at normal ESKOM rates. The average cost of electricity has been taken as 0.3 R/kW.h, which includes both kWh as well as kVA (Eskom, 2008).

Membrane replacement cost per year:

GrahamTek RO specialists supplied membrane information in order to calculate the membrane replacement cost per year. According to GrahamTek the membrane depreciation will be approximately 20 percent per year. Step 4 provided the number of membranes required and, if above deprecation is taken into account, the specific membrane replacement cost is calculated to be 0.319 R/m^3. Table 8 gives the summary of the membrane replacement cost per year.

Table 8: Membrane specifications and performances

Item	Units	Value	Reverence
Hydranautics & CSM membrane elements	#	2,466	Equation 12
Hydranautics & CSM membrane elements cost	R	20,625	
Total membrane cost	R	50,854,898	
Membrane depreciation per year	%	20%	20% per year
Membrane depreciation cost per year	R	10,170,980	
Maximum annual production	m^3/y	31,890,016	
Membrane replacement cost per year	**R/m^3**	**0.319**	Equation 22

Specific chemical, labour and maintenance cost:

According to GrahamTek the specific chemical cost for the RO plant will be 0.5 R/m^3. GrahamTek also projected the cost of labour and maintenance to be 0.941 R/m^3.

Capital redemption:

The capital redemption has been calculated over an operating period of 25 years with a conservative interest rate of 13 % per year.

Economic Evaluation Result:

Table 9 gives a summary of the RO plant performance and the economic analysis. The product water cost for the RO plant was calculated to 5.64 R/m^3 or 0.75 \$/m^3.

Table 9: RO plant performance and economic analysis

RO Plant Design and Economic Analysis			
RO plant performance			**Reverence / Comment**
PBMR MHSS water fallout	m^3/day	216,000	PBMR
Supply temperature	°C	40	PBMR
RO plant availability	%	95	
Maximum water supply to Pre-treatment plant	m^3/day	205,200	Due to availability factor
Pre-treatment water waste due to backwashes	%	10	Backwash system, etc.
Maximum water supply available to RO plant		184,680	
Recovery ratio of RO plant	%	47.18	Obtained from Step 1
Maximum product water produced by RO plant	m^3/day	87,131	
Maximum Annual production	m^3/y	31,890,016	
Economic evaluation			
Operating Cost of the RO plant	**R/m^3**	**2.519**	
Electricity Cost	R/kW.h	0.3	ESKOM
Specific Energy Consumption	kW / m^3	2.532	
Specific Electricity Cost	R/m^3	0.759	
Membrane Replacement Cost per Year	R/m^3	0.319	
Specific Chemical Cost	R/m^3	0.500	
Specific Labour and Maintenance cost	R/m^3	0.941	
Capital Redemption	**R/m^3**	**3.116**	
Operating lifetime of RO plant (25 years)	Months	300	
Specific Capital Cost	R/m^3	8,288	
Total Capital Cost	R	722,130,680	
Interest Rate Yearly	%	13.00%	
Monthly Interest rate	%	1.08%	
Monthly Capital Redemption	R/month	8,144,445	
Product water cost (Rand)	**R/m^3**	**5.64**	
Product water cost (USD)	**\$/m^3**	**0.75**	

The Ashkelon desalination plant produces water at a cost of 0.52 \$/m^3 (Water-technology.net, 2008a). Compared to above calculation the product water cost is much higher. During the economic evaluation some conservative parameters have been chosen and for that reason the cost of the water is high. A detailed cost model needs to be developed to ensure that the economic evaluation is done correctly.

Sensitivity Analysis:

A sensitivity analysis was conducted to determine which economic parameters are critical and will have the greatest effect on the product water cost, if it should change. Each parameter was individually varied over a predicted range and the percentage change of the parameter was plotted against the percentage change of the product water cost. The criticality of the parameter can be determined from the magnitude of the plotted line. Hence, the higher the slope, the more critical the parameter becomes. The following economic parameters were investigated:

- Labour cost
- Membrane replacement cost
- Chemical cost
- Electrical consumption
- Electricity cost
- Contract duration
- Capital cost
- Interest rate
- Original design value

Outcome of the Sensitivity Analysis:

Figure 38 shows the effect of a varying interest rate on the product water cost. Water can be produced at a cost of 5.64 R/m^3 at an interest rate of 13 %. However, if the interest rate is increased by only 10 % the water cost will increase by almost 5 %. Compared to the other economic parameters, the interest rate is a critical parameter for a RO plant. Due to South Africa's high interest rates it penalizes the cost of the water significantly.

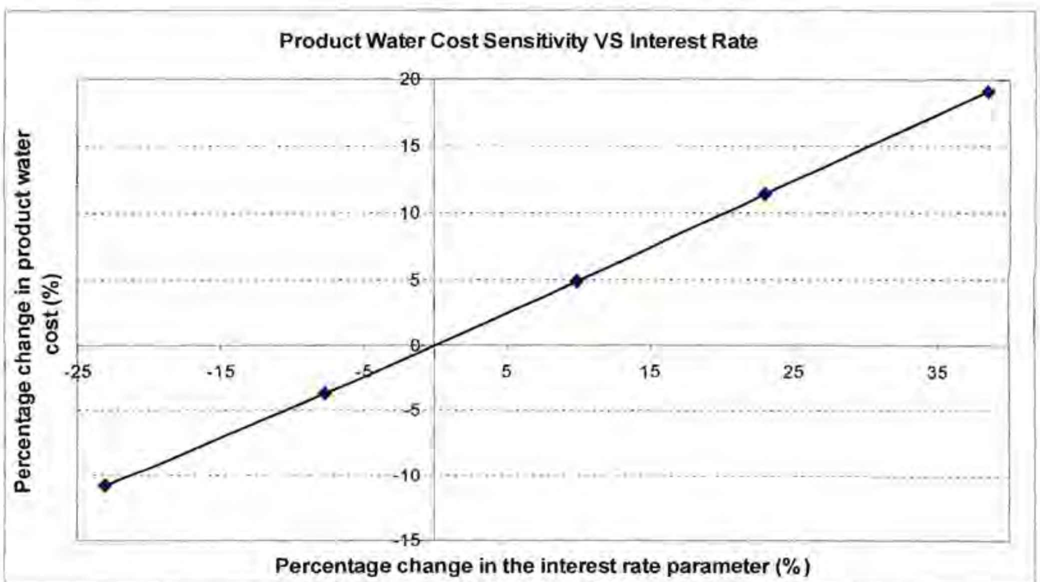

Figure 38: Product water cost sensitivity due to different interest rate

Figure 39 investigates the capital cost economic parameter. If the capital cost should rise with 10 % the product water cost will increase with 5.53 %. From the sensitivity analysis the capital cost parameter is the most critical factor regarding the cost of the product water.

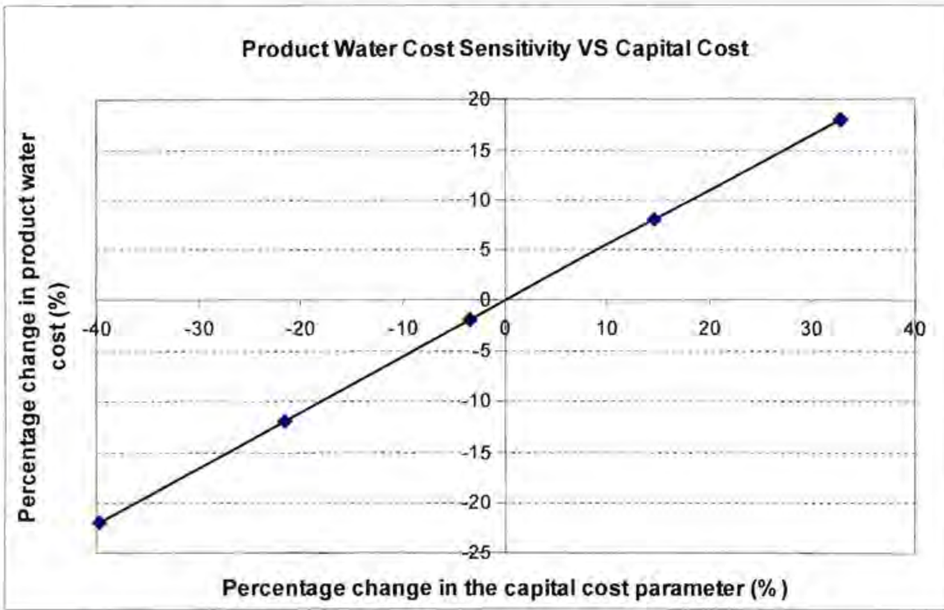

Figure 39: Product water cost sensitivity due to different capital cost

The South African electricity cost is substantially low compared to other countries. Therefore the electricity economic parameter is not as influential on an RO process compared to above parameters. However, the South African power utility ESKOM made a proposal for an electricity hike of more than 50%. An electricity raise of this magnitude will increase the product water cost with almost 7 %, making it a critical economic parameter (See Figure 40).

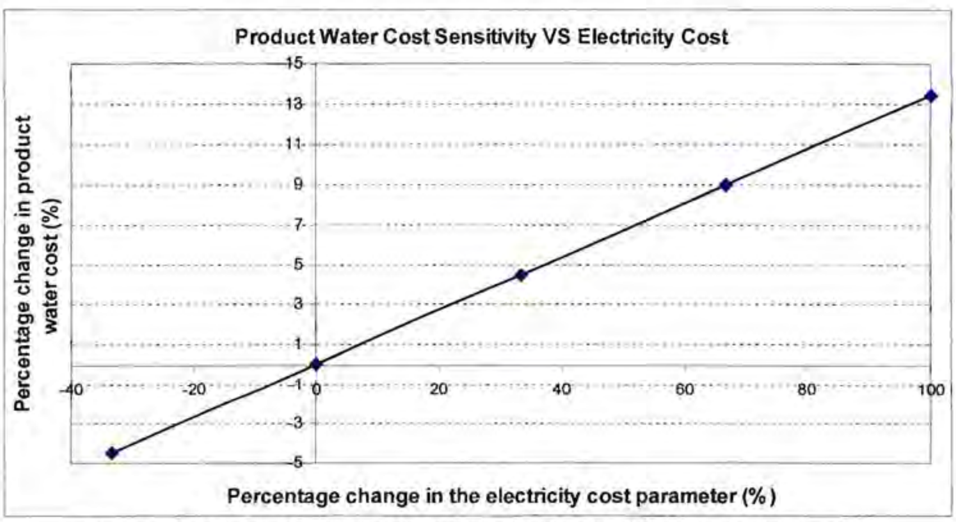

Figure 40: Product water cost sensitivity due to different electricity fees

Figure 41 presents the effect of varying contract duration on the water cost. Note that the duration is not a critical economic parameter. However, if the contract duration should be less than 15 years it could increase the cost of water significantly. Therefore the RO plant must be designed to last at least 15 years.

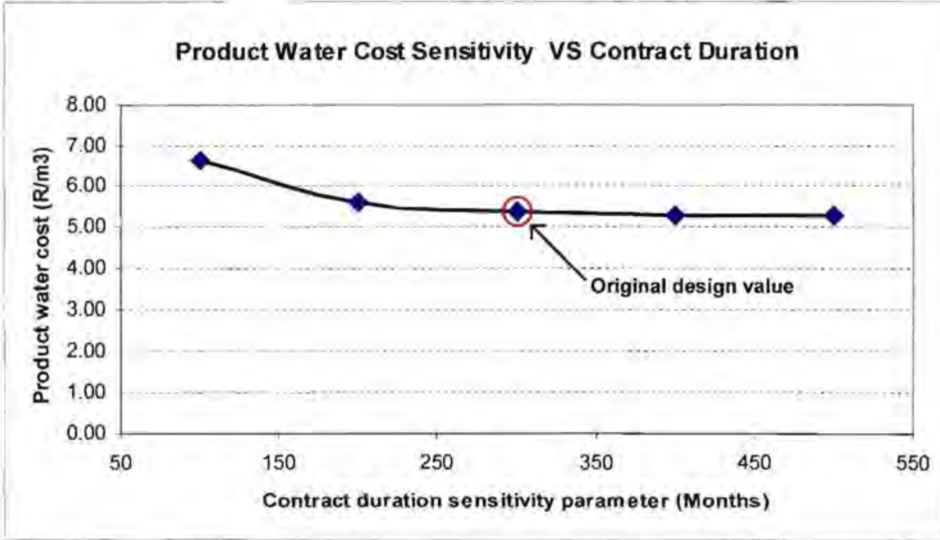

Figure 41: Product water cost sensitivity due to different contract durations

Figure 42 to Figure 45 shows the effect on the product water cost, should there be a variation in the membrane replacement cost, labour & maintenance cost, chemical cost and the electrical consumption of the RO plant. No significant increase on the water cost is detected and it can be assumed that these economic parameters are not critical. Table 10 shows the effect on the product water cost if each parameter should increase with 10 %.

Table 10: Percentage change on the product water cost with a 10 % increase on the economic parameters.

Economic parameter	Percentage change in the product water cost %
Labour	1.67
Chemical Cost	0.89
Electrical Consumption	1.35
Membrane Replacement	0.57

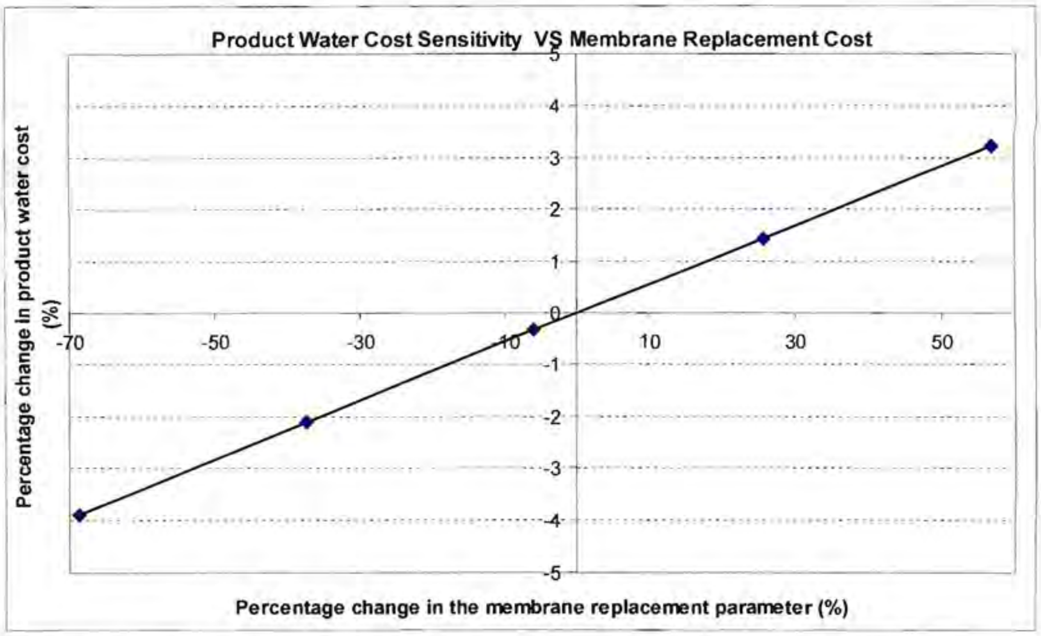

Figure 42: Product water cost sensitivity due to a variation in membrane replacement costs

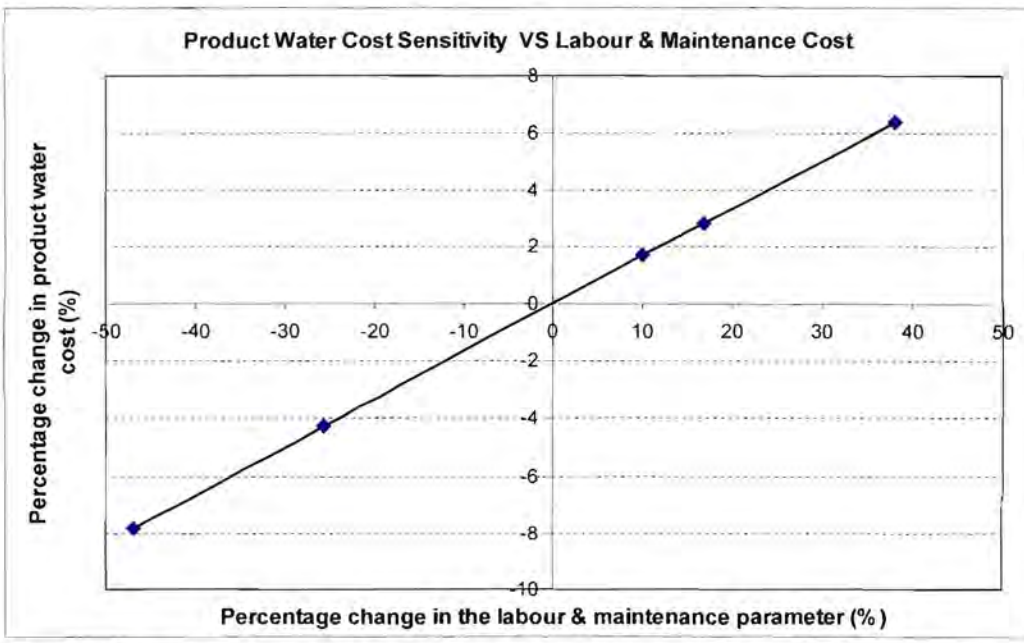

Figure 43: Product water cost sensitivity due to a variation in labour & maintenance costs

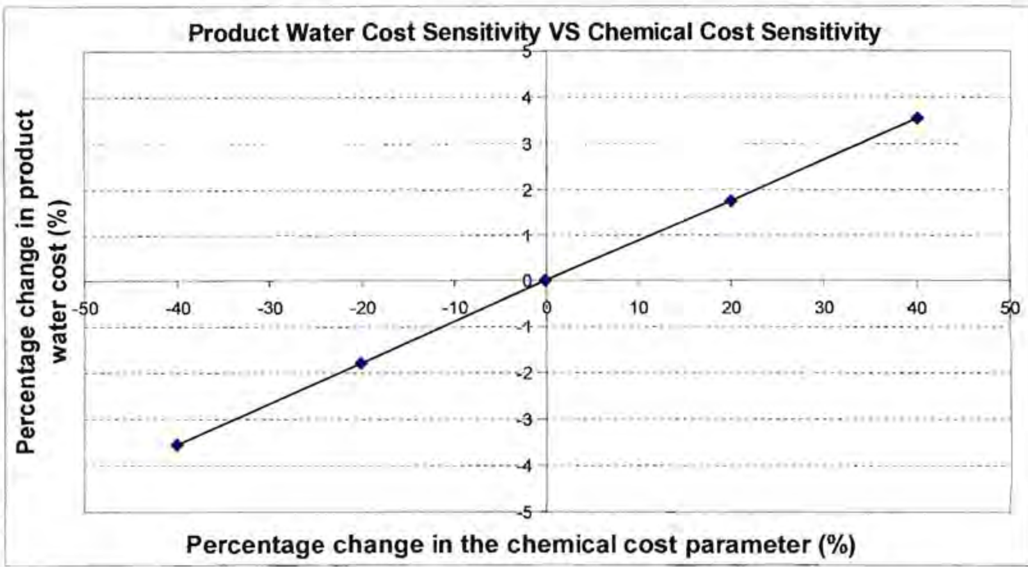

Figure 44: Product water cost sensitivity due to a variation in the chemical cost

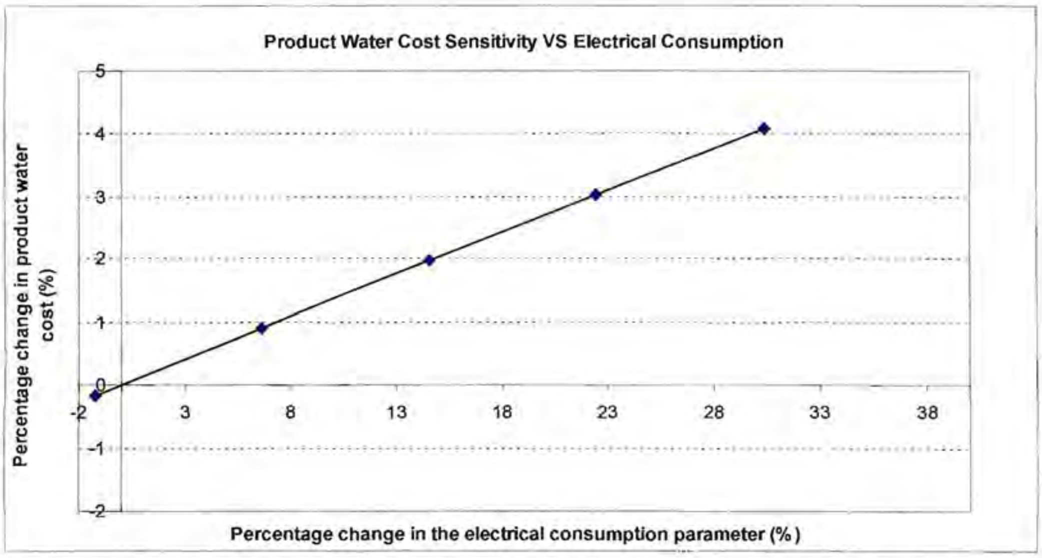

Figure 45: Product water cost sensitivity due to an increase in the electricity consumption

4.3.2 Design of the reverse osmosis plant using software programs

Three software programs were used to simulate the RO plant coupled to the PBMR MHSS. The RO plant performance was calculated in CSMPRO and the economic evaluation was simulated in the DEEP program. For an illustration of a pressure recovery system, the ERI program was used for the simulation.

4.3.2.1 RO plant design in CSM-PRO

CSM-PRO was developed by Customer Satisfaction Membrane (CSM). CSM-PRO is easy to use and detailed information regarding the program can be found in Appendix C. For the first input window (Figure 46) the following assumptions were made during the simulation:

- Water source with an SDI < 5
- Water characteristics as stated in Table 5
- Feed flow of 10 m^3/h
- No adjustment was selected for the Na or NaCl

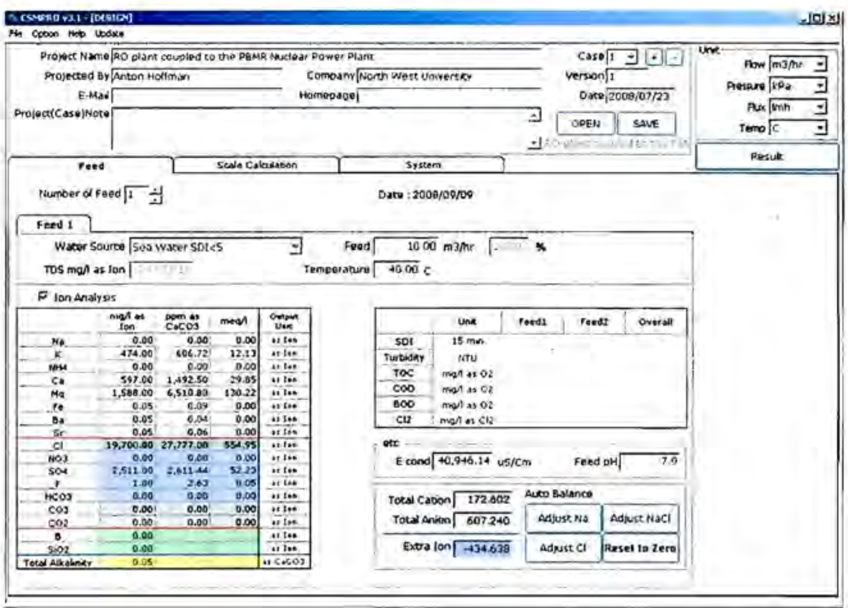

Figure 46: Input window of the feed characteristics in CSMPRO

Scale Calculations:

No calculations were made in the program regarding the scaling tendency of the membranes due to the fact that it needs to be compared to the design guidelines outcome that also does not include scaling calculations. This can be done easily by simply selecting the scale calculation tab next to the feed tab.

System Design:

The system design input window is complicated to some extent and all the assumptions made during the design phase were based on the simplicity of the RO design steps given in Chapter 3. The following assumptions and inputs were made in the system tab button:

- Number of passes: 2
- Same element types within the passes
- Same vessel length within the passes
- Array 1:
    - Number of pressure vessels: 1
    - Number of elements per vessel: 6
    - No booster pump
    - Membrane type: RE8040-SR (Please refer to Figure 54 in Appendix B for the data sheet)
- Array 2:
    - Number of pressure vessels: 1
    - Number of elements per vessel: 6
    - No booster pump
    - Membrane type: RE8040-SR (Please refer to Figure 54 in Appendix B for the data sheet)

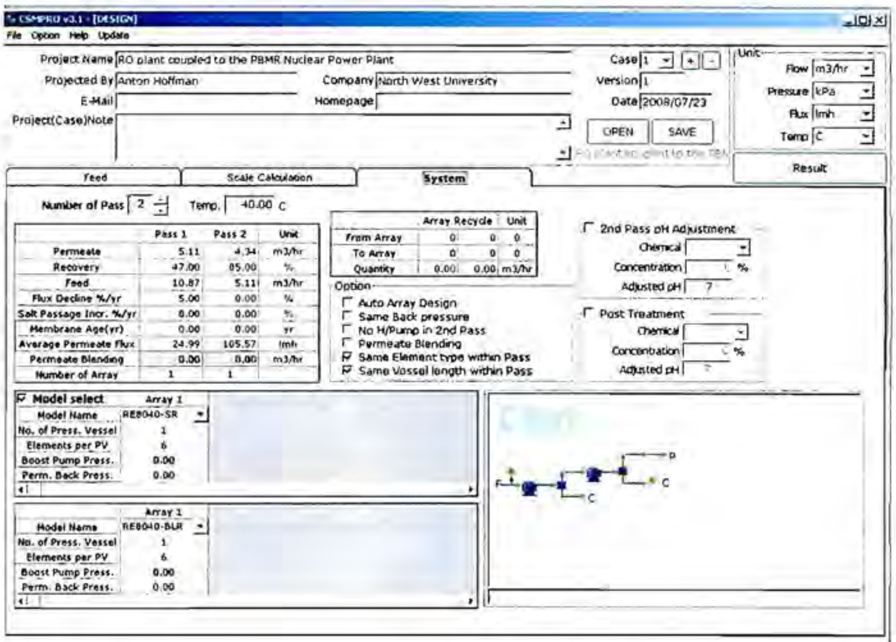

Figure 47: Input window or the system characteristics in CSMPRO

Result of the RO design in CSM-PRO:

CSM-PRO gives two result files. One result file contains more detail such as the osmotic pressure, etc. Figure 48 gives a view of the second results window which shows the flow rate, TDS and pressure values of the RO plant at various positions in the RO system. Results obtained are a recovery ratio of 43.4 % and a product flow rate of 4.34 m^3/h. Table 11 gives a summary of the results obtained.

Table 11: Results obtained from CSMPRO

	Parameter	Unit	Value
Inlet	Feed - Mass flow	m^3/h	10
	Feed - TDS	mg/L	35 000
Outlet	Product water mass flow	m^3/h	4.34
	Feed - TDS	mg/L	14.32
	Recovery ratio	%	43.4

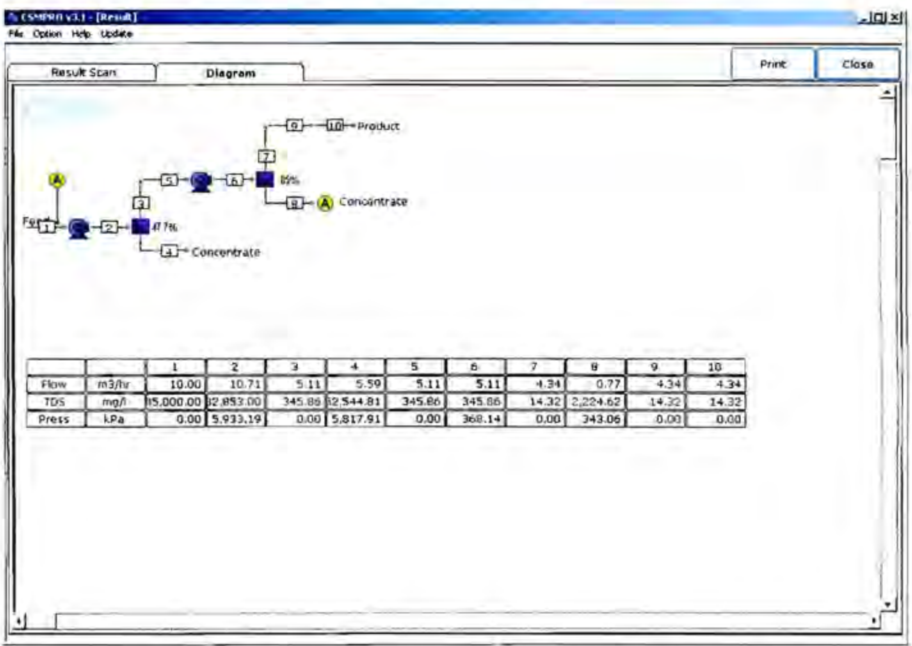

Figure 48: Results diagram of the RO design in CSMPRO

Compare Results:

The results obtained from the CSM-PRO program compares well to the results obtained from the design guidelines in Chapter 3. CSM-PRO calculated a recovery ratio of 43.4 % and the design guidelines a recovery ratio of 47.18 %. Given that CSM-PRO is a commercial package it was taken as the benchmark for this study, therefore the percentage difference for the value obtained with the design guidelines is 8.7 %.

4.3.2.2 Simulation in ERI SIMULATION PROGRAM

Note that the ERI program is not for design purposes, but it will illustrate the use of pressure recovery devices (See Figure 49). Table 12 gives the results of a RO plant using pressure recovery units and a RO plant without. Note that the power consumption is 998 kW and 1649 kW respectively.

Table 12: Results obtained from ERI SIMULATION PROGRAM

	Parameter	Unit	Value
Without pressure recovery	Production rate	m^3/day	10 501
	Total power	kW	1649.53
	Specific energy	kWh/m^3	3.77
With pressure recovery	Production rate	m^3/day	10 501
	Total power	kW	998
	Specific energy	kWh/m^3	2.28

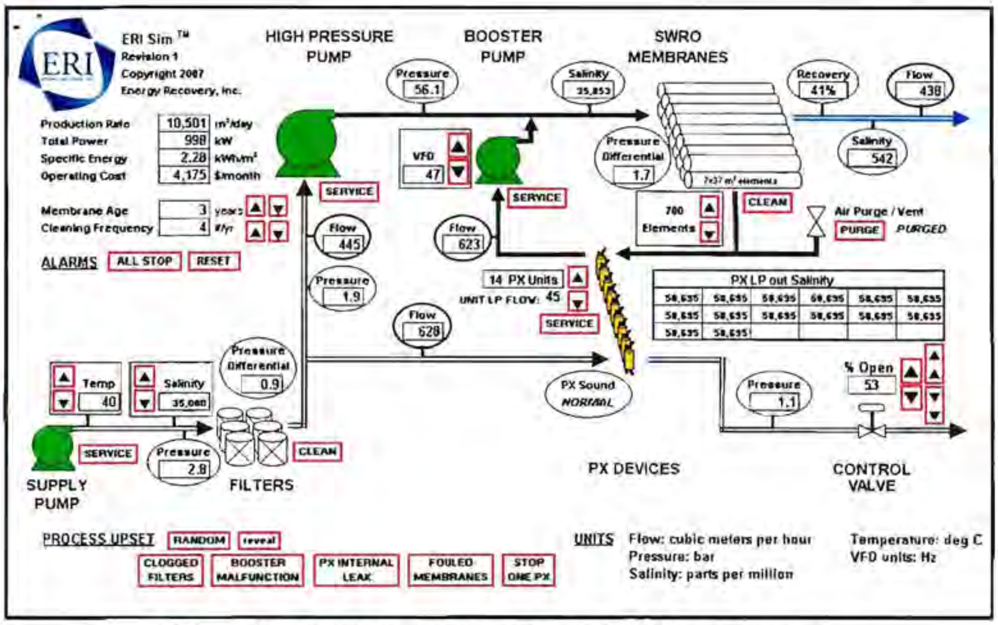

Figure 49: Simulation window of the ERI software program.

Compare Results:

The results obtained from the ERI simulator compares well to the results obtained from the design guidelines in Chapter 3. ERI calculated a specific power consumption of 2.28 kWh/m^3 and the design guidelines a specific power consumption of 2.53 kWh/m^3. The percentage difference between the two is 10.9 %.

4.3.2.3 Economical study in DEEP

The DEEP program is capable of simulating complex distillation processes. A combination of multiple processes can also be chosen in order to simulate hybrid plants, for instance a RO plant coupled to a MED plant (See Figure 50). However, in this case a stand-alone RO plant has been chosen which implies that only the reverse osmosis information is needed. Note that the transport cost or carbon tax emission calculations have not been selected. The following parameters have been chosen for the input window in the DEEP program.

- Firstly, a STAND-ALONE RO plant was selected
- Total plant capacity 81 132 m^3/day
- Feed salinity 35 000 ppm
- Interest rate 13%
- Feed temperature 40°C
- Purchased electricity cost 0.04 $/kWh
- Energy recovery fraction 90%
- Recovery ratio 47.18%
- Design flux 20 l/(m^2.h)
- Specific construction cost 1105 $/($m^3$/day)

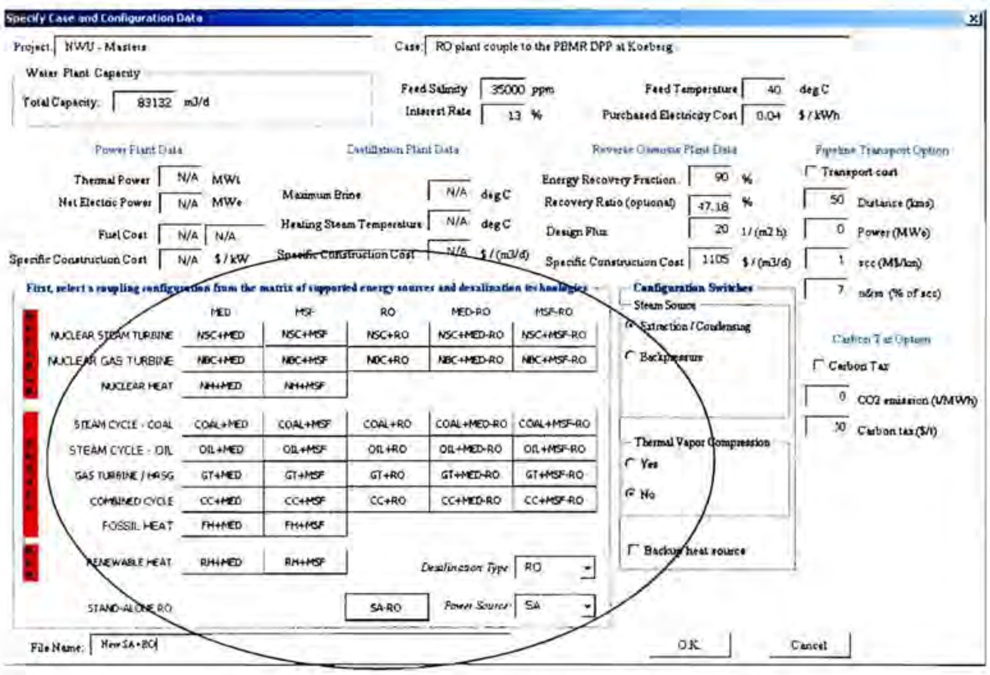

Figure 50: Input window for the DEEP program

RO Plant Design Results:

The outcome of the DEEP program revealed that the plant will be using 3.15 kWh/m^3 and that the specific water cost will be 0.644 \$/m^3. Additional results showed a feed pressure requirement of 59.8 bar. Figure 51 gives a summary of the design results calculated by the DEEP program.

28			Performance Results			Close
29						
30	Lost Electricity Production	N/A	MW	Power-to-Heat Ratio	N/A	MWe/MWt
31	Plant Thermal Utilization	N/A	%			
32						
33	Distillation Performance			RO Performance		
34	# of Effects/Stages	N/A				
35	GOR	N/A		Recovery Ratio	0.47	
36	Temperature Range	N/A	°C	Permeate Flow	83,132	m³/d
37	Distillate Flow	N/A	m³/d	Feed Flow	176,202	m³/d
38	Feed Flow	N/A	m³/d	Feed Pressure	59.8	bar
39	Steam Flow	N/A	kg / s	Product Quality	255	ppm
40	Brine Flow	N/A	m³/d	Brine Flow	93,070	m³/d
41	Brine salinity	N/A	ppm	Brine Saliniy	66,263	ppm
42	Specific Heat Consumption	N/A	kWh / m³	Specific Power Consumption	3.15	kWh / m³
43						
44			Cost Results			Close
45						
46	Specific Power Costs			Specific Water Costs		
47	Fixed charge	N/A	\$ / kWh	Fixed charge	0.355	\$ / m³
48	Fuel cost	N/A	\$ / kWh	Heat cost	N/A	\$ / m³
49	O&M cost	N/A	\$ / kWh	Plant electricity cost	0.000	\$ / m³
50	Decommissioning cost	N/A	\$ / kWh	Purchased electricity	0.126	\$ / m³
51	Total carbon cost	N/A	\$/kWh	O&M cost	0.163	\$ / m³
52	Levelized Electricity Cost	N/A	\$ / kWh	Water production cost	0.644	\$/m³
53				Water transport cost	0.000	\$/m³
54				Total Specific Water Cost	0.644	\$ / m³
55						

Figure 51: Summary of the performance and cost results

Compare Results:

Some results obtained from the DEEP program compares well to the results obtained from the design guidelines in Chapter 3. Table 13 gives both the design processes' values with a percentage difference. Note that there is a substantial difference regarding the specific energy. With new technology on the market a specific energy of below 3 kWh/m^3 is achievable. However, a large difference (almost 20%) was discovered between the DEEP software program and the design guidelines regarding the specific energy parameter. On the other hand an article written by John P. MacHarg stated that the electric consumption of a reverse osmosis plant has reached a staggering 2 kWH/m^3 or even less with the help of modern pressure recovery systems (MacHarg, 2005:53).

Table 13: Results obtained from DEEP compared to the design guidelines outcome

Parameter	Unit	DEEP	Design Guidelines	Percentage difference
Feed Pressure	Bar	59.8	64.89	7.8 %
Specific energy	kWh/m^3	3.15	2.53	19.68 %
Specific water cost	\$/m^3	0.664	0.75	11.5 %

4.3.3 Conclusion

In Chapter 4 the potential of adding a reverse osmosis plant to a new generation nuclear power plant was investigated. The investigation involved using the design guidelines provided in Chapter 3 to determine a RO plant's performance coupled to the waste water stream of a PBMR nuclear plant. The main results obtained were the specific product cost of R5.64 / m^3 and the specific electricity consumption of 2.53 kWh/m^3. Software programs were then used to simulate the RO design and the results were presented and compared to the outcome of the design guidelines. Most of the parameters conducted from the two design approaches compared well to each other. Furthermore a sensitivity analysis was conducted which established that the interest rate, capital cost and a high increase in the electricity cost are critical economic parameters. If these parameters should change it could influence the product water cost significantly.

From the above mentioned it seems viable for the PBMR to investigate the possibility of connecting an RO system to the MHSS of the planned nuclear power plant.

5 Chapter

CONCLUSION AND RECOMMENDATION

At the moment there are people around the globe that do not have water for drinking and sanitation purposes. Due to this 3800 children die each day! According to studies this will not get better in time and there might be a water scarcity in countries around the world by the year 2025. Clearly the world must recognize that responsible people need to take action, not only to sustain future fresh water availability, but to increase the quantity and quality for a healthier lifestyle for the human race and also to conserve the ecosystem. One option to relieve pressure on the water demand is by using desalination technologies.

This project started with a thorough literature study on all the major desalination processes available in the industry and a brief summary was given on each. The literature study recognized that reverse osmosis technology was comparing very well to the traditional distillation processes with respect to the product cost. Furthermore it showed that the reverse osmosis process is gaining a larger market share compared to the traditional distillation processes. The reverse osmosis process is continuously improving its effectiveness with new innovations and technologies.

One superb option for a reverse osmosis plant to increase its efficiency, is by using warm waste water from industrial processes, such as from a PBMR nuclear power plant. The PBMR waste water temperature will be approximately 40°C and this is ideal for a RO plant. Waste energy from Nuclear power can effectively be used to preheat the feed water of a reverse osmosis plant.

All the major components of a reverse osmosis plant were discussed and it was realized that every component is important for a reverse osmosis plant to operate at maximum efficiency. Therefore, every component must be designed in detail to interact optimally with other components in the reverse osmosis system. During the literature study design guidelines for a reverse osmosis plant was obtained. The guidelines are presented in Chapter 3 and are given in 9 steps. The nine steps can be implemented during a concept (basic component) design for a reverse osmosis plant.

In Chapter 4 the guidelines were used to perform a basic design on a case study. The case study was aimed at investigating a coupling scheme between a RO plant and the waste water of a PBMR nuclear power plant. The outcome of the design showed that the RO plant can produce water at a specific cost of R 5.64/m^3 with a specific electricity consumption of 2.53 kWh/m^3. The figures compare well to existing RO plants that operate at relatively similar conditions. By using the warm waste water (approximately 40°C) as feed water to the RO plant, the RO plant efficiency is increased. Furthermore, a sensitivity analysis was conducted to establish which economic parameters will have the greatest influence on the product cost, if it should change. Interest rate, capital cost and a high increase of the electricity cost were found to be critical economic parameters.

In order to verify the outcome of the design guidelines, reverse osmosis software programs where obtained from leading RO manufactures to simulate the case study. The overall data obtained from the software programs correlated well with the results obtained from the design guidelines. However, a large difference (almost 20%) was discovered between the DEEP software program and the design guidelines regarding the specific energy parameter. On the other hand, literature showed that new technology made it possible to desalinate seawater with a specific energy consumption of less than 3 kWH/m^3.

From the study we can conclude that the validity of a coupling scheme between a RO plant and a PBMR nuclear power plant is very promising and advantageous. Furthermore the study showed that the design guidelines presented is an excellent starting point for any RO design. This project also forms a small step in positioning the North West University for future opportunities in water desalination. A base was established on the reverse osmosis process within this dissertation and the following recommendations can be built onto this study.

Recommendations:

New technology is continuously improving the performance of the reverse osmosis process. From this study many different areas regarding the reverse osmosis process has been identified that can be improved by further research and development. This section will give some guidance for further studies regarding the RO process.

Pre-treatment system:

One of the most critical components in a RO process is the pre-treatment system. If the pre-treatment system is not designed properly, the reverse osmosis membranes could be damaged, which will result in a lower product water quality. It will also increase the RO plant operating cost.

It is recommended that a detailed design of the pre-treatment system should be done in order to treat the waste water from a PBMR plant. In addition a cost model should be developed to determine the capital and operating cost of the pre-treatment plant.

Reverse osmosis membranes:

There are two possibilities where the reverse osmosis membrane could be improved by further research on the material used. The first improvement can be done by reducing the required operating pressure. If the operating pressure is reduced by using new materials for the membranes, it will decrease the specific energy consumption and operating cost of the RO plant significantly. The second investigation should be aimed at developing fouling-resistant membranes. Fouling is the main problem in a reverse osmosis plant that results in performance loss and higher operating costs.

Both these investigations are material related and an investigation regarding new membrane types should be helpful for the reverse osmosis industry.

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7 APPENDIX

Appendix A – Reverse Osmosis plant design in Excel

As stated above an excel program was written to calculate the design equations (provided in Chapter 3) for a RO plant coupled to the PBMR MHSS (Chapter 4). Each window is shown with the parameter, units, values and reverence or comment.

Excel Worksheet number 1

Table 14: Maximum recovery ratio achievable due to feed water characteristics

Ion	Unit	Value	Reverence / Comment
TDS	mg/L	35000	Please enter the water analysis results into appropriate space
Alkalinity	mg/L	128	
Ca	mg/L	597	
$CaCO_3$	mg/L	8028	
SO_4	mg/L	2511	
F	mg/L	1	
SiO_2	mg/L		
Fe	mg/L	0.1	
Mg	mg/L	1588	
Ba	mg/L	0.1	
Sr	mg/L	0.1	
Maximum Recovery Ratio			
Ion	**Name**	**Max. RR (%)**	**Reverence**
$CaCO_3$	Calcium Carbonate	86.18%	Equation 4
$CaCO_4$	Calcium Sulphate	51.03%	Equation 5
CaF_2	Calcium Fluoride	79.39%	Equation 6
Fe	Oxides/hydroxides of iron	96.67%	Equation 8
Ba	Salts with barium	47.18%	Equation 9
Sr	Salts with strontium	96.04%	Equation 10

Maximum Recovery	**47.18%**

Excel Worksheet number 2

Table 15: Membrane area required and number of membranes

Item	Units	Value	Reverence / Comment
Number of passes	1 or 2	2	Choose number of passes
Hourly production rate	m^3/h	3630.466327	Equation 3
Pass 1 - Membrane A (Seawater type)			
Manufacture		Hydranautics	
Model		SWC3-16X40	
Permeate flow rate	m^3/day	80	
Stabilized salt rejection	%	99.5	
Effective area	m^2	120.8	
Flux rate	L / h.m^2	19.00	70 % of maximum flux
Pass 2 - Membrane B (Brackish water type)			
Manufacture		CSM	
Model		RE 1640-BLR	
Permeate flow rate	m^3/day	136.8	
Stabilized salt rejection	%	99.5	
Effective area	m^2	116.2	
Flux rate	L / h.m^2	34.00	70 % of maximum flux
Total Membrane Area Required	m^2	**297855.60**	Equation 11
GrahamTek Model - SS 1640	#	2,466	Equation 12
Hydranautics Membrane Element SWC3 - 16x40	R/membrane	20,625	
Total Membrane Cost	R	50,854,898	
Membrane depreciation per year	%	20%	Take 20% per year
Membrane depreciation per year	R	10,170,980	
Maximum Annual production	m3/y	31,890,016	
Membrane Replacement Cost per year	R/m^3	**0.319**	Equation 22

Excel Worksheet number 3

Table 16: Feed pressure requirement

Item	Units	Value	Reverence / Comment
Feed water temperature	^oC	40	Enter the feed water temperature
Osmotic pressure	TDS (mg/l)	0.00076	Estimated value
System pressure losses	bar	5	Estimated value
Pressure loss for first pass	**bar**	**64.89**	Equation 13
Flux through membrane A	L / h.m^2	19.00	
Membrane A flux per driving pressure	ξ	1	For seawater a value between 1 and 2
Recovery ratio of first pass	%	47.18%	
Pressure loss for second pass	**bar**	**9.38**	Equation 13
Flux through membrane B	L / h.m^2	34.00	
Membrane A flux per driving pressure	ξ	4.5	For fresh water a value between 4 and 5
Recovery ratio of second pass	%	85.00%	Normally between 70% and 90%

Excel Worksheet number 4

Table 17: Energy consumption of the RO plant

Estimated Energy Consumption of the RO Plant			
Item	Units	Value	Reverence / Comment
Pressure recovery system installed	0 or 1	1	0 - not installed ; 1 - installed
Pressure recovery system efficiency	%	90%	Estimate
Pump efficiency	%	70%	Estimate
Combined permeate flow of the 2 passes	m^3/h	3630.466327	
Estimated energy consumption for first pass	**kW**	**6631.92**	Equation 15
First pass recovery ratio	%	47.18%	
Hourly production rate	m^3/h	1957.124705	
Feed Pressure Required	bar	64.89	
Estimated energy consumption for second pass	**kW**	**692.65**	Equation 15
Second pass recovery ratio	%	85.00%	
Hourly production rate	m^3/h	1673.341623	
Feed Pressure Required	bar	9.38	
Pump efficiency	%	75	
Estimated energy consumption for feed pumps	**kW**	**1866.07**	Equation 16
Pressure inlet	bar	5.5	Estimate
Flow rate into the plant	m^3/h	8550	
Energy Consumption	**MW**	**9.19**	
Specific Energy Consumption	**kWh / m^3**	**2.53**	Equation 18

Excel Worksheet number 5

Table 18: Cost of RO plant

Item	Units	Value	Reverence / Comment
Total Membrane Area Required	m^2	297,856	
Installation cost of desalination segment	R	244,830,846	
Maximum feed flow rate	m^3/h	8,550	
Correction factor for pre-treatment cost		3	Estimate 2.5
Installation cost of pretreatment system	R	259,010,550	
Cost of intake, outfall and post-treatment	R	25,192,070	Estimate 5%
Cost of environmental assessments and contractual items	R	26,451,673	Estimate 5%
Cost increment due to inflation	%	1.3	30%
Total capital investment	**R**	**722,130,680**	
Total capital investment	**$**	**96,284,091**	
Specific capital cost	**R/m3/day**	**8,288**	
Specific capital cost	**$/m3/day**	**1,105**	

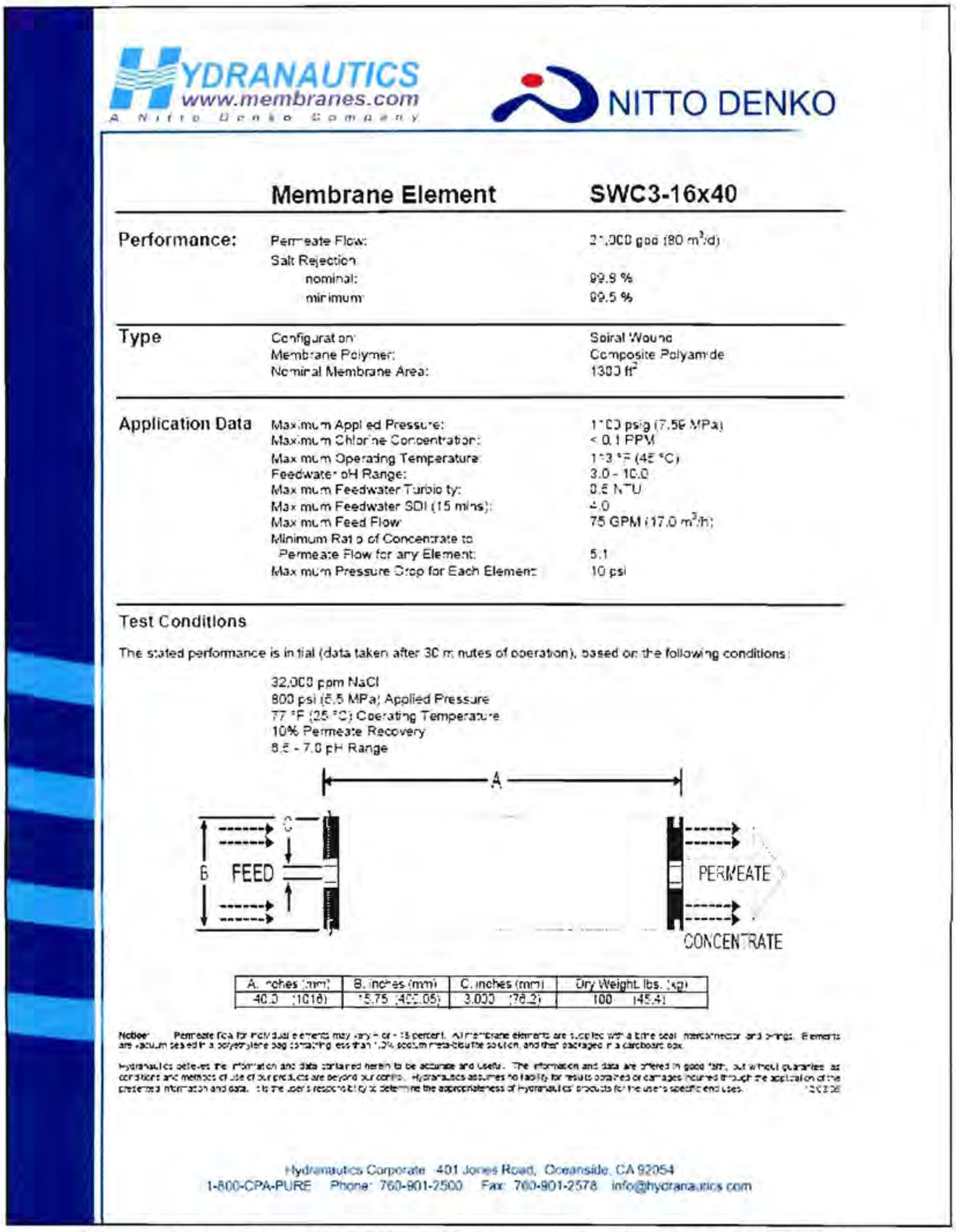
Excel Worksheet number 6

Table 19: RO plant performance and economic analysis

RO Plant Design and Economic Analysis			
RO plant performance			**Reverence / Comment**
PBMR MHSS water fallout	m^3/day	216,000	PBMR
Supply temperature	°C	40	PBMR
RO plant availability	%	95	
Maximum water supply to Pre-treatment plant	m^3/day	205,200	Due to availability factor
Pre-treatment water waste due to backwashes	%	10	Backwash system, etc.
Maximum water supply available to RO plant		184,680	
Recovery ratio of RO plant	%	47.18	Obtained from Step 1
Maximum product water produced by RO plant	m^3/day	87,131	
Maximum Annual production	m^3/y	31,890,016	
Economic evaluation			
Operating Cost of the RO plant	**R/m^3**	**2.519**	
Electricity Cost	R/kW.h	0.3	ESKOM
Specific Energy Consumption	kW / m^3	2.532	
Specific Electricity Cost	R/m^3	0.759	
Membrane Replacement Cost per Year	R/m^3	0.319	
Specific Chemical Cost	R/m^3	0.500	
Specific Labour and Maintenance cost	R/m^3	0.941	
Capital Redemption	**R/m^3**	**3.116**	
Operating lifetime of RO plant (25 years)	Months	300	
Specific Capital Cost	R/m^3	8,288	
Total Capital Cost	R	722,130,680	
Interest Rate Yearly	%	13.00%	
Monthly Interest rate	%	1.08%	
Monthly Capital Redemption	R/month	8,144,445	
Product water cost (Rand)	**R/m^3**	**5.64**	
Product water cost (USD)	**$/$m^3$**	**0.75**	

Appendix B – RO Membrane Specification Sheets

Seawater membrane:



HYDRANAUTICS
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NITTO DENKO

	Membrane Element	SWC3-16x40
Performance:	Permeate Flow:	21,000 gpd (80 m³/d)
	Salt Rejection	
	nominal:	99.8 %
	minimum:	99.5 %
Type	Configuration:	Spiral Wound
	Membrane Polymer:	Composite Polyamide
	Nominal Membrane Area:	1300 ft²
Application Data	Maximum Applied Pressure:	1100 psig (7.59 MPa)
	Maximum Chlorine Concentration:	< 0.1 PPM
	Maximum Operating Temperature:	113 °F (45 °C)
	Feedwater pH Range:	3.0 - 10.0
	Maximum Feedwater Turbidity:	0.5 NTU
	Maximum Feedwater SDI (15 mins):	4.0
	Maximum Feed Flow:	75 GPM (17.0 m³/h)
	Minimum Ratio of Concentrate to Permeate Flow for any Element:	5:1
	Maximum Pressure Drop for Each Element:	10 psi

Test Conditions

The stated performance is initial (data taken after 30 minutes of operation), based on the following conditions:

32,000 ppm NaCl
800 psi (5.5 MPa) Applied Pressure
77 °F (25 °C) Operating Temperature
10% Permeate Recovery
6.5 - 7.0 pH Range

A, inches (mm)	B, inches (mm)	C, inches (mm)	Dry Weight lbs. (kg)
40.0 (1016)	15.75 (400.05)	3.000 (76.2)	100 (45.4)

Notice: Permeate flow for individual elements may vary + or - 15 percent. All membrane elements are supplied with a brine seal, interconnector, and o-rings. Elements are vacuum sealed in a polyethylene bag containing less than 1.0% sodium meta-bisulfite solution, and then packaged in a cardboard box.

Hydranautics believes the information and data contained herein to be accurate and useful. The information and data are offered in good faith, but without guarantee, as conditions and methods of use of our products are beyond our control. Hydranautics assumes no liability for results obtained or damages incurred through the application of the presented information and data. It is the user's responsibility to determine the appropriateness of Hydranautics' products for the user's specific end uses. [illegible]

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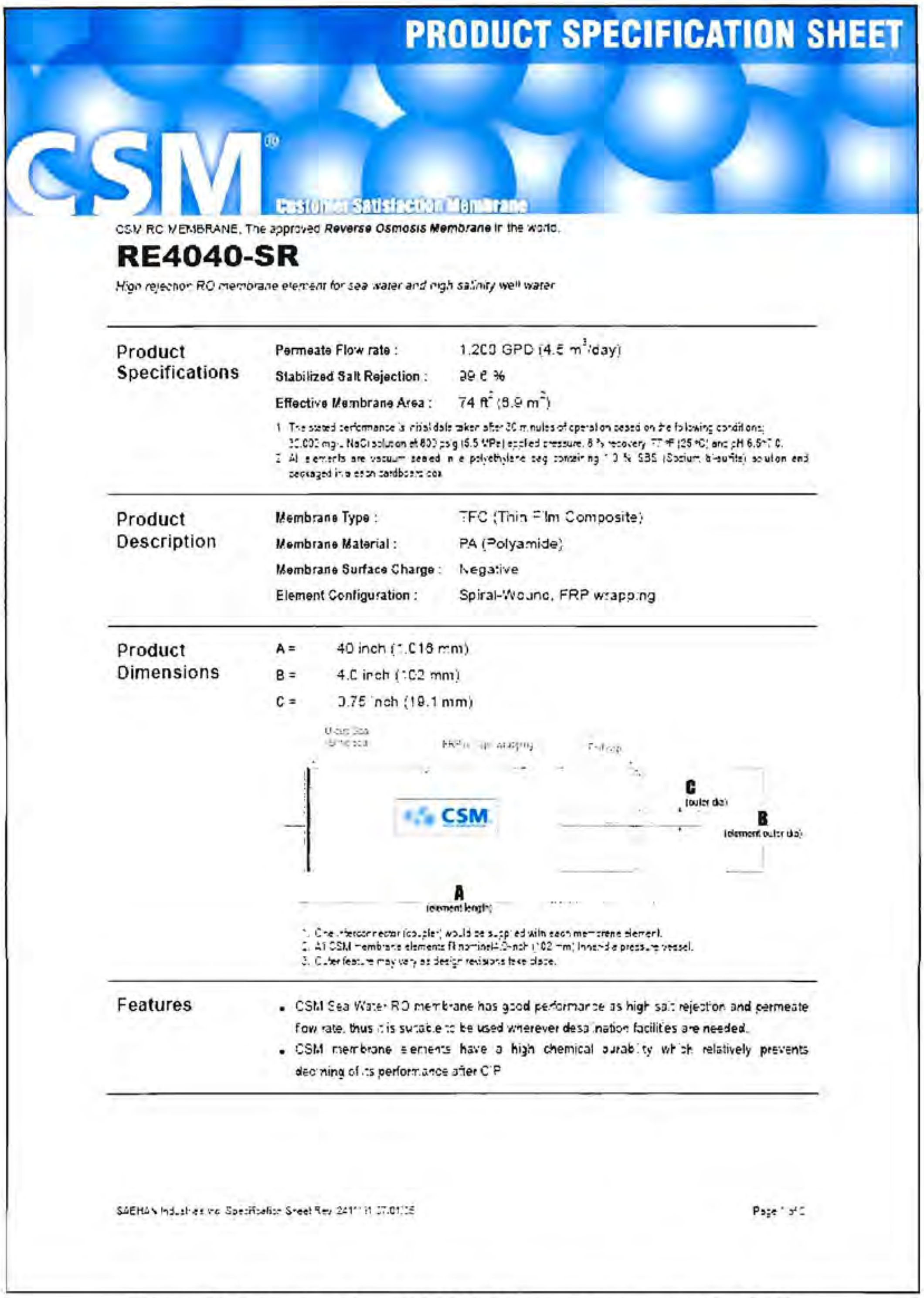
1-800-CPA-PURE Phone: 760-901-2500 Fax: 760-901-2578 info@hydranautics.com

Figure 52: Data sheet for a SWC3-16x40 membrane created by Hydranautics.

Brackish water membrane:



PRODUCT SPECIFICATION SHEET

CSM®

Customer Satisfaction Membrane

CSM RO MEMBRANE, The approved **Reverse Osmosis Membrane** in the world.

RE4040-SR

High rejection RO membrane element for sea water and high salinity well water

Product Specifications

Permeate Flow rate :	1,200 GPD (4.5 m^3/day)
Stabilized Salt Rejection :	99.8 %
Effective Membrane Area :	74 ft^2 (6.9 m^2)

1. The stated performance is initial data taken after 30 minutes of operation based on the following conditions: 32,000 mg/L NaCl solution at 800 psig (5.5 MPa) applied pressure, 8 % recovery, 77 ºF (25 ºC) and pH 6.5~7.0.
2. All elements are vacuum sealed in a polyethylene bag containing 1.0 % SBS (Sodium bi-sulfite) solution and packaged in a carton cardboard box.

Product Description

Membrane Type :	TFC (Thin Film Composite)
Membrane Material :	PA (Polyamide)
Membrane Surface Charge :	Negative
Element Configuration :	Spiral-Wound, FRP wrapping

Product Dimensions

A =	40 inch (1,016 mm)
B =	4.0 inch (102 mm)
C =	0.75 inch (19.1 mm)

1. One interconnector (coupler) would be supplied with each membrane element.
2. All CSM membrane elements fit nominal 4.0-inch (102 mm) I.D. pressure vessel.
3. Outer feature may vary as design revisions take place.

Features

- CSM Sea Water RO membrane has good performance as high salt rejection and permeate flow rate, thus it is suitable to be used wherever desalination facilities are needed.
- CSM membrane elements have a high chemical durability which relatively prevents declining of its performance after CIP.

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Figure 53: Data sheet for a RE4040-SR membrane created by CSM

PRODUCT SPECIFICATION SHEET

CSM®

Customer Satisfaction Membrane

CSM RO MEMBRANE, The approved ***Reverse Osmosis Membrane*** in the world.

RE8040-SR

High rejection RO membrane element for sea water and high salinity well water

Product Specifications

Permeate Flow rate : 6,000 GPD (22.7 m^3/day)

Stabilized Salt Rejection : 99.6 %

Effective Membrane Area : 370 ft^2 (34.4 m^2)

1. The stated performance is initial data taken after 30 minutes of operation based on the following conditions; 32,000 mg/L NaCl solution at 800 psig (5.5 MPa) applied pressure, 8 % recovery, 77 °F (25 °C) and pH 6.5~7.0.
2. Minimum salt rejection is 99.5%.
3. Boron rejection is 90.0 % at pH 8.0 and 5 mg/L boron feed with the test condition as above note 1.
4. Permeate Flow rate for individual elements may vary but will be no more than 15 below the value shown.
5. Effective membrane area may vary within 5 %.
6. All elements are vacuum sealed in a polyethylene bag containing 1.0 % SBS (Sodium bisulfite) solution and packaged individually in a cardboard box.

Product Description

Membrane Type : Thin-film Composite

Membrane Material : PA (Polyamide)

Membrane Surface Charge : Negative

Element Configuration : Spiral-Wound, FRP wrapping

Product Dimensions

A = 40 inch (1,016 mm)

B = 8.0 inch (203 mm)

C = 1.12 inch (28 mm)

1. One interconnector (coupler) would be supplied for each membrane element.
2. All CSM membrane elements fit nominal 2.5-inch (64 mm) I.D. pressure vessel.
3. Outer feature may vary as design revisions take place.

Features

- CSM SR element shows higher salt rejection than CSM SN, suitable for normal desalination process.
- CSM SR element has a high chemical durability which prevents declining of its performance after CIP.

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Figure 54: Data sheet for a RE8040-SR membrane created by CSM

Appendix C – RO Design Software Programs

Design Software

In the 20th century the computer has become part of every day life in most engineering fields. Major suppliers of reverse osmosis systems have developed design software programs that can simulate and optimize complex RO designs. A few of these programs can also conduct economic calculations. In the following section three different software programs are briefly discussed which is also used during the design in Chapter 4.

A. Customer Satisfaction Membrane PRO (CSM-PRO)

Saehan Industries, Inc. situated in Korea is the originator of Customer Satisfaction Membranes (CSM). Saehan is continuously developing new innovative products to satisfy customer needs and also sets the standard for the industry regarding membrane technology, performance, stability and consistency. CSMPRO was developed to ease the design of a membrane driven desalination plant. The program is very similar to the ROSA design program and therefore the program will not be discussed in detail, such as with the ROSA program.

The CSMPRO design program is divided into 4 input files, namely:

- Feed water characteristics
- Scale calculation section
- System configuration
- Design results window

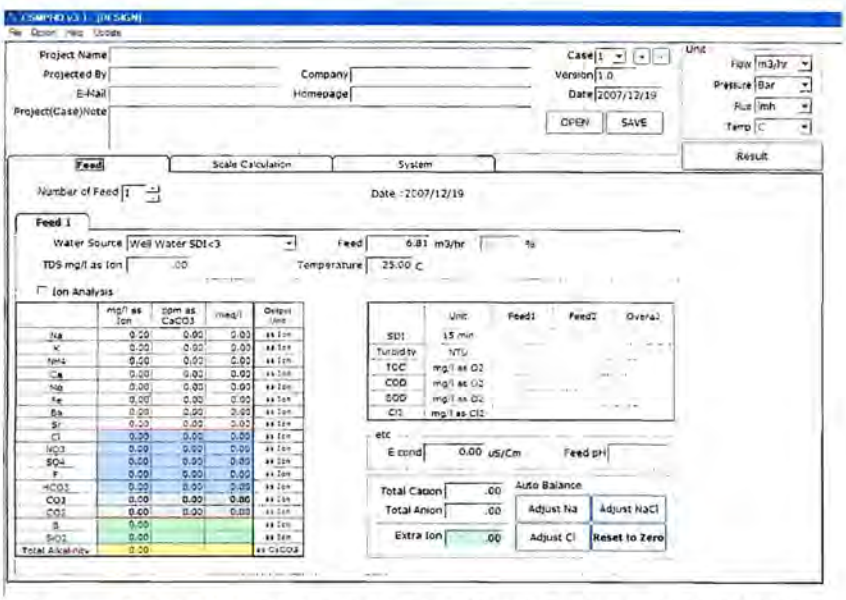

Figure 55: Input window for a Reverse Osmosis element in CSMPRO.

B. Desalination Economic Evaluation Programme (DEEP)

The International Atomic Energy Agency (IAEA) recognized the need for a program that can provide good comparisons between different desalination processes with various coupling configurations and energy sources. General Atomics was the first company to develop such a program and it was called the DEEP program. After some time the IAEA took the program to a higher level with new desalination configurations and technologies. The latest version includes options for desalination via MSF, MED, RO and hybrid systems. Alternative power options have also been updated and can vary between nuclear, fossil and renewable sources.

The design program has 4 main windows, namely:

- New case
- View case
- Edit Input Data
- Show Case Results

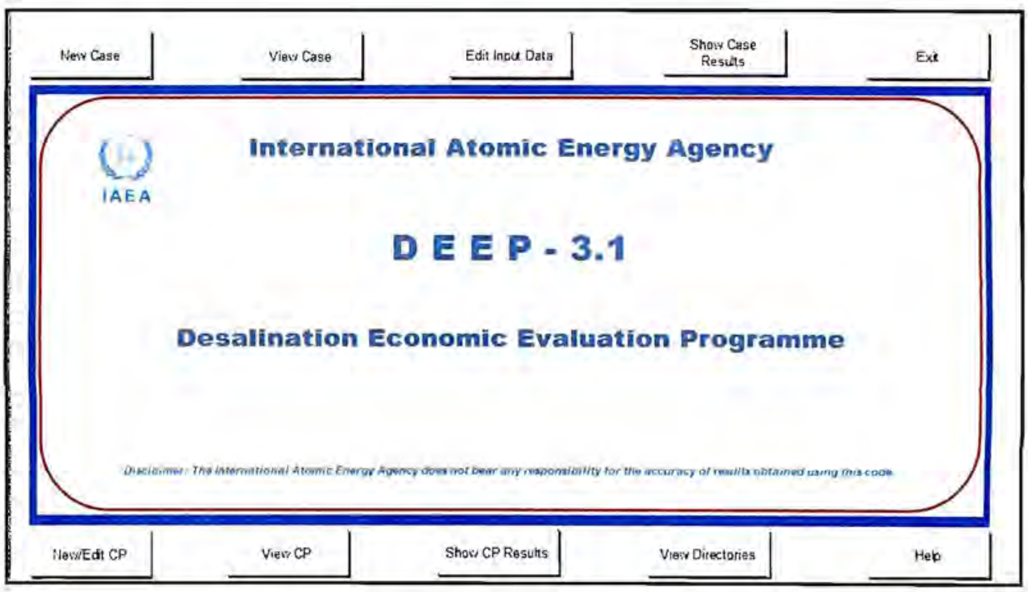

Figure 56: Main interface of the DEEP program.

New Case:

If the new case button is selected a window will appear similar to Figure 57. Different desalination configurations can be chosen. For the reverse osmosis system a hybrid configuration can be chosen or a stand alone (SA-RO) system. Table 20 gives an overview of the different parameters that needs to be inserted into the program. On the right hand side of the window the program makes provision for transportation cost and carbon tax emissions!

Table 20: Specification and configuration parameters for the DEEP program

Parameter	Unit
Feed salinity	ppm
Interest Rate	%
Feed water temperature	°C
Cost of electricity	$/kWh
Energy recovery fraction	%
Recovery ratio	%
Design flux	L / (m^2.h)
Specific construction cost	$ / (m^3/day)

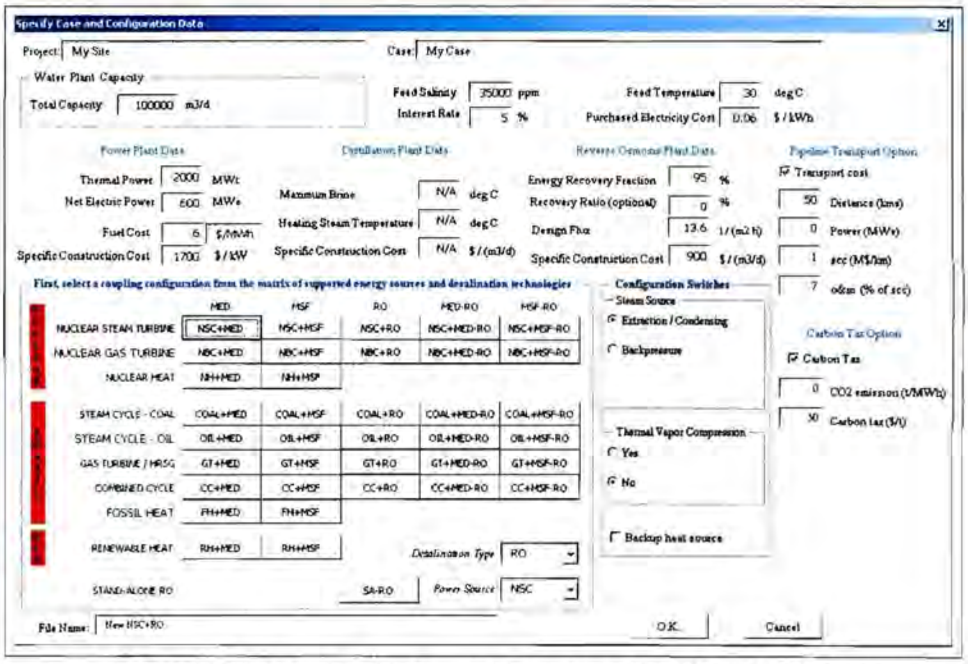

Figure 57: Specification and configuration input window of the DEEP program.

View Case and Edit Input Data:

View case gives the option to reopen previous simulations that were saved on the computer hard drive. In the edit input data option, a designer can change certain parameters in the program itself. Note that the designer has to know what he is doing.

Show Case Results:

The results are given in table format and are well structured. First of all the main input parameters are given (Figure 58) and the designer can do a recap. After this, the performance calculations are given together with the cost results. In the last line the program gives the specific water cost in $\$/m^3$.

	A	B	C	D	E	F	G	H
1				**Summary of Performance and Cost Results**				Close
2								
3				**Main Input Parameters**				
4								
5	**Project**	SA Reverse Osmosis Plant			**Case**	DPP at Koeberg		
6								
7	**Power Plant Data**			**Water Plant Data**				
8	Type	N/A		Type	RO			
9	Ref. Thermal Power	N/A	MW	Required capacity	100,000	m^3/d		
10	Ref. Net Electric Power	N/A	MW	Hybrid Dist. Capacity	N/A	m^3/d		
11	Construction Cost	N/A	$ / kW	Dist. Construction Cost	N/A	$\$ / (m^3/d)$		
12	Fuel Cost	N/A	$/MWh	Maximum Brine Temp.	N/A	°C		
13	Purchased Electricity Cost	0.03	$/kWh	Heating Steam Temp.	N/A	°C		
14	Interest Rate	5	%	Dist. Feed Temp.	N/A	°C		
15				Seawater Feed Salinity	35000.0	ppm		
16	**Configuration Switches**			Hybrid RO Capacity	N/A	m^3/d		
17	Steam Source	N/A		RO Construction Cost	900	m^3/d		
18	Intermediate Loop	Y		RO Recovery Ratio	0.00			
19	TVC Option	N/A		RO Energy Recovery Fraction	0.95			
20	Backup Heat	N/A		RO Design Flux	13.6	$l / (m^2 \text{ hour})$		
21				RO Feed Temp.	40.0	°C		
22	**Water Transport**							
23	Distance	50	km	**Carbon Tax**				
24	Pipeline System Construction Cost	1	M$ / km	Specific Carbon Tax	N/A	$ / ton		
25	Pumping Power	0	MWe	Specific CO2e Emission	N/A	tons / MWh		
26	O&M Cost	7	% of scc					
27								

Figure 58: Summary of the performance and cost results – Main input parameters

	A	B	C	D	E	F	G	H
28				**Performance Results**				Close
29								
30	Lost Electricity Production	N/A	MW	Power-to-Heat Ratio	N/A	MWe/MWt		
31	Plant Thermal Utilization	N/A	%					
32								
33	**Distillation Performance**			**RO Performance**				
34	# of Effects/Stages	N/A						
35	GOR	N/A		Recovery Ratio	0.42			
36	Temperature Range	N/A	°C	Permeate Flow	100,000	m^3/d		
37	Distillate Flow	N/A	m^3/d	Feed Flow	240,000	m^3/d		
38	Feed Flow	N/A	m^3/d	Feed Pressure	51.1	bar		
39	Steam Flow	N/A	kg / s	Product Quality	352	ppm		
40	Brine Flow	N/A	m^3/d	Brine Flow	140,000	m^3/d		
41	Brine salinity	N/A	ppm	Brine Salinity	60,000	ppm		
42	Specific Heat Consumption	N/A	kWh / m^3	Specific Power Consumption	2.77	kWh / m^3		
43								
44				**Cost Results**				Close
45								
46	**Specific Power Costs**			**Specific Water Costs**				
47	Fixed charge	N/A	$ / kWh	Fixed charge	0.278	$\$ / m^3$		
48	Fuel cost	N/A	$ / kWh	Heat cost	N/A	$\$ / m^3$		
49	O&M cost	N/A	$ / kWh	Plant electricity cost	0.000	$\$ / m^3$		
50	Decommissioning cost	N/A	$ / kWh	Purchased electricity	0.033	$\$ / m^3$		
51	Total carbon cost	N/A	$/kWh	O&M cost	0.175	$\$ / m^3$		
52	Levelized Electricity Cost	N/A	$ / kWh	Water production cost	0.536	$\$/m^3$		
53				Water transport cost	0.131	$\$/m^3$		
54				Total Specific Water Cost	0.667	$\$ / m^3$		
55								

Figure 59: Summary of the performance and cost results

C. Energy Recovery INC. (ERI)

Over the years engineers investigated a number of possibilities to reduce the energy demand of a reverse osmosis process. The major breakthrough was made with the pressure recovery systems. Pressure recovery was used in the RO process, but it did not have a great influence due to the low efficiencies.

In 1992 a company named Energy Recovery, Inc. (ERI) was established with the goal to reduce energy demands of reverse osmosis systems. They invested in pressure recovery systems and had made a technological breakthrough. The technology makes use of a rotary positive displacement pump (PX) and recovers the energy of the brine water with a staggering 98% efficiency. By applying the PX they have reduced the desalination cost by more than half the cost without energy recovery.

The company has developed a simulator to illustrate the performance of a reverse osmosis plant with PX recovery components. Note that the software is not for designing purposes and that the figures give in the program are only for the illustration purposes.

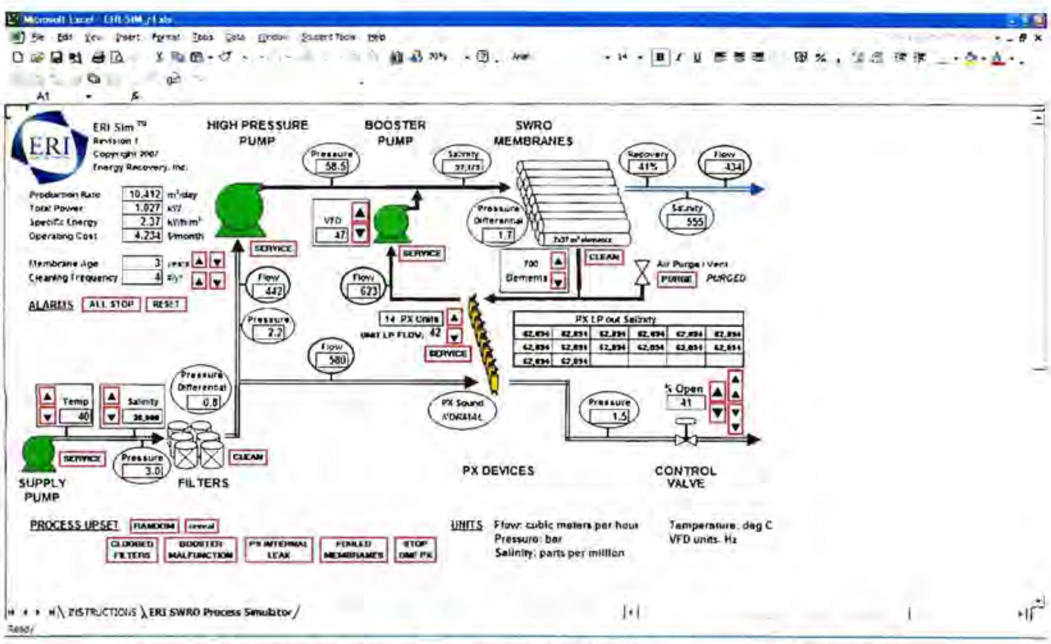

Figure 60: Input window for a Reverse Osmosis element in CamelPro.

Appendix D – RO Flow Configurations[11]

The following paragraph will only provide background on the different flow configurations and will not give design guidelines. Note that the *following* information was obtained from the DOW Chemical Company, 2007.

- Continuous Process
- Batch Process
- Single Element System
- Single Array Multi Element System
- Multi Array System

The Continuous Process:

The continuous process is the most straightforward RO design and is typically used for a continuous production of fresh water. Figure 61 gives a schematic illustration of the Continuous Process. Feed water enters the plant via the high pressure pump and is delivered to the membrane elements where the separation process takes place. There are now two water streams, namely the brine and product water. The product water is normally processed further with chemicals for disinfection and pH stabilization purposes. If the flow rate is small enough the brine stream could be fed into an evaporation pond or else it is returned to the source (i.e. the sea).

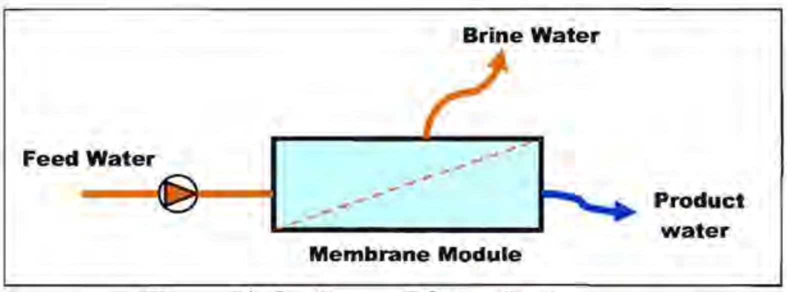

Figure 61: Continuous RO desalination process

The Batch Process:

Figure 62 illustrates the configuration for the Batch System. After the separation process in the membrane module the waste (brine) water is returned to the feed water supply. This layout is normally used where the feed water is unique and the volume is small. During operation, the feed water will become more concentrated and the rate at which the product water is produced will decrease with time. Because of the high concentration build up the membranes are normally cleaned after each batch, reducing the risk of membrane fouling.

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[11] Obtained from THE DOW CHEMICAL COMPANY. 2007. Dow Liquid Separations, Filmtec Reverse Osmosis Membranes, Technical Manual - From No. 609-00071-0705. Page *75-80*

The advantage of the batch process compared the continuous process is:

- A higher recovery of product can be achieved
- The cleaning of the system is simple

However, the disadvantages are:

- Special membranes have to be designed and manufactured for the batch process
- A larger pump is necessary and therefore a higher energy consumption is required
- Product rate decreases over time
- Total running cost is higher

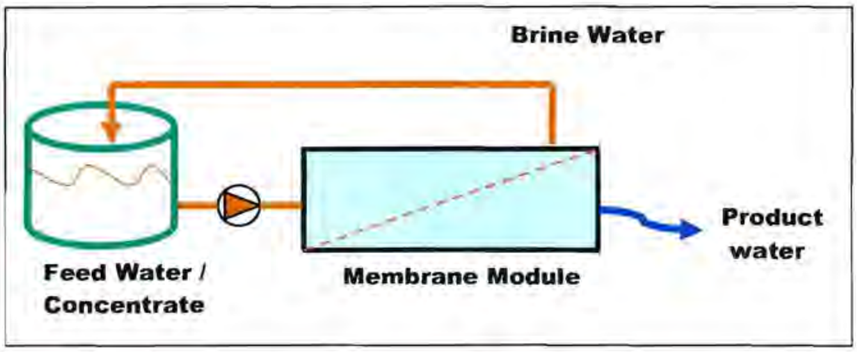

Figure 62: RO Batch Desalination process

Single Element System:

The Single Element System (See Figure 63) consists of a pressure vessel containing as much as 8 membrane elements. These elements are connected in series. The first element waste (brine) becomes the feed water to the second membrane, and so on. As a result the performance of each element differs because of the quality of the feed water it receives. The first element will have the highest recovery ratio and the last element will have the lowest due to the fact that the last membrane will receive feed water with the highest salt concentration. An individual membrane element contributes only a small percentage (± 5%) to the total product water stream.

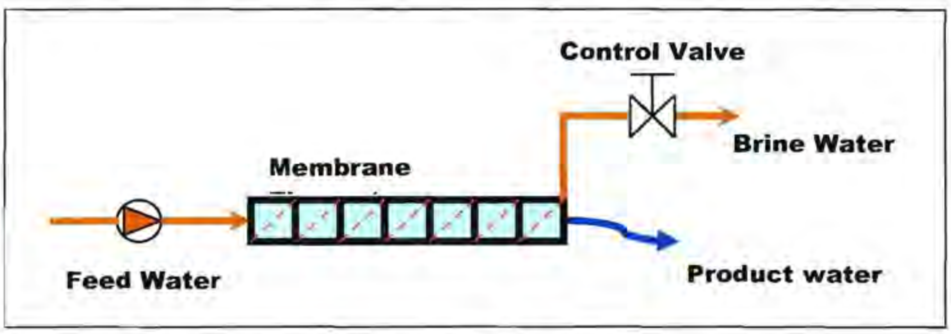

Figure 63: Single RO Membrane Element process

Single Array Multi Element System:

In order to increase the product volume, resulting from a low recovery ratio, a single array Multi-Element (See Figure 64) is often used if the feed water has a higher salt concentration. The pressure vessel and membrane configuration is exactly the same as the Single Element System, but with a number of elements in parallel. A larger pump is required to supply the right amount flow rate to the membranes. In Ashkelon this configuration was used. Three large pumps (5.5 MW) were connected in parallel to supply 16 RO banks with feed water. Note that each bank contains 105 pressure vessels. That is more than 20 000 membrane elements!

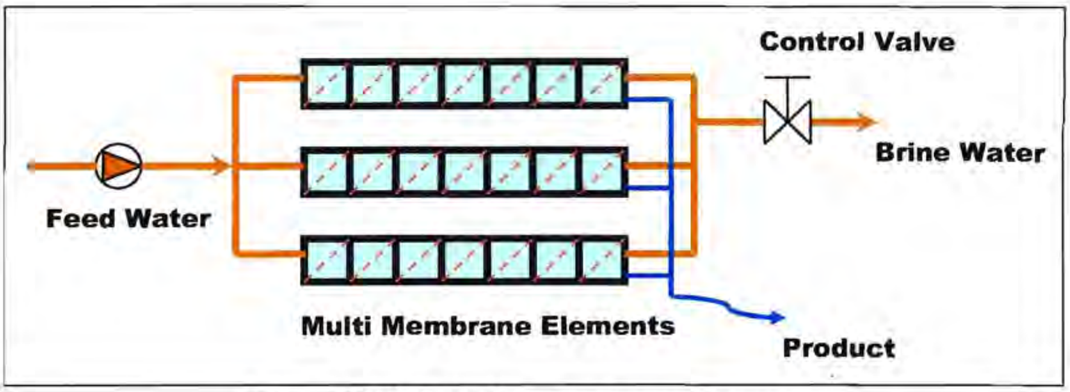

Figure 64: Multi RO Membrane Element process

Multi Array System:

A Multi Array system (See Figure 65) is designed in such a way that the brine water of the first array will be used as the feed water of the second array membranes. Normally a ratio of 2:1 is used between the arrays. The recovery ratio of this design is much higher than the previous layouts and more arrays can be introduced to increase the recovery ratio. On the other hand, the cost will also increase and the optimum point between the cost and performance of this layout should be calculated.

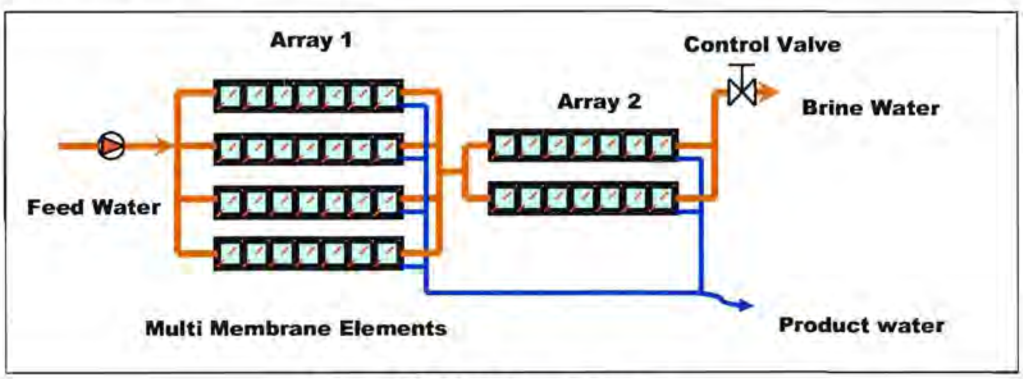

Figure 65: Multi Array RO process