DEVELOPMENT OF A SOLAR POWERED REVERSE OSMOSIS PLANT FOR THE TREATMENT OF BOREHOLE WATER

by

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CONTRACT REPORT TO THE

WATER RESEARCH COMMISSION

by

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WRC REPORT NO 1042/1/01 April 2001

ISBN 1 86845 743 5

EXECUTIVE SUMMARY

Background

The South African Constitution dictates that every South African has the right to have access to potable water. The South Africa government has been especially active in the supply of water to township and rural areas, but the expansion of the electrical grid to supply electricity to all these areas is still lagging behind. Several alternative energy sources are being evaluated in the interim, with diesel, car batteries, LPG and paraffin power being the norm. However, these forms of energy can only be applied for low energy requirements, ie. cooking and lighting requirements or at best, the transport of potable water.

Solar power has become an effective method of supplying low cost energy to those in remote areas. It assists with the development of our country by providing electricity for household appliances, cooking utensils, heated water, etc. to those in need. Further development of solar technology, including the development of applications for solar power, is indeed a challenge for our industries.

The development of reliable solar powered DC borehole pumps has indeed helped with bringing water to people in remote areas. Several small installations, more than often in very remote areas, have made it possible to supply water from active boreholes to animals, farms and people. Unfortunately, the typical areas where the use of boreholes is required for the supply of water, are also those areas with very brackish water – not fit for human consumption.

The next logical step is therefore a water treatment unit, driven by solar power in order to render the water potable.

Reverse Osmosis, a process where an external hydraulic pressure is applied to a concentrated solution thus forcing pure water through a permeable membrane, is a novel technology used to provide purified water to industry and people. The process requires a high energy input for the high pressure feed pumps and has made it difficult to use the alternative energy sources such as those named in the first paragraph. The development and implementation of a solar powered RO unit will not only be of great benefit for communities in rural areas, but is also seen as a cost effective method of supplying potable water from brackish sources in disadvantaged and or remote areas.

The decision was made to develop a pilot demonstration unit to evaluate the feasibility of the combined technologies; as well as the operation, application and commercialisation in the local market.

The concept is relevant to areas where small communities are spread over large areas, where the high cost of erecting large desalination plants and reticulation of desalinated water, or alternatively the piping of fresh water from other sources, is neither practically nor economically viable. The use of solar panels, which generate the power required to drive the RO unit, constitutes an initial capital investment that can be written off over the lifetime of the unit. Results gained from the test runs with the demonstration unit will significantly contribute toward the optimisation of future units and plants of increased capacity.

Objective

The aims of the project may be summarised as follows:

- To design and construct a Reverse Osmosis unit, powered by solar energy, capable of producing potable water from brackish borehole feed, for rural households or small communities.
- To select desalination membranes which will deliver the maximum amount of potable water at the prevailing operating conditions.
- To demonstrate the operation of such a unit by field trials.

Equipment and Site

The following sites were used to conduct tests for the Solar RO unit:

- Weir Envig Laboratory Sites – Paarl
- Eendekuil – Piketberg
- Basjanskloof – Calvinia
- Koperberg – Springbok

The reverse osmosis unit that was used for the pilot tests consisted of the following key equipment:

- *Waterhog* C® submersible borehole pump – solar driven dc
- Two 2 ½" LP Reverse Osmosis membranes
- Permeate and brine flow indicators
- Membrane inlet and outlet pressure gauges
- Back-pressure control valve

Test work

The following test conditions were identified to simulate or evaluate real life conditions:

1. **Variation in location.** The sites were representative of an area where the unit could be applied in future. The areas that were used were Paarl, Piketberg, Springbok and Calvinia.
2. **Variation in feed water conductivity.** The sites had a range of water qualities. Laboratory exercises were required to add additional high conductivity experiments.
3. **Variation in season.** The test runs were completed from autumn to early summer.
4. **Variation in daytime.** The test runs were conducted throughout the day in order to establish a "Time of Day" profile for unit production.

The following parameters were monitored and evaluated as being relevant to the efficient operation of the unit:

- Level of Sunlight
- Feed Conditions of Well Water
- Permeate Product Quality and Capacity
- Brine Effluent Quality and Capacity
- Auxiliary Process Data for Optimised Production

The detail with regards to each of these parameter sets can be viewed in any of the data sheets attached in Appendix C of the full report.

Results

The data realised a *product-per-day* figure that revealed an average production of permeate under different operating conditions.

The Solar RO unit performed well under all the conditions that were evaluated. The unit proved to be easy to operate, very durable, with little maintenance required. Additional operator input did however prove to increase production even though stand-alone operation rendered excellent production figures.

The test work, mainly completed during the winter months, indicated that the unit comfortably produced at 750 l/day with little input from an operator. This is sufficient to supply a full water service to five rural units or meet the drinking water requirements for up to 50 people in a rural setting. It was shown that, in theory, this could be pushed to a maximum of 1350 l/day for a continually optimised unit. This figure would drop to a yearly average of 620 l/day for Paarl taking cognisance of historical rainfall and sunshine figures for this area. Performances for several other areas are estimated in Section 5 of the full report.

The unit proved to be well adapted to a variety of borehole water sources although it must be emphasised that high fouling waters were avoided. The dosing of pre-treatment chemicals was not required and will generally not be necessary under these operating conditions. Before the system is employed, the end user should evaluate his water source to determine his/her specific needs.

The unit showed very little difference in performance at different sites considering the difference in water sources and sunlight conditions. Further tests would be required to optimise the sunlight angle required for maximum performance at a range of sites. It will be in the best interest of the end user to consult a solar power specialist to install the solar panel at an optimal angle for his/her area.

What next?

The success of the unit has made it a very viable consideration for marketing as a saleable product. The end-user will however need to evaluate the following before he/she should purchase this unit:

- Determine the water quantity required per day
- Determine the storage and distribution network available or required to implement this unit
- Determine the quality and quantity of the brackish water source and the integrity of the borehole
- Operate on borehole water only and not on surface waters
- Prepare a pre-treatment system for high fouling waters – a specialist company, such as Membratek (Pty) Ltd., should be approach for such an exercise
- Consult a solar panel specialist, such as Van Heerden Solar Power, to suggest an optimal installation for the solar panels

As a follow on for this project, it is suggested that the unit is exposed to Highveld conditions to evaluate the performance under different sunlight conditions. A range of fouling and non-fouling waters can further be evaluated along with generic or proprietary chemicals as pre-treatment.

ACKNOWLEDGEMENTS

Grateful acknowledgement is given to the WRC for their financial support in the form of project funds without which the project entitled:

Development of a Solar Powered Reverse Osmosis Plant for the Treatment of Borehole Water

would not have been possible.

The author would like to express his sincere thanks to the staff of Weir Envig and Membratek for their support and assistance in the execution of this project as well as the farms Koperberg, Eendekuil and Basjanskloof for their assistance.

Gratitude is extended to Ludwig van Heerden, of Van Heerden Solar Power, for his assistance with the solar powered equipment in this project.

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GLOSSARY

AC	Alternating Current
CIP	Clean in Place – Chemical cleaning of RO membrane
C_F	Conductivity of Feed [μS/cm]
C_P	Conductivity of Permeate [μS/cm]
Cloudy	Cloud cover more than 50% of sky.
DC	Direct Current
F_F	Flow Feed [l/h]
F_P	Flow Permeate [l/h]
Flux	Product flow rate per unit membrane area [l/m^2h]
lmh	l/m^2h (*See* Flux)
LP	Low Pressure
NOC	Normal Operating Condition
Normalised Flux	Permeate production under standard temperature, pressure and feed concentration.
Partly Cloudy	Cloud cover less than 50% of sky but more than 10%.
Passage	Percentage of soluble salts reporting to RO permeate. $\%P = 100\ (1 - SR)$
Permeate	Low conductivity product of RO process
Photovoltaic Effect	Process of converting light into electricity
PPD	Product per Day [litres permeate per day]
PV	Photovoltaic
Recovery	Product as percentage of feed. $\%\ R = 100\ (F_P/\ F_F)$
Retentate	High conductivity effluent of RO process
RO	Reverse Osmosis
Salt Rejection	Percentage of soluble salts reporting to RO retentate. $\%SR = 100\ (1 - C_p/C_F)$
SMBS	Sodium Meta Bisulphite – Cleaning chemical acting as biocide
Solar Panel	An array of one or more Solar Modules linked in series or parallel for voltage addition or current addition respectively.
Sunny	No cloud cover
TDS	Total Dissolved Solids

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1 INTRODUCTION

1.1 Background to Reverse Osmosis and Solar Applications

Reverse Osmosis is extensively applied in the water treatment industry. These applications include both the industrial sector as well as (to a lesser extent) the municipal sector. Reverse osmosis for the production of potable water is still not widely applied despite high feed TDS and low flow rate requirements being the prevailing characteristics for potable applications. The exception is of course the production of potable water from seawater by reverse osmosis, but this has thus far found limited application in South Africa.

Reverse Osmosis has however found use in several small-town areas. Here, the treatment of brackish water, with typically high levels of hardness or Fluoride content, has been favoured by Reverse Osmosis as opposed to Ion Exchange and other technologies. Typically the main water source for such towns is an active borehole or aquifer. Unfortunately, though there is an abundance of boreholes for possible treatment, these sites are often in remote areas with little or no infrastructure to install a reverse osmosis treatment unit.

The South African Constitution dictates that every South African has the right to have access to potable water. The South Africa government has been especially active in the supply of water to township and rural areas, but the expansion of the electrical grid to supply electricity to all these areas is still lagging behind(1). Several alternative energy sources are being evaluated in the interim, with diesel, car batteries, LPG and paraffin power being the norm. However, these forms of energy can only be applied for low energy requirements, ie. cooking and lighting requirements or at best the transport of potable water. These energy resources are however not viable for reverse osmosis systems where high energy requirements from the high pressure feed pumps add severe operating costs to the equation.

For some time one of the most promising and widely applied energy sources has been the use of solar energy. Thus far solar power has, as with diesel, LPG and paraffin, also been applied to mainly cooking and lighting requirements with severe limitations on the size and application of typical cooking utensils. Here solar power is typically combined with wood, LPG, paraffin or diesel to supply refrigeration, cooking and other energy intensive applications.

The development of reliable solar powered DC borehole pumps, has further helped with bringing water to the people. Several small installations, more than often in very remote areas, have made it possible to supply water from active boreholes to animals, farms and people. Unfortunately, the typical areas where the use of boreholes is required for the supply of water, are also those areas with very brackish water – not fit for human consumption.

The next logical step is therefore, a water treatment unit, driven by solar power, to render the water potable.

1.2 Solar RO Trials

The development and implementation of a solar powered RO unit will not only be of great benefit for communities in rural areas; but is also seen as a cost effective method of supplying potable water from brackish sources, in disadvantaged and or remote areas.

The concept is relevant to areas where small communities are spread over large areas, where the high cost of erecting large desalination plants and reticulation of desalinated water, or alternatively, the piping of fresh water from other sources, is neither practically nor economically viable.

The use of solar panels, which generate the power required to drive the RO unit, constitutes an initial capital investment that can be written off over the lifetime of the unit.

Results, gained from the test runs with the demonstration unit, will significantly contribute toward the optimisation of future units and plants of increased capacity.

1.3 Study Objectives

The aims of the project may be summarised as follows:

- To design and construct a Reverse Osmosis unit , powered by solar energy, capable of producing potable water from brackish borehole feed for rural households or small communities.
- To select desalination membranes which will deliver the maximum amount of potable water at the prevailing operating conditions.
- To demonstrate the operation of such a unit by field trials.

1.4 Research Investigations

The research programme was formulated in such a way as to establish a study protocol in order to obtain results and conclusions for each of the project objectives.

The order, or project, execution was as follows:

- Determine Membrane Production Capabilities
- Determine Solar Panel Production Capabilities
- Determine Solar Powered Submersible Pump Capabilities
- Specify Pump, Solar Panels and Membranes
- Design and Construct Pilot Unit
- Laboratory Tests and Optimisation of Unit
- Laboratory Tests – Production vs. Time of Day
- Identify Field Test Sites
- Field Tests – Continuous Unassisted Operation
- Laboratory Tests – Production vs. Conductivity of Feed
- Field Tests – Daily Optimised Operation
- Data Analysis and Conclusions

The field trials included under the research programme included the monitoring and logging of the following process parameters:

- Level of Sunlight
- Feed Conditions of Well Water
- Permeate Product Quality and Production
- Brine Effluent Quality and Production
- Auxiliary Process Data for Optimised Production

The detail with regards to each of these parameter sets can be viewed in any of the data sheets attached in Appendix C.

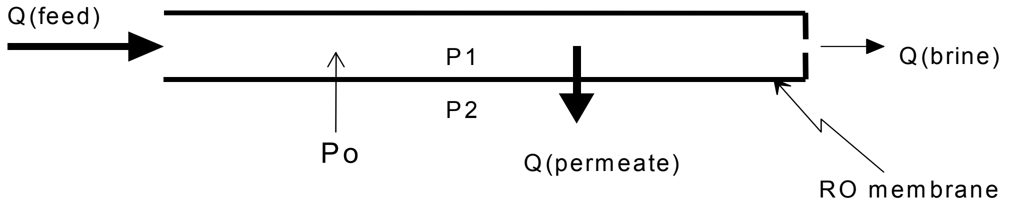
2 LITERATURE SURVEY

2.1 Reverse Osmosis

The heart of any osmotic process is a semi-permeable membrane that separates a strong solution and a dilute solution of salts. Under natural circumstances (such as in the roots of plants) pure water from the dilute solution will permeate through the membrane to dilute the concentrated solution, while the membrane acts as an impermeable barrier to salts. The higher the concentration differential across the membrane, the higher the tendency for water to permeate to the concentrated solution. This hydraulic force is called the osmotic pressure of the system. Osmotic pressures can be high, ie. sea water has an osmotic pressure of about 24.5 bar, while the cell sap of a certain plant (*atriplex confertifolia*) has an osmotic pressure in the order of 150 bar.

In the reverse osmosis process, an external hydraulic pressure is applied to the concentrated solution, thus forcing pure water through the membrane against the osmotic pressure of the system. This external pressure obviously needs to be higher than the osmotic pressure. Figure 2.1.1 illustrates the basic principle of an RO process.

Figure 2.1.1: A Schematic Description of the Reverse Osmosis Process



Po = Osmotic pressure of feed water
P1 = Inlet pressure (after high pressure pump)
P2 = Pressure in permeate stream

P1-P2-Po = Effective pressure driving force

Recovery = 100 x Q(permeate)/Q(feed)

2.1.1 Reverse Osmosis Systems

Four basic types of RO module designs are in commercial use: tubular, plate and frame, spiral wound, and hollow fibre modules.

Below is a set of comparisons(2) between the four basic module designs. Comparing their energy requirements, one will immediately conclude that spiral reverse osmosis is the required module type to link with a solar powered water supply.

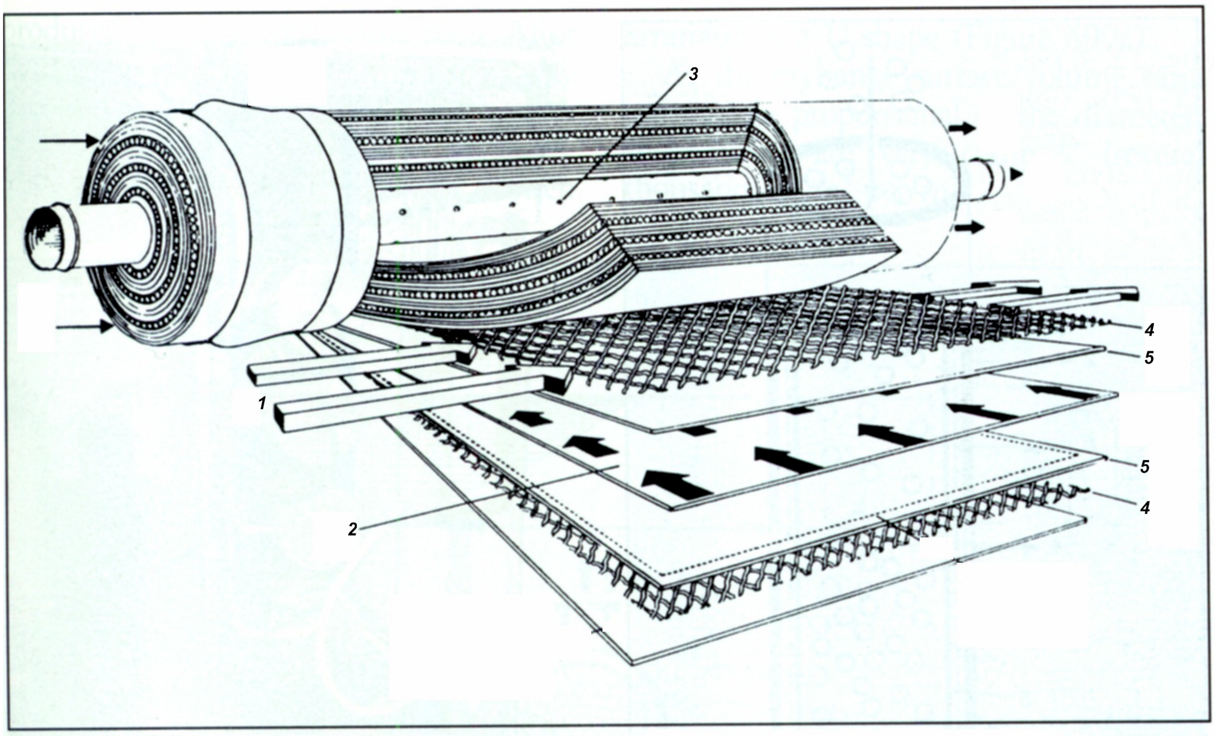
Table 2.1.1: Comparison of Reverse Osmosis Types

CRITERIA	ORDER OF COMPARISON
System Costs	**Tubular, Plate & Frame >> Hollow Fibre, Spiral**
Flexibility in Design	Spiral >> Hollow Fibre > Plate & Frame > Tubular
Cleaning Behaviour	Plate & Frame > Tubular > Spiral > Hollow Fibre
Space Requirements	Tubular > Plate & Frame > Spiral > Hollow Fibre
Susceptibility to Fouling	Hollow Fibre >> Spiral > Plate & Frame > Tubular
Energy Requirement	Tubular > Plate & Frame > Hollow Fibre > Spiral

2.1.2 Spiral Reverse Osmosis Membranes

The construction of a spiral wound reverse osmosis membrane element is schematically shown in Figure 2.1.2.

Figure 2.1.2: A Typical Reverse Osmosis Membrane



1 – Direction of flow of raw water.
2 – Direction of flow of permeate.
3 – Holes collecting the permeate.
4 – Spacer.
5 – Membrane.

The design of the spiral wound elements is such that it contains two layers of membrane glued back-to-back onto a permeate collector fabric (permeate channel spacer) in order to form an envelope. This membrane envelope is wrapped around a perforated tube into which the permeate empties from the permeate channel spacer. Plastic netting is wound into the device, and maintains the feed stream channel spacing. It also promotes turbulence of the feed stream to prevent concentration polarisation.

2.1.3 Factors Influencing Reverse Osmosis Performance

Permeate flux and salt rejection are the key performance parameters of a reverse osmosis process. They are mainly influenced by variable parameters as indicated in the table below. The effect on both flux and passage is also indicated(2).

Table 2.1.2: Factors Influencing Reverse Osmosis Performance

INCREASING	PERMEATE FLOW	SALT PASSAGE
Effective Pressure	Increase	Decrease
Temperature	Increase	Increase
Recovery	Decrease	Increase
Feed Salt Concentration	Decrease	Increase

2.2 Solar Energy

There are a variety of technologies that have been developed to take advantage of solar energy. These include:

- Photovoltaic (solar cell) systems: Producing electricity directly from sunlight.
- Concentrating solar systems: Using the sun's heat to produce electricity.
- Passive solar heating and daylighting: Using solar energy to heat and light buildings.
- Solar hot water: Heating water with solar energy.
- Solar process heat and space heating and cooling: Industrial and commercial uses of the sun's heat.

2.2.1 Photovoltaic Cells

Photovoltaic (PV) cells, the solar cells typically applied to power calculators and watches, convert sunlight directly into electricity. These cells are made of semi-conducting materials similar to those used in computer chips. When these materials absorb sunlight, the solar energy release electrons from their atoms, allowing the electrons to flow through the material to produce electricity. This process of converting light (photons) to electricity (voltage) is called the photovoltaic effect.

PV cells are typically combined into modules that hold many cells; two or more of these modules are mounted in PV arrays that can measure up to several meters on a side. These flat-plate PV arrays can be mounted at a fixed angle facing north, or they can be mounted on a tracking device that follows the sun, allowing them to capture the most sunlight over the course of a day. About 2 to 3 PV arrays can provide enough power to run a borehole pump; and even more for a large electric utility or industrial application.

Some PV cells are designed to operate with concentrated sunlight. These cells are built into concentrating collectors that use a lens to focus the sunlight onto the cells. This approach has both advantages and disadvantages compared with flat-plate PV arrays. The main idea is to use very little of the expensive semi-conducting PV material while collecting as much sunlight as possible. But because the lenses must be pointed at the sun, the use of concentrating collectors is limited to the sunniest parts of the country. Some concentrating collectors are designed to be mounted on simple tracking devices, but most require sophisticated tracking devices, which further limit their use for electric utilities, industries and large buildings.

The performance of a PV cell is measured in terms of its efficiency at turning sunlight into electricity. Only sunlight of certain energy will work efficiently to create electricity, and much of it is reflected or absorbed by the material that make up the cell. Because of this, a typical commercial PV cell has an efficiency of 15% – about one-sixth of the sunlight striking the cell generates electricity. Low efficiencies mean that larger arrays are needed, resulting in higher costs. Improving PV cell efficiencies, while holding down the cost per cell, is an important goal of the PV industry and they have made significant progress. The first PV cells, built in the 1950s, had efficiencies of less than 4%.

2.3 Domestic Water Requirements

Historical and projected household water consumption figures have been collected at some municipalities since early nineteen hundreds. Reports by the Department of Community Development, the Department of National Housing, the WRC and the CSIR have contributed to determine average domestic water requirements per capita.

Van Duuren (3) list the following as design guidelines for domestic water requirements:

Table 2.3.1: Domestic Water Requirements

AREA AND CATEGORY	**PER CAPITA REQUIREMENT *(litre/capita.day)***	
Urban Areas	*Minimum*	*Maximum*
Upper	200	300
Middle	100	200
Lower	50	100
Rural Areas		
Drinking, cooking, personal hygiene	15	50
Drinking water for an adult	3	10
Communal Taps (400m)	20	40
Stand Pipes (200 m)	30	50
Private Connections	100	
Full Services	150	

Van Duuren continues to summarise[1] the *South African water Quality Guidelines* with the important physical factors being:

Electrical Conductivity	0 – 700 µS/cm
TDS	0 – 450 mg/l
pH	6.0 – 9.0
Turbidity	0 – 1 NTU

See Appendix A for a full list of parameters.

2.4 Climate

South Africa enjoys a wide and varied climate with respect to rainfall and sunshine. Appendix I show diagrams that summarise the daily rainfall and sunshine averages for several towns at the outskirts of the country.(7) These figures are the average from 1961 to 1990.

Note the low sunshine average for the far eastern parts of the country while towns like Upington and Windhoek enjoy long hours of sunshine all year round. Capetown, with its winter rainfall season, has quite a significant loss in sunshine hours during the winter while the low rainfall for Upington further maintains long sunshine hours even through their rainy season.

The average sunshine hours for South Africa range between 8 and 9.5 hours per day from winter to summer.

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[1] See Appendix A

3 EXPERIMENTAL EQUIPMENT AND SITE

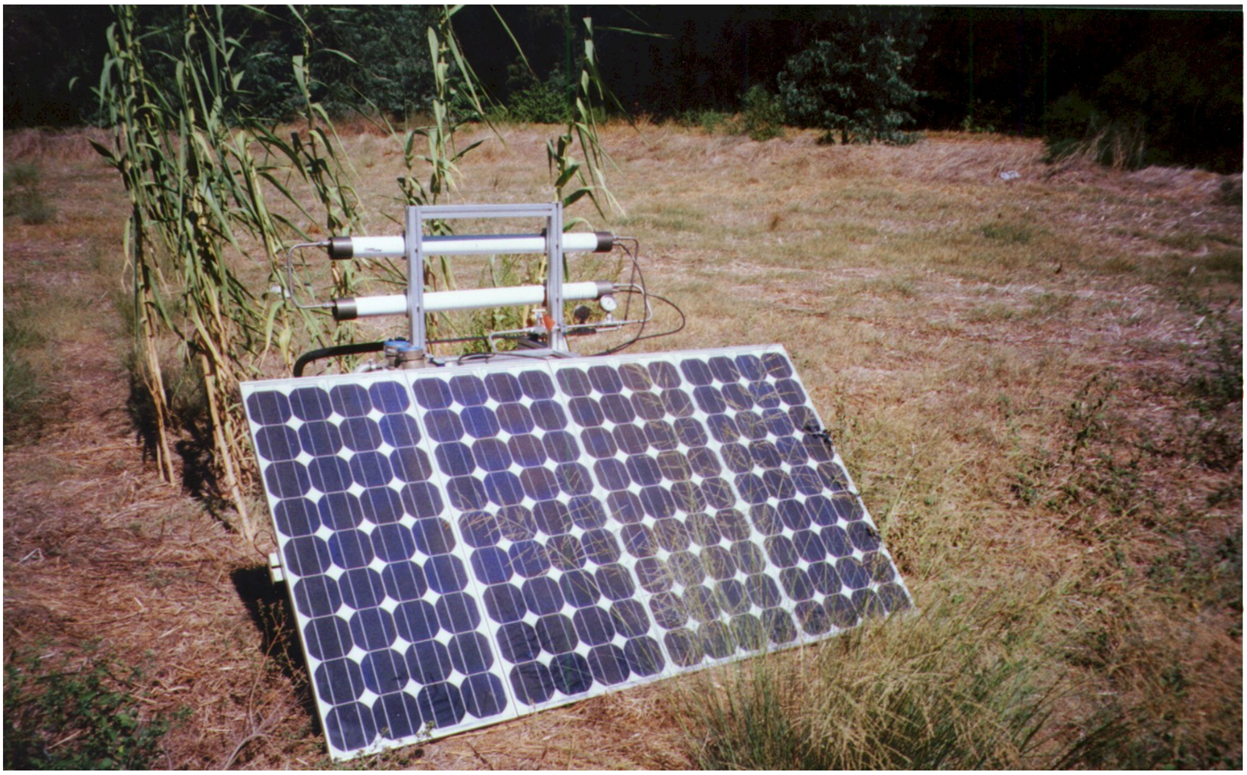
3.1 Reverse Osmosis Unit

The reverse osmosis unit that was used for the pilot tests consisted of the following equipment:

- *Waterhog* C® submersible borehole pump – solar driven dc
- Pressure release valve
- 10” cotton wound 5 μ cartridge filter
- Two 2 ½” membrane pressure vessels
- Two 2 ½” LP membranes
- Permeate flow indicator
- Brine flow indicator
- Membrane inlet pressure gauge
- Membrane outlet pressure gauge
- Backpressure control valve
- Piping
- Portable pH and conductivity meters

The construction of the test unit is depicted in the photo below. Note the light aluminium frame as well as the compact nature of the design. The overall (boxed) dimensions of the unit is (L x W x H) 1300 x 600 x 600 mm.

Figure 3.1.1: Photo of Solar RO Unit



The following specifications are relevant to the LP membranes used for the Solar RO unit:

Table 3.1.1: 2 ½" LP Membrane Specifications[2]

CHARACTERISTIC	SPECIFICATION
Model No	FLU 2540 LP
Length	40"
Diameter	2 ½"
Flow (min / nom / max)	100 / 118 / 139 l/h
Rejection (min / nom)	98% / 99%

3.2 Solar Unit

3.2.1 Solar Panels

The solar power supply consisted of a solar panel consisting of three Siemens Solar *ProCharger*® JF Solar Electric Modules. The following specifications apply to the modules used:

Table 3.2.1: Solar Module Specifications[3]

CHARACTERISTIC	SPECIFICATION
New Model Number	SP75
Configuration	12V
Rated Power (P_{max})	75 W
Min Power (P_{min})	70 W
Open Circuit Voltage (V_{oc})	21.7 V
Short Circuit Current (I_{sc})	4.8 A
Voltage as Load	17 V
Current at Load	4.4 A

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[2] Membratek Product Bulletin; 689 kPa @ 25°C; pH = 7.0 ±0.5; 15% Recovery

[3] "Rated electrical characteristics are within 10% of measured values at Standard Test Conditions of: 1000 W/m^2, 25°C cell temperature and solar spectral irradiance per ASTM E 892." Siemens Installation Guide Supplement

Current at NOC	3.5 A
Cell Type	Mono
Max System V_{oc}	600 V
Length	1200 mm
Width	527 mm
Depth	34 mm
Weight	7.6 kg

3.2.2 Solar Driven Pump

Solastar(9) list the following fundamental design requirements for the operation of a solar water pumping system to render it durable, cost effective and affordable:

- High / low head flexibility
- Low long-term maintenance cost and long maintenance intervals
- High generic efficiency (power in/water out)
- A low starting torque requirement
- The system must run without batteries and invertors
- The pump should run "dry " without damage
- Generous warranty period
- High generic efficiency in conditions of deep submersion
- Low time/skill/cost required for installation

In light of the above, the project team purchased the solar powered pump from the *WaterHog*® series supplemented by a *Pumpmaster*® power converter. The *Pumpmaster*® was developed to accommodate DC submersible pumps giving maximum brush life and efficiency. They are high quality state-of-the-art DC power converters designed to interface photovoltaic arrays with DC motors. The primary functions[4] of the converter are to:

- *"Boost the current of the PV array to match the requirements of the load."*
- *"Hold the voltage of the PV array constant, approximately around its maximum power point."*
- *"In performing the above functions the water outputs increase by no less than 30% per day under all load and light conditions."*

Table 3.2.2 summarise the pump performance under various NOCs.

Assuming a peak production of 7.5 hours per day, the maximum feed flow conditions would range between 180 l/h at 150 m to 316 l/h at 100 m total operating head. This would render the membrane flux between 15 and 30 lmh under NOC.

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[4] WaterHog® product brochure.

Table 3.2.2: Pump Performance[5]

TOTAL HEAD	LITRES / DAY (3 PANEL SYSTEM)
100 m	2372
110 m	2166
120 m	1962
130 m	1758
140 m	1554
150 m	1350

3.3 Experimental Site Preparation and Arrangement

3.3.1 Preparation Before Going to Site

The following sites were used to conduct tests for the Solar RO unit:

- Weir Envig Laboratory Sites – Paarl
- Eendekuil – Piketberg
- Basjanskloof – Calvinia
- Koperberg – Springbok

The typical site preparation consisted of pre-sampling[6] the borehole and to analyse at least the following:

- TDS / Conductivity
- pH
- Total Hardness
- M - Alkalinity
- Iron
- Silica

In addition to these, analyses also included Ca^{2+}, Mg^{2+}, Na^{+}, Cl^{-}, SO_4^{2-}, Mn^{2+} and F^{-}. The results were used to run RO projection software to determine scaling potential and maximum operating recovery.

The sites that offered representative water analyses (typical TDS for the area), without causing problems with high scaling potential, were used to evaluate the solar unit. The objective of the study was not to evaluate the performance of several membranes and anti-scalant chemicals, but to rather identify a good representative membrane that could operate under a variety of

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[5] These are maximum figures obtained with radiation levels of 1000 Watt/m^2 using 75 W modules. WaterHog® product brochure

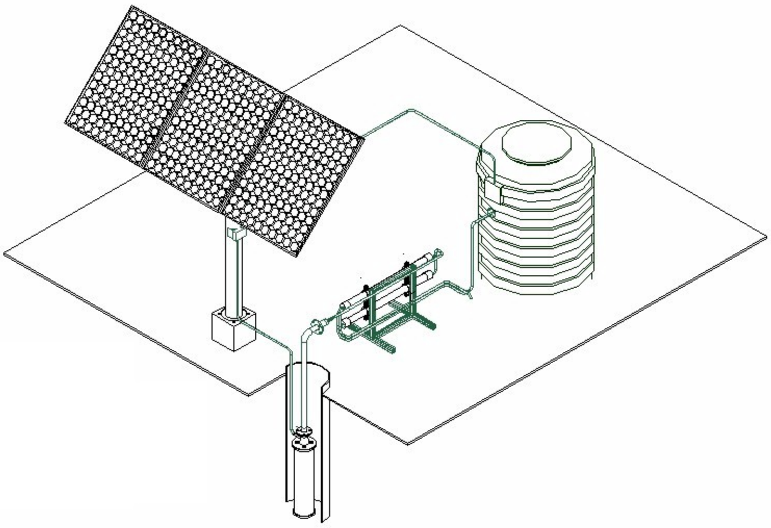
[6] Results in Appendix B

conditions. The end user of the Solar RO system will have to identify the scaling potential of his/her water by independent analyses and decide whether anti-scalant chemicals or other forms of chemical treatment will be required to increase production or stabilise the product water.

3.3.2 Preparation on Site

Figure 3.3.1 is a graphical representation of the typical site arrangement.

Figure 3.3.1: Typical Site Arrangement



The procedure for site preparation included the following:

1. **Setting up of the solar panel to maximise the angle with the sun.** The knowledge of the locals was used to identify the sun's track in the specific season. The solar panel was fixed such that it was sturdy and not able to be moved by wind or other factors. The panel was erected at an optimum angle to maximise sunlight on the panel. Attention was given to safety when using large equipment and electrical components.
2. **Submersing of the solar driven diaphragm pump.** A safety rope was connected to the solar pump before it was released inside a large diameter pipe into the borehole. Boreholes with precarious walls and surface bases were avoided for safety reasons as well as to prevent the loss of equipment. Care was given not to disturb the well walls and thereby introducing unnecessary turbidity to the water.
3. **Connection of the solar driven pump with the power supply.** The pump was tested prior to connection with the membrane system to optimise the *Pumpmaster*® power control settings. Care was taken to ensure that no open wires, which may cause damage to persons or equipment, were visible.

4. **Connection of the RO plant to the water supply.** The submersible pump was connected to the membrane plant with flexible polypropylene agricultural hose. A pressure release valve, set at 10 bar was installed upstream of the cartridge filter to protect the pump diaphragm from overpressure while maintaining the system within the cartridge filter housing's pressure rating.
5. **Startup of the RO plant.** The system was started with the backpressure control valve fully open to minimise recovery. The valve was slowly closed in order to reach the predetermined recovery setting for the water.
6. **Monitoring of the unit.** All the system parameters were continually monitored to optimise the production conditions. Certain tests were run at one "fixed" setting to determine production capacity under stand-alone conditions without operator intervention.

3.4 Operation and Test Conditions

The following parameters were monitored and evaluated as being relevant to the efficient operation of the unit:

- Level of Sunlight
- Feed Conditions of Well Water
- Permeate Product Quality and Production
- Brine Effluent Quality and Production
- Auxiliary Process Data for Optimised Production

The detail with regards to each of these parameter sets can be viewed in any of the data sheets attached in Appendix C.

The following test conditions were identified to simulate or evaluate real life conditions:

5. **Variation in location.** The sites were representative of an area where the unit could be applied in future. The areas that were used were Paarl, Piketberg, Springbok and Calvinia.
6. **Variation in feed water conductivity.** The sites had a range of water qualities. Laboratory exercises were required to add additional high conductivity experiments.
7. **Variation in season.** The test runs were completed from autumn to early summer.
8. **Variation in daytime.** The test runs were conducted throughout the day in order to establish a "Time of Day" profile for unit production.

The data realised a *product-per-day* figure that revealed an average production of permeate under different operating conditions.

4 DISCUSSION OF DATA

The test data, as well as summaries of the average test data and the respective graphs are added in Appendices C to G.

4.1 Continuous Operation

The first official test[7] that was conducted was a continuous run at Springbok. The unit was prepared and set-up to be operated by the farm employees. Data was taken on a daily base with the daily production calculated from the flow meter totaliser.

Initially the unit was optimised for permeate flow to enable the unit to be operated on a stand-alone basis. The unit produced approximately 1200 litres of permeate per day at a recovery of 45%. The unit was then left to operate on its own, with little intervention by the operator on a daily basis. The average results for the 10 weeks is summarised in Table 4.3.1.

Table 4.1.1: Summary of Springbok Test Data

LOCATION	DATE	AVG. FEED CONDUCTIVITY	TOTAL RECOVERY	AVG. FLUX	PPD
		(μS/cm)	%	*(lmh)*	*(l/day)*
Springbok	March – May 99	632	23	7	727

The overall low recovery can be attributed to the obvious lack of optimisation as well as a few days with very low flow due to cloudy/rainy conditions. It is clear from this data that theoretically the unit should have been able to produce up to 1350 l/day at a recovery of 45%. The unit therefore does require some input in order for it to produce at maximum levels.

Figure 4.1.1 show all the data for daily production and recovery. Note that this flow is the average for 24 hours and should therefore be multiplied in order to determine the PPD for each data point.

It is clear that the unit production decreased as time went on. The decrease can be contributed to the reduction in sunlight quantity and strength as the winter approached and more over-cast days were experienced. In addition to this, the decrease in ambient temperature further contributed to the reduction in recovery. It was realised during this experiment, that the membranes were experiencing fouling conditions owing to the low crossflow velocities early and late in the day.

The data points for the cloudy days are easily identified among the rest of the data.

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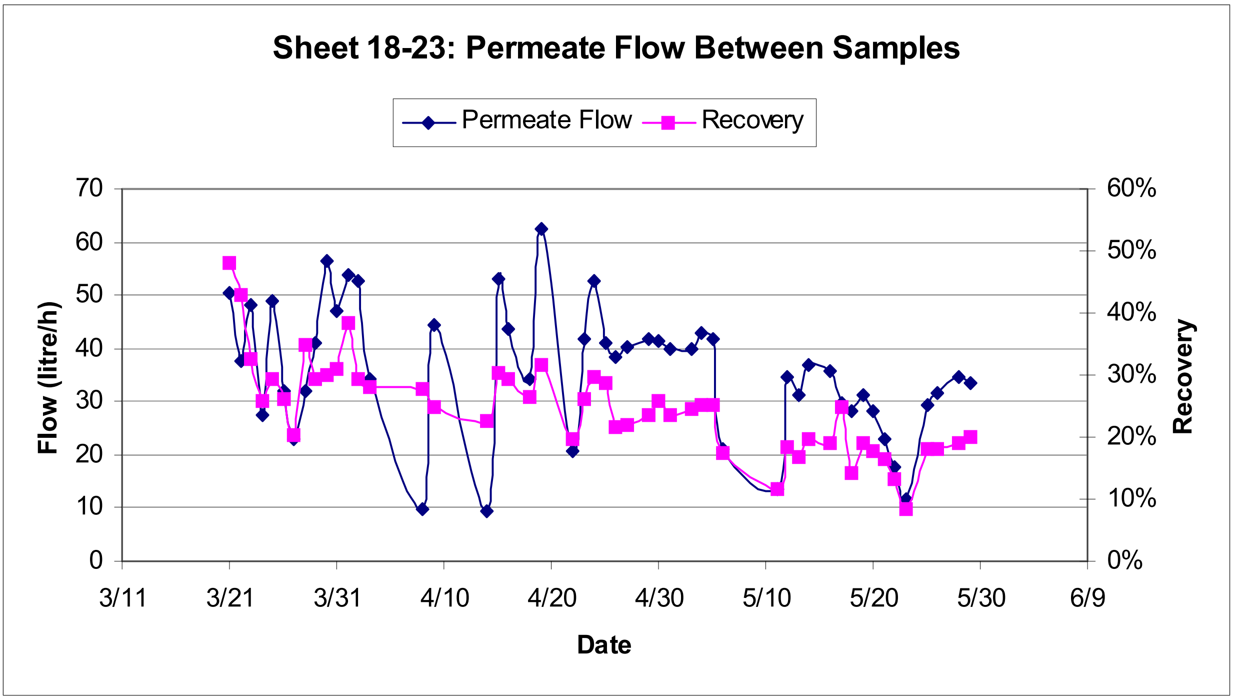
[7] No data was captured for the preliminary preparation tests due to the fact that these were done under continually varying conditions in order to develop a “feel” for the unit.

Figure 4.1.1: Average Flow per Day - Springbok



4.2 Laboratory Tests

All the laboratory tests were conducted at the Weir Envig laboratories in Paarl. The feed water was prepared from RO water (< 20 µS/cm) and sodium chloride. The salt was added to reach a predetermined feed water conductivity while continuously being stirred for proper dilution. The averaged results for each of the individual test days are summarised in Table 4.2.1.

The June tests were done to prepare TOD profiles for increasing conductivity. The results show that the initial increase in conductivity resulted in an equivalent loss in recovery. Attempts to optimise the unit during the second test led to erratic pressure changes and therefore inconsistent results.

The third day was very cloudy and the unit only managed to operate during the peak sunshine hours of the day with the help of continuous adjustment by the operator to realise maximum production under the prevailing conditions.

The next few days were used to determine the reproducibility of the results under similar conditions. Although there was some cloud covering throughout these days, it was usually no more than 10% of the sky. The temperature was approximately 18°C during this time and the water was prepared at a conductivity of 1400 µS/cm.

The results show excellent reproducibility. Little adjustment of the process set-up was allowed during these days and this is clear from the graphs in Appendix C. These graphs were also the first indication that the solar unit production was more in the late afternoon than in the early morning, with the expected peak from around 13:00 – 14:00. Unfortunately, due to manpower issues, it was not possible to run the system to exhaustion towards the end of the day and most tests were completed around 17:00.

Additional data points, in the form of measuring the “immediate recovery” at the time of data sampling, were introduced in order to ascertain the consistency of the recovery between data points. The closer the immediate value is to the value between samples, the more consistent the process is performing and less changes is required. The results from this data did show that there was a fair amount of consistency between the corresponding data points but there was always room for improvement of the overall recovery setting.

The results for the three days showed an average recovery of 34% with just over 700 l/day produced. The last day, with the biggest indication of fluctuating recoveries, was also the lowest producing of the three days, although within 12% from the average. It is important to again emphasise that the unit was switched off at the end of the day to simulate the prevention of low cross-flow conditions. Further test work will be needed to determine the exact advantage or disadvantage to operate the unit at low cross-flow conditions.

Table 4.2.1: Summary of Laboratory Test Data

LOCATION	**DATE**	**AVG. FEED CONDUCTIVITY**	**TOTAL RECOVERY**	**AVG. FLUX**	**PPD**
		(µS/cm)	%	*(lmh)*	*(l/day)*
Paarl	1-Jun-99	953	47	35	856
Paarl	3-Jun-99	1305	44	22	681
Paarl	4-Jun-99	1232	52	25	301
Paarl	7-Jun-99	1451	38	26	790
Paarl	8-Jun-99	1427	33	26	717
Paarl	9-Jun-99	1446	31	25	624
Paarl	16-Aug-99	1099	35	22	211
Paarl	28-Oct-99	4984	40	20	379
Paarl	1-Nov-99	3116	45	28	602
Paarl	2-Nov-99	7231	38	18	654
Paarl	3-Nov-99	4373	44	20	573

The test in August was done in preparation for the second site visit at Piketberg. The system was operated under fairly conservative conditions and performed well considering the low level of sunlight during August.

The final batches of tests were run in November with the sunlight level increasing daily. All these tests were run at high conductivity as an epilogue to the visit in Piketberg. Conditions for the third field tests were also known and simulated in the laboratory.

The October test was done on a 5000 µS/cm prepared sample with clear spring conditions prevailing. The flux was good for the high conductivity of the feed water and a respectable PPD of 339 l/d was achieved. This value, very conservative for the day due to time loss in the early parts of the day, is felt to be representative for October in Paarl and was therefore not corrected for time loss.

The November tests were done with 3100 to 7200 µS/cm prepared water. The increase in operating pressures due to the increase in osmotic pressure is clear from the data with the associated loss in recovery. Although the PPD is very similar, the actual l/h production is more indicative of the performance of the unit.

4.3 Field Tests

The first field test completed at Springbok was discussed above under Section 4.1. The second field test, completed at Piketberg, was done in the middle of the winter in the Cape.

The results for Eendekuil were promising for winter conditions, since most of the day was used for production and a very realistic 354 l/d was achieved. The recovery for the unit was 37%, within the limit of the projected maximum water recovery.

Table 4.3.1: Summary of Field Test Data

LOCATION	DATE	AVG. FEED CONDUCTIVITY	TOTAL RECOVERY	AVG. FLUX	PPD
		(µS/cm)	%	*(lmh)*	*(l/day)*
Eendekuil	18-Aug-99	5239	37	15	354
Basjanskloof	9-Nov-99	3037	25	9	461
Basjanskloof	10-Nov-99	3810	34	11	569
Basjanskloof	12-Nov-99	3348	45	15	418

The final field test was done in Calvinia where three boreholes of similar nature were tested. The borehole characteristics were as follow:

- Borehole A 8.57 pH 3140µS/cm
- Borehole E: 7.93 pH 3840µS/cm
- Borehole F: 7.3 pH 3380µS/cm

Boreholes B, C and D had a conductivity of less than 750µS/cm and was not included in the test programme.

The boreholes were all fairly deep (±30m) with the resulting head loss realising significant recovery loss. The last day was run from a concrete tank due to silt problems in the borehole. The operator did reduce the pressure to simulate values for the borehole but the increases temperature of the tank allowed for a somewhat optimistic water recovery to be reported.

The data from Borehole E was collected over the full day with the unit started by dawn and switch off at dusk. The results are therefore truly representative of a typical real life installation and clearly indicate that the typical test values for produce per day are conservative up to 20%.

4.4 Operability and Maintenance

The unit proved to be durable and could easily stand up to abuse. It was transported often, at the back of a bakkie, travelling on rough terrain. The unit was fairly easy to set up, with initial manpower required for the solar panels. Although these panels are not to heavy, they are quite large and one does need assistance during site preparation. The RO unit itself is comfortably handled by two people and showed no signs of wear and tear.

The solar pump had the roughest time of all being dropped and pulled from borehole to borehole. The pump showed exemplary performance throughout the project even though it started looking fairly scruffy by the end of the project. The only problem that was experienced with any of the equipment was the pump's start switch. The box was not sealed properly and it got wet in the rain. When the unit was used again after some weeks of storage, all the circuitry tracks were corroded and needed to be replaced.

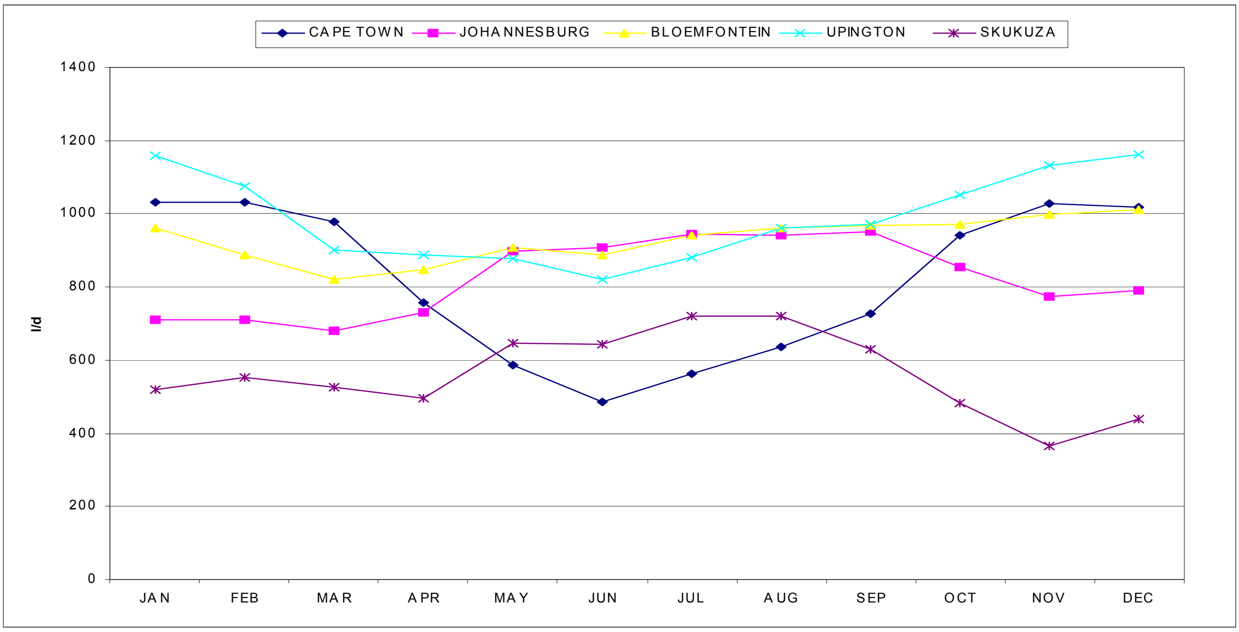
The RO membranes performed well throughout the project. Care was taken not to over commit the membranes under high recovery conditions and in this way fouling was minimised. The only time that flux loss was noticed was during the continuous operation at Springbok but the extent was unfortunately not noted. A CIP once back at the laboratory returned conditions to normal.

The membranes, when not in use for extended periods of time, were stored with a dilute SMBS solution.

5 GUIDELINES FOR APPLICATION

A guideline for the application of the Solar RO unit was developed to enable the sizing of a unit required in a certain area. The graph below represents a summary of this guideline.

Figure 5.1: Guideline for the Application of the RO System



The normalised flux data captured during all the trail runs, as well as knowledge of the prevailing weather and sunlight conditions enable one to estimate the proposed production capability of a unit. The graph was specifically developed for a two-membrane system, with a total surface area of 4.8 m^2 treating water with a conductivity of 5000 μS/cm. Furthermore, the system consisted of three solar modules required for the power supply.

Variations of the Solar RO unit configuration with regards to pump size and number of membranes is possible. This unit is however a good combination and multiple units should first be considered.

The level of operator input available should also be considered when sizing the system. Recovery can be increased by 50% for a twice-daily visit compared to a once weekly visit.

6 CONCLUSIONS

The Solar RO unit performed well under all the conditions that were evaluated. The unit proved to be easy to operate, very durable, with little maintenance required. Additional operator input did however prove to increase production even though stand-alone operation rendered excellent production figures.

The test work, mainly completed during the winter months, indicated that the unit comfortably produced at 750 l/day with little input from an operator. This is sufficient to supply a full water service to five rural units or meet the drinking water requirements for up to 50 people in a rural setting. It was shown that in theory this could be pushed to a maximum 1350 l/day for a continually optimised unit. This figure would drop to a yearly average of 620 l/day for Paarl taking cognisance of historical rainfall and sunshine figures for this area. Performances for several other areas are estimated in Section 5.

The unit proved to be well adapted to a variety of borehole water sources although it must be emphasised that high fouling waters were avoided. The dosing of a pre-treatment chemicals were not required and will generally not be necessary under these operating conditions. Before the system is employed, the end user should evaluate his water source to determine his/her specific needs.

The unit showed very little difference in performance at different sites considering the difference in water sources and sunlight conditions. Further test would be required to optimise the sunlight angle required for maximum performance at a range of sites. It will be in the best interest of the end user to consult a solar power specialist to install the solar panel at an optimal angle for his/her area.

7 RECOMMENDATIONS

The success of the unit has made it a very viable consideration for marketing as a saleable product. The end-user will however need to evaluate the following before he/she should purchase this unit:

- Determine the water quantity required per day
- Determine the storage and distribution network available or required to implement this unit
- Determine the quality and quantity of the water source and the integrity of the borehole
- Operate on borehole water only and not on surface waters
- Prepare a pre-treatment system for high fouling waters – a specialist company such as Membratek (Pty) Ltd. should be approached for such an exercise
- Consult a solar panel specialist such as Van Heerden Solar Power to suggest an optimal installation for the solar panels

As a follow on for this project, it is suggested that the unit is exposed to Highveld conditions to evaluate the performance under different sunlight conditions. A range of fouling and non-fouling waters can further be evaluated along with generic or proprietary chemicals as pre-treatment.

8 REFERENCES

Literature:

1) Hochmuth F, Demand and Market Potential for Photovoltaic Solar Home Systems in South Africa, 1997 (Renewable Energy Consultant)
2) Dow Liquid Separations, Filmtec Membranes, Technical Manual, 1999
3) Van Duuren FA (Editor), Water Purification Works Design, Water Research Commission, 1997
4) Fourie HO, An Estimation of the Health Implications of Chemical Contaminants in Food and Water – A Total Diet ("Market Basket") Study; Faculty of Medicine, University of Cape Town, WRC Report 173/1/89
5) Implementation Resource Directed Measures for Protection of Water Resources - Water Resources Protection Policy; Department of Water Affairs and Forestry, South Africa; Groundwater Component Version 1.0. September 1999
6) Goodall J and Phil M. Process Water Purification; RO techniques and Economics. Filtration and Separation, Vol 14, No 6. pp 649 – 654

Web-Sites:

7) South African Weather Bureau http://www.sawb.gov.za/
8) Climate Prediction Centre http://www.cpc.ncep.noaa.gov/
9) BP Solarex http://www.solarex.com/
10) Solastar http://www.divwatt.co.za/
11) Renewable Energy for Rural African Households http://home.global.co.za/~ren-ener/www_refah.html
12) South African National Energy Association (SANEA) http://mbendi.co.za/sanea/energy.htm#alt

Brochures:

13) Fluid Systems Membranes
14) Siemens Solar Electric Modules
15) WaterHog DC Submersible Solar Driven Pumps

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Appendix A

Summary of Water Quality Guidelines for Domestic Use(3)

WATER QUALITY CONSTITUENT	WATER QUALITY GUIDELINES FOR DOMESTIC USE
Physical and organoleptic properties	
• Electrical Conductivity	0 – 70 mS/m 0 – 450 mg/l TDS
• Odour	TON[8] = 1
• PH	6.0 – 9.0
• Turbidity	0 – 1 [9]NTU
Physico-chemical constituents	
• Aluminium	0 – 0.15 mg/l
• Dissolved Organic Carbon	0 – 5 mg/l C
• Fluoride	0 – 1.0 mg/l
• Iron	0 – 0.1 mg/l
• Manganese	0 – 0.05 mg/l
• Mercury Heavy Metals	0 – 0.005 mg/l
• Nitrate and Nitrite	0 – 6 mg/l
Biological and microbiological constituents	
• Algae	0 – 5 mg/l chlorophyll a
• Coliphages	< 1 per 100 ml
• Enteric viruses	< 1 TCID[10]$_{50}$/ 10 l
• Faecal coliforms / *E. coli*	0 per 100 ml
• Protozoan parasites	V 1 *Cardia* cyst/10 l

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[8] TON Total odour number

[9] NTU Nephelometric Turbidity Unit

[10] TCID$_{50}$ Tissue culture infective doses

Appendix B

Results from Water Analyses

ELEMENT	SPRINGBOK	CALVINIA	EENDEKUIL	
			WELL A	WELL B
Potassium as K mg/l	7,1			
Sodium as Na mg/L	577			
Calcium as Ca mg/L	360	169	57	52
Magnesium as Mg mg/L	165	38	26	19
Ammonia as N mg/L	0,10			
Sulphate as SO_4 mg/L	636	333	45	45
Chloride as Cl mg/L	1445			
Alkalinity as $CaCO_3$ mg/L	117		331	335
Nitrate + Nitrate -N mg/L	0,19			
Phosphate as P mg/L	<0,1			
Iron as Fe mg/L	0,05	<0.05	<0.05	0.19
Manganese as Mn mg/L	<0,05			
Zinc as Zn mg/L	<0,03			
Fluoride as F mg/L	2,9			
Conductivity mS/m 25°C	540	380	74	74
pH (Lab)	7,1		7.9	8.1
pHs (20 deg C)	7,0		7.3	7.4
Total Dissolved Solids (Calc) mg/L	3456	2432	474	474
Total Hardness as $CaCO_3$ mg/L	1579		249	209

Appendix C

Test Data

SOLAR RO Test sheet

Weir Envig Laboratory **1000 µS/cm** **01-Jun-99** **Sheet No: 1**

☐ Time:		10:30	11:10	11:45	12:35	13:00	14:00	15:00	16:00		Average
☐ Sunlight		Sunny	Sunny	Sunny	Sunny	Sunny	Sunny	Sunny	Sunny		All
FEED											
☐ Feed Temperature	°C	17.1	17	17.8	17.7	18.9	19.4	20.5	20.9		**19**
☐ Feed pH	pH	8.8	7.61	7.82	7.71	7.74	7.65	7.55	7.12		
☐ Feed Conductivity	µS/cm	400	1015	1024	1019	1025	1083	1019	1039		**953**
☐ Immediate Feed Flowrate	l/h										
☐ Feed Flowrate between Samples	l/h		116	312	319	512	446	267	418		**342**
PERMEATE PRODUCT											
☐ Permeate pH	pH	6.17	8.19	8.42	7.69	8.2	8.12	7.81	7.52		
☐ Permeate Conductivity	µS/cm	180.5	23.7	15.16	21.4	14.22	14.3	26.3	22.4		**40**
☐ Permeate Watermeter Reading	m3	0.4637	0.5258	0.6153	0.7517	0.8485	1.0926	1.1519	1.3198		
☐ Permeate Water Produced	m3		0.0621	0.0895	0.1364	0.0968	0.2441	0.0593	0.1679		
☐ Permeate Flowrate	s/l										
☐ Immediate Permeate Flowrate	l/h										
☐ Permeate Flowrate between Samples	l/h		93	215	164	232	244	59	168		**168**
BRINE WASTE											
☐ Brine Conductivity	µS/cm	500	1988	1624	1922	1656	1678	1697	2010		
☐ Brine Watermeter Reading	m3	0.9267	0.9419	0.9824	1.1122	1.2288	1.4304	1.6385	1.8889		
☐ Brine Water to Waste	m3		0.0152	0.0405	0.1298	0.1166	0.2016	0.2081	0.2504		
☐ Brine Flowrate	s/l										
☐ Immediate Brine Flowrate	l/h										
☐ Brine Flowrate between Samples	l/h		23	97	156	280	202	208	250		
PROCESS DATA											
☐ Inlet Pressure	kPa	200	950	1040	1075	990	950	875	855		**867**
☐ Outlet Pressure	kPa	200	950	1025	1075	975	925	850	850		
☐ Membrane Pressure Drop	kPa	0	0	15	0	15	25	25	5		**11**
☐ Salt Rejection	%	54.9%	97.7%	98.5%	97.9%	98.6%	98.7%	97.4%	97.8%		**93%**
☐ Immediate Recovery	%										
☐ Recovery between samples	%		80.3%	68.8%	51.2%	45.4%	54.8%	22.2%	40.1%		**52%**
☐ Flux	lmh		19	45	34	48	51	12	35		**35**
☐ Normalised Flux	lmh		21	44	32	48	52	13	38		
COMMENTS		Solar Panel 80%								Produce per day:	
		covered by light								856 litre	
			10 min							Total Recovery:	
			downtime							47%	
			40	25	50	25	60	60	60		

SOLAR RO Test sheet

Weir Envig Laboratory **1300 µS/cm** **03-Jun-99** **Sheet No: 2**

☐ Time:		10:30	11:30	12:30	13:30	14:30	15:30	16:00	16:30	17:00	**Average**
☐ Sunlight		Sunny	Sunny	Sunny	Sunny	Sunny	Sunny	Sunny	Sunny	Sunny	All
FEED											
☐ Feed Temperature	°C	18.2	18.4	18.9	19.3	20.7	20.9	21	21.1	21.3	20
☐ Feed pH	pH	7.15	7.25	7.37	7.2	7.26	7.25	7.22	7.27	7.33	
☐ Feed Conductivity	µS/cm	1240	1146	1115	1319	1248	1226	1292	1315	1843	1306
☐ Immediate Feed Flowrate	l/h										
☐ Feed Flowrate between Samples	l/h		91	174	167	646	61	299	260	234	242
PERMEATE PRODUCT											
☐ Permeate pH	pH	6.52	7.26	7.36	7.18	7.36	6.82	6.92	7.19	7.61	
☐ Permeate Conductivity	µS/cm	872	126.8	34.8	17.22	24.1	24.2	21.7	25.62	33.4	131
☐ Permeate Watermeter Reading	m3	1.405	1.4444	1.5211	1.6099	1.8664	1.9059	1.9674	2.0292	2.0859	
☐ Permeate Water Produced	m3		0.0394	0.0767	0.0888	0.2565	0.0395	0.0615	0.0618	0.0567	
☐ Permeate Flowrate	s/l										
☐ Immediate Permeate Flowrate	l/h										
☐ Permeate Flowrate between Samples	l/h		39	77	89	257	39	123	124	113	108
BRINE WASTE											
☐ Brine Conductivity	µS/cm	1300	2150	2250	2240	1625	1878	2030	2120	2050	
☐ Brine Watermeter Reading	m3	1.8095	1.8616	1.9589	2.0375	2.4266	2.4486	2.5367	2.6047	2.665	
☐ Brine Water to Waste	m3		0.0521	0.0973	0.0786	0.3891	0.0220	0.0881	0.0680	0.0603	
☐ Brine Flowrate	s/l										
☐ Immediate Brine Flowrate	l/h										
☐ Brine Flowrate between Samples	l/h		52	97	79	389	22	176	136	121	
PROCESS DATA											
☐ Inlet Pressure	kPa	150	910	930	1000	300	550	470	705	365	598
☐ Outlet Pressure	kPa	145	905	920	975	295	545	450	700	360	
☐ Membrane Pressure Drop	kPa	5	5	10	25	5	5	20	5	5	9
☐ Salt Rejection	%	29.7%	88.9%	96.9%	98.7%	98.1%	98.0%	98.3%	98.1%	98.2%	89%
☐ Immediate Recovery	%										
☐ Recovery between samples	%		43.1%	44.1%	53.0%	39.7%	64.2%	41.1%	47.6%	48.5%	48%
☐ Flux	lmh		8	16	19	53	8	26	26	24	22
☐ Normalised Flux	lmh		9	17	18	175	14	52	34	62	
COMMENTS										Produce per day:	
										681 litre	
										Total Recovery:	
										44%	
			60	60	60	60	60	30	30	30	

SOLAR RO Test sheet

Weir Envig Laboratory **1200 µS/cm** **04-Jun-99** **Sheet No: 3**

☐ Time:		13:30	14:00	14:30	15:00	15:30	16:00				Average
☐ Sunlight		Cloudy	Cloudy	Cloudy	Cloudy	Cloudy	Cloudy				All
FEED											
☐ Feed Temperature	°C	18.8	19.2	19.3	19.3	19.4	19.6				19
☐ Feed pH	pH	6.85	6.59	6.6	6.83	6.71	6.52				
☐ Feed Conductivity	µS/cm	1234	1223	1341	1047	1279	1265				1232
☐ Immediate Feed Flowrate	l/h	126	157	255	138	294	251				
☐ Feed Flowrate between Samples	l/h		135	250	244	230	292				230
PERMEATE PRODUCT											
☐ Permeate pH	pH	6.18	6.3	5.97	6.45	5.91	6.02				
☐ Permeate Conductivity	µS/cm	223	52.8	44.3	22.2	28.4	21.8				65
☐ Permeate Watermeter Reading	m3	2.0915	2.1322	2.2179	2.2785	2.3256	2.3924				
☐ Permeate Water Produced	m3		0.0407	0.0857	0.0606	0.0471	0.0668				
☐ Permeate Flowrate	s/l	53	49	31	40	24	26				
☐ Immediate Permeate Flowrate	l/h	68	73	116	90	150	138				
☐ Permeate Flowrate between Samples	l/h		81	171	121	94	134				120
BRINE WASTE											
☐ Brine Conductivity	µS/cm	1445	2830	2190	1868	2236	1898				
☐ Brine Watermeter Reading	m3	2.6876	2.7144	2.7538	2.8151	2.8832	2.9625				
☐ Brine Water to Waste	m3		0.0268	0.0394	0.0613	0.0681	0.0793				
☐ Brine Flowrate	s/l	62	43	26	75	25	32				
☐ Immediate Brine Flowrate	l/h	58	84	138	48	144	113				
☐ Brine Flowrate between Samples	l/h		54	79	123	136	159				
PROCESS DATA											
☐ Inlet Pressure	kPa	445	550	950	350	955	700				658
☐ Outlet Pressure	kPa	440	545	945	345	950	695				
☐ Membrane Pressure Drop	kPa	5	5	5	5	5	5				5
☐ Salt Rejection	%	81.9%	95.7%	96.7%	97.9%	97.8%	98.3%				95%
☐ Immediate Recovery	%	53.9%	46.7%	45.6%	65.2%	51.0%	55.2%				
☐ Recovery between samples	%		60.3%	68.5%	49.7%	40.9%	45.7%				53%
☐ Flux	lmh		17	36	25	20	28				25
☐ Normalised Flux	lmh		31	37	73	20	39				
COMMENTS										Produce per day:	
										301 litre	
										Total Recovery:	
										52%	
			30	30	30	30	30				

SOLAR RO Test sheet

Weir Envig Laboratory **1400 μS/cm** **07-Jun-99** **Sheet No: 4**

☐ Time:		10:30	11:00	12:00	13:30	14:00	15:00	15:30	16:00	16:30	Average
☐ Sunlight		90% clear	90% clear	90% clear	90% clear	90% clear	90% clear	90% clear	90% clear	90% clear	All
FEED											
☐ Feed Temperature	°C	17.1	17.3	17.8	19.1	19.4	20	20.1	20.2	20.3	19
☐ Feed pH	pH		5.42	5.25	5.89	5.82	5.57	5.85	5.86	5.93	
☐ Feed Conductivity	μS/cm		1475	1461	1464	1437	1420	1491	1483	1373	1451
☐ Immediate Feed Flowrate	l/h		448	407	390	369	356	338	314	288	
☐ Feed Flowrate between Samples	l/h		282	358	388	403	327	394	286	296	342
PERMEATE PRODUCT											
☐ Permeate pH	pH	5.24	5.48	5.44	5.38	5.88	5.49	5.5	5.74		
☐ Permeate Conductivity	μS/cm		24.1	14.34	24.3	31.1	32.2	29.7	37.6	31.7	28
☐ Permeate Watermeter Reading	m3	2.4032	2.4147	2.5323	2.7721	2.8513	2.9968	3.0739	3.1333	3.1929	
☐ Permeate Water Produced	m3		0.0115	0.1176	0.2398	0.0792	0.1455	0.0771	0.0594	0.0596	
☐ Permeate Flowrate	s/l		41	24	24	25	25	26	29	34	
☐ Immediate Permeate Flowrate	l/h		88	150	150	144	144	138	124	106	
☐ Permeate Flowrate between Samples	l/h		23	118	160	158	146	154	119	119	125
BRINE WASTE											
☐ Brine Conductivity	μS/cm		1851	2230	2180	2240	2150	2260	2330	1887	
☐ Brine Watermeter Reading	m3	2.9827	3.1123	3.3531	3.6958	3.8179	3.9998	4.1199	4.2033	4.2919	
☐ Brine Water to Waste	m3		0.1296	0.2408	0.3427	0.1221	0.1819	0.1201	0.0834	0.0886	
☐ Brine Flowrate	s/l	57	10	14	15	16	17	18	19	20	
☐ Immediate Brine Flowrate	l/h	63	360	257	240	225	212	200	189	180	
☐ Brine Flowrate between Samples	l/h		259	241	228	244	182	240	167	177	
PROCESS DATA											
☐ Inlet Pressure	kPa	30	600	900	890	890	880	820	775	640	714
☐ Outlet Pressure	kPa	25	575	875	865	865	855	800	750	620	
☐ Membrane Pressure Drop	kPa	5	25	25	25	25	25	20	25	20	22
☐ Salt Rejection	%		98.4%	99.0%	98.3%	97.8%	97.7%	98.0%	97.5%	97.7%	98%
☐ Immediate Recovery	%		19.6%	36.8%	38.5%	39.0%	40.5%	40.9%	39.6%	37.0%	
☐ Recovery between samples	%		8.2%	32.8%	41.2%	39.3%	44.4%	39.1%	41.6%	40.2%	36%
☐ Flux	lmh		5	25	33	33	30	32	25	25	26
☐ Normalised Flux	lmh		9	28	37	36	33	38	31	37	
COMMENTS										Produce per day:	
										790 litre	
										Total Recovery:	
										38%	
			30	60	90	30	60	30	30	30	

Prepared by Johan Louw

SOLAR RO Test sheet

Weir Envig Laboratory **1400 μS/cm** **08-Jun-99** **Sheet No: 5**

☐ Time:		10:30	11:00	12:00	13:00	14:00	15:00	15:30	16:05	16:30	**Average**
☐ Sunlight		95% clear	95% clear	95% clear	95% clear	95% clear	95% clear	95% clear	95% clear	95% clear	All
FEED											
☐ Feed Temperature	°C	12.7	15.1	15.8	16.5	17.6	18.5	18.6	18.9	19.2	17
☐ Feed pH	pH	6.07	6.16	6.18	6.14	6.05	6.33	6.31	6.35	6.34	
☐ Feed Conductivity	μS/cm	1450	1472	1307	1481	1411	1381	1424	1443	1474	1427
☐ Immediate Feed Flowrate	l/h		446	381	386	386	364	328	304	220	
☐ Feed Flowrate between Samples	l/h		242	110	586	325	428	538	346	264	356
PERMEATE PRODUCT											
☐ Permeate pH	pH		5.88	5.85	5.77	5.86	5.95	6.07	6.11	6.22	
☐ Permeate Conductivity	μS/cm		34.2	20.1	21.6	17.35	27.3	17.67	29.4	21	24
☐ Permeate Watermeter Reading	m3	3.2791	3.2968	3.3389	3.4641	3.6171	3.7379	3.8936	3.9612	3.9961	
☐ Permeate Water Produced	m3		0.0177	0.0421	0.1252	0.1530	0.1208	0.1557	0.0676	0.0349	
☐ Permeate Flowrate	s/l		42	29	28	28	29	31	39	74	
☐ Immediate Permeate Flowrate	l/h		86	124	129	129	124	116	92	49	
☐ Permeate Flowrate between Samples	l/h		35	42	125	153	121	311	116	84	123
BRINE WASTE											
☐ Brine Conductivity	μS/cm	1472	1801	2000	2140	2090	2170	2100	2010	2100	
☐ Brine Watermeter Reading	m3	4.3	4.4033	4.47095	4.9322	5.1037	5.4104	5.5238	5.6579	5.733	
☐ Brine Water to Waste	m3		0.1033	0.0677	0.4613	0.1715	0.3067	0.1134	0.1341	0.0751	
☐ Brine Flowrate	s/l	62	10	14	14	14	15	17	17	21	
☐ Immediate Brine Flowrate	l/h	58	360	257	257	257	240	212	212	171	
☐ Brine Flowrate between Samples	l/h		207	68	461	172	307	227	230	180	
PROCESS DATA											
☐ Inlet Pressure	kPa		620	900	890	860	810	760	610	320	721
☐ Outlet Pressure	kPa		610	890	880	850	800	750	600	310	
☐ Membrane Pressure Drop	kPa		10	10	10	10	10	10	10	10	10
☐ Salt Rejection	%		97.7%	98.5%	98.5%	98.8%	98.0%	98.8%	98.0%	98.6%	98%
☐ Immediate Recovery	%		19.2%	32.6%	33.3%	33.3%	34.1%	35.4%	30.4%	22.1%	
☐ Recovery between samples	%		14.6%	38.4%	21.3%	47.1%	28.3%	57.9%	33.5%	31.7%	34%
☐ Flux	lmh		7	9	26	32	25	65	24	17	26
☐ Normalised Flux	lmh		13	11	31	38	31	86	40	56	
COMMENTS										Produce per day: 717 litre Total Recovery: 33%	
			30	60	60	60	60	30	35	25	

Weir Envig Laboratory **Sheet No: 6**

☐ Time:		10:30	12:00	13:00	14:00	14:30	15:00	15:30	16:00	16:30	Average
☐ Sunlight		95% clear	95% clear	95% clear	95% clear	95% clear	95% clear	95% clear	95% clear	95% clear	All
FEED											
☐ Feed Temperature	°C	14.3	16.6	16.9	19.1		Data Not Complete		19.2	19.3	18
☐ Feed pH	pH	6.37	6.43	6.42	6.35		Data Not Complete		6.49		

SOLAR RO Test sheet

Weir Envig Laboratory **1000 μS/cm** **01-Jun-99** **Sheet No: 1**

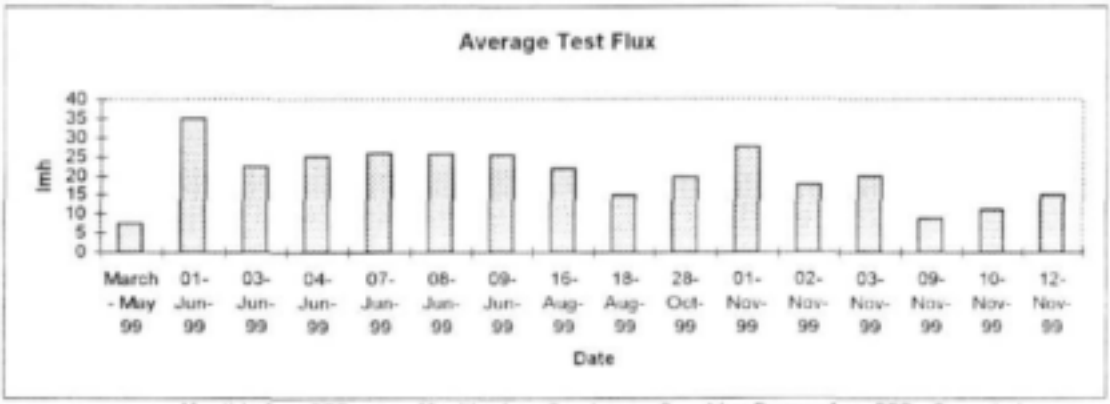
☐ Time:		10:30	11:10	11:45	12:35	13:00	14:00	15:00	16:00		Average
☐ Sunlight		Sunny	Sunny	Sunny	Sunny	Sunny	Sunny	Sunny	Sunny		All
FEED											
☐ Feed Temperature	°C	17.1	17	17.8	17.7	18.9	19.4	20.5	20.9		19
☐ Feed pH	pH	8.8	7.61	7.82	7.71	7.74	7.65	7.55	7.12		
☐ Feed Conductivity	μS/cm	400	1015	1024	1019	1025	1083	1019	1039		953
☐ Immediate Feed Flowrate	l/h										
☐ Feed Flowrate between Samples	l/h		116	312	319	512	446	267	418		342
PERMEATE PRODUCT											
☐ Permeate pH	pH	6.17	8.19	8.42	7.69	8.2	8.12	7.81	7.52		
☐ Permeate Conductivity	μS/cm	180.5	23.7	15.16	21.4	14.22	14.3	26.3	22.4		40
☐ Permeate Watermeter Reading	m3	0.4637	0.5258	0.6153	0.7517	0.8485	1.0926	1.1519	1.3198		
☐ Permeate Water Produced	m3		0.0621	0.0895	0.1364	0.0968	0.2441	0.0593	0.1679		
☐ Permeate Flowrate	s/l										
☐ Immediate Permeate Flowrate	l/h										
☐ Permeate Flowrate between Samples	l/h		93	215	164	232	244	59	168		168
BRINE WASTE											
☐ Brine Conductivity	μS/cm	500	1988	1624	1922	1656	1678	1697	2010		
☐ Brine Watermeter Reading	m3	0.9267	0.9419	0.9824	1.1122	1.2288	1.4304	1.6385	1.8889		
☐ Brine Water to Waste	m3		0.0152	0.0405	0.1298	0.1166	0.2016	0.2081	0.2504		
☐ Brine Flowrate	s/l										
☐ Immediate Brine Flowrate	l/h										
☐ Brine Flowrate between Samples	l/h		23	97	156	280	202	208	250		
PROCESS DATA											
☐ Inlet Pressure	kPa	200	950	1040	1075	990	960	875	855		867
☐ Outlet Pressure	kPa	200	950	1025	1075	975	925	850	850		
☐ Membrane Pressure Drop	kPa	0	0	15	0	15	25	25	5		11
☐ Salt Rejection	%	54.9%	97.7%	98.5%	97.9%	98.6%	98.7%	97.4%	97.8%		93%
☐ Immediate Recovery	%										
☐ Recovery between samples	%		80.3%	68.8%	51.2%	45.4%	54.8%	22.2%	40.1%		52%
☐ Flux	lmh		19	45	34	48	51	12	35		36
☐ Normalised Flux	lmh		21	44	32	48	52	13	38		
COMMENTS		Solar Panel 80%								Produce per day:	
		covered by light								856 litre	
			10 min							Total Recovery:	
			downtime							47%	
			40	25	50	25	60	60	60		

Appendix D

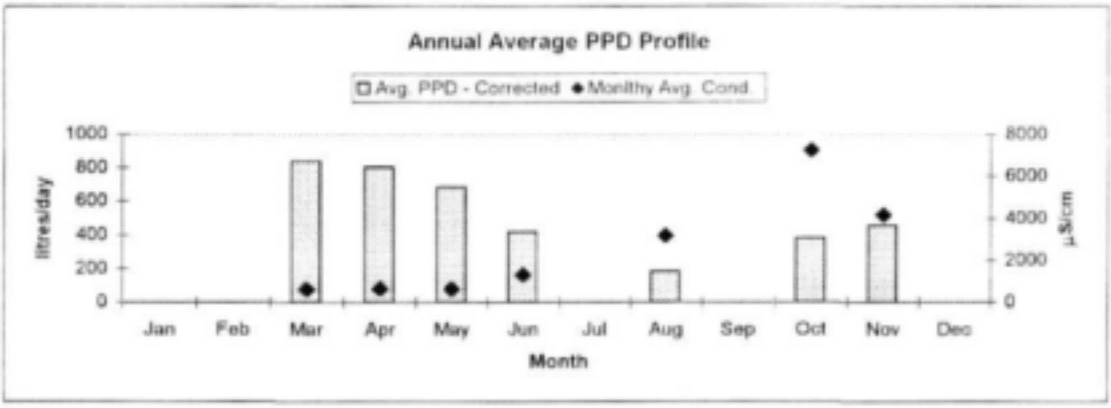
Averaged Test Data

Average Test Values - Chronologicaly Sorted

	Date	Avg. Conductivity (µS/cm)	Avg. Recovery	Avg. Flux (lmh)	PPD (l/day)
Sheet 18-23	March - May 99	632	25%	7	727
Sheet 1	01-Jun-99	953	52%	35	856
Sheet 2	03-Jun-99	1305	48%	22	681
Sheet 3	04-Jun-99	1232	53%	25	301
Sheet 4	07-Jun-99	1451	36%	26	790
Sheet 5	08-Jun-99	1427	34%	26	717
Sheet 6	09-Jun-99	1446	33%	25	624
Sheet 7	16-Aug-99	1099	40%	22	211
Sheet 12	18-Aug-99	5239	37%	15	354
Sheet 8	28-Oct-99	4984	40%	20	379
Sheet 9	01-Nov-99	3116	47%	28	602
Sheet 10	02-Nov-99	7231	40%	18	654
Sheet 11	03-Nov-99	4373	46%	20	573
Sheet 13-14	09-Nov-99	3037	27%	9	461
Sheet 15-16	10-Nov-99	3810	34%	11	569
Sheet 17	12-Nov-99	3348	50%	15	418
Average		**2793**	**40%**	**20**	**557**



	Monthly Avg. PPD (litres/day)	Monithy Avg. Cond. (µS/cm)	Sunshine Days at Test Site	Avg. PPD - Corrected
Jan				
Feb				
Mar	968	615	27	843
Apr	805	648	27	805
May	687	626	28	687
Jun	661	1302	19	419
Jul				
Aug	282	3169	20	182
Sep				
Oct	379	7231	31	379
Nov	546	4153	25	455
Dec				
Average	**618**	2535	25	**539**



Appendix E

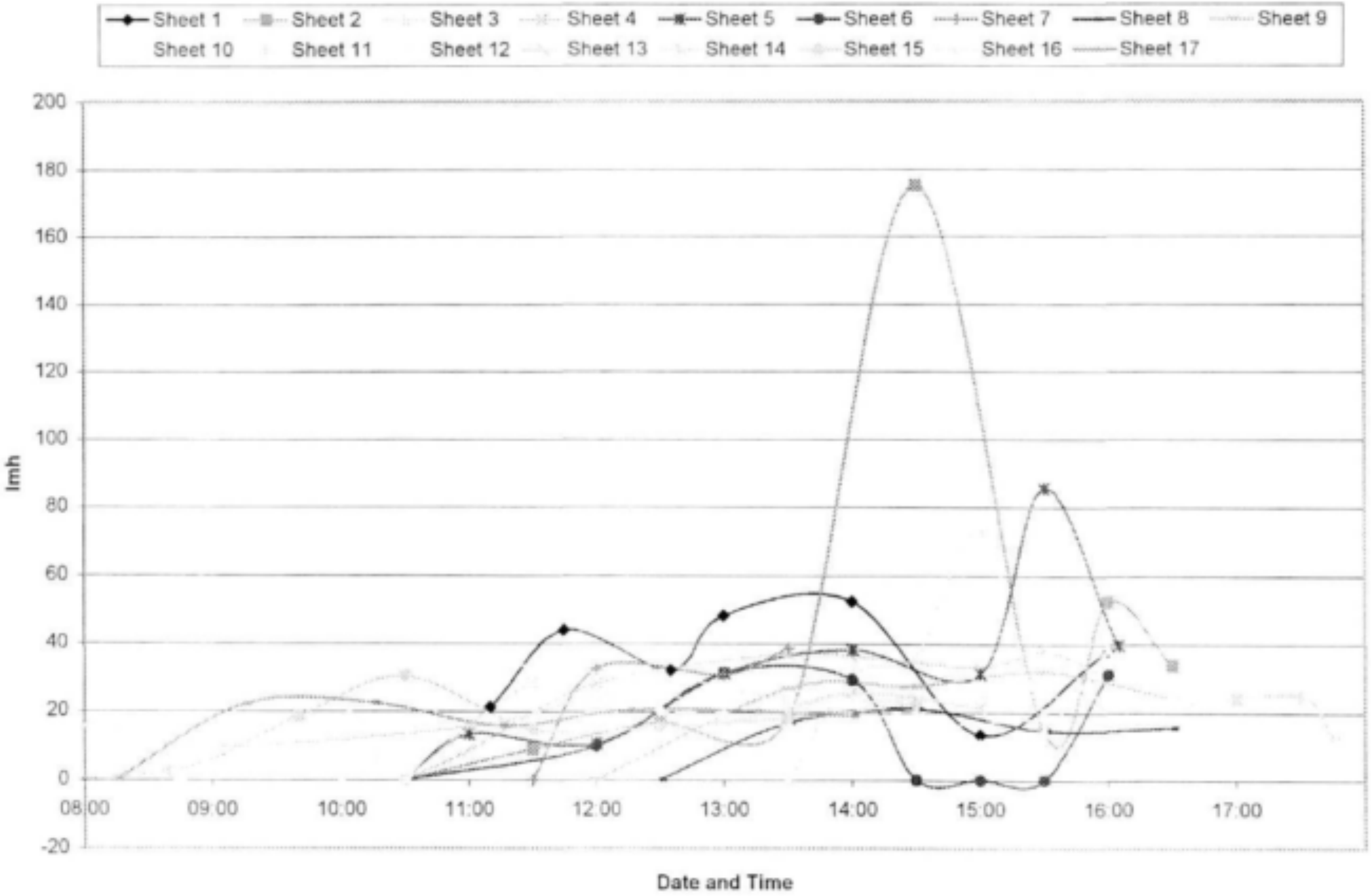
Averaged Normalised Flux Profile

Average Normalised Flux Profile - TOD

All tests excluding Springbok

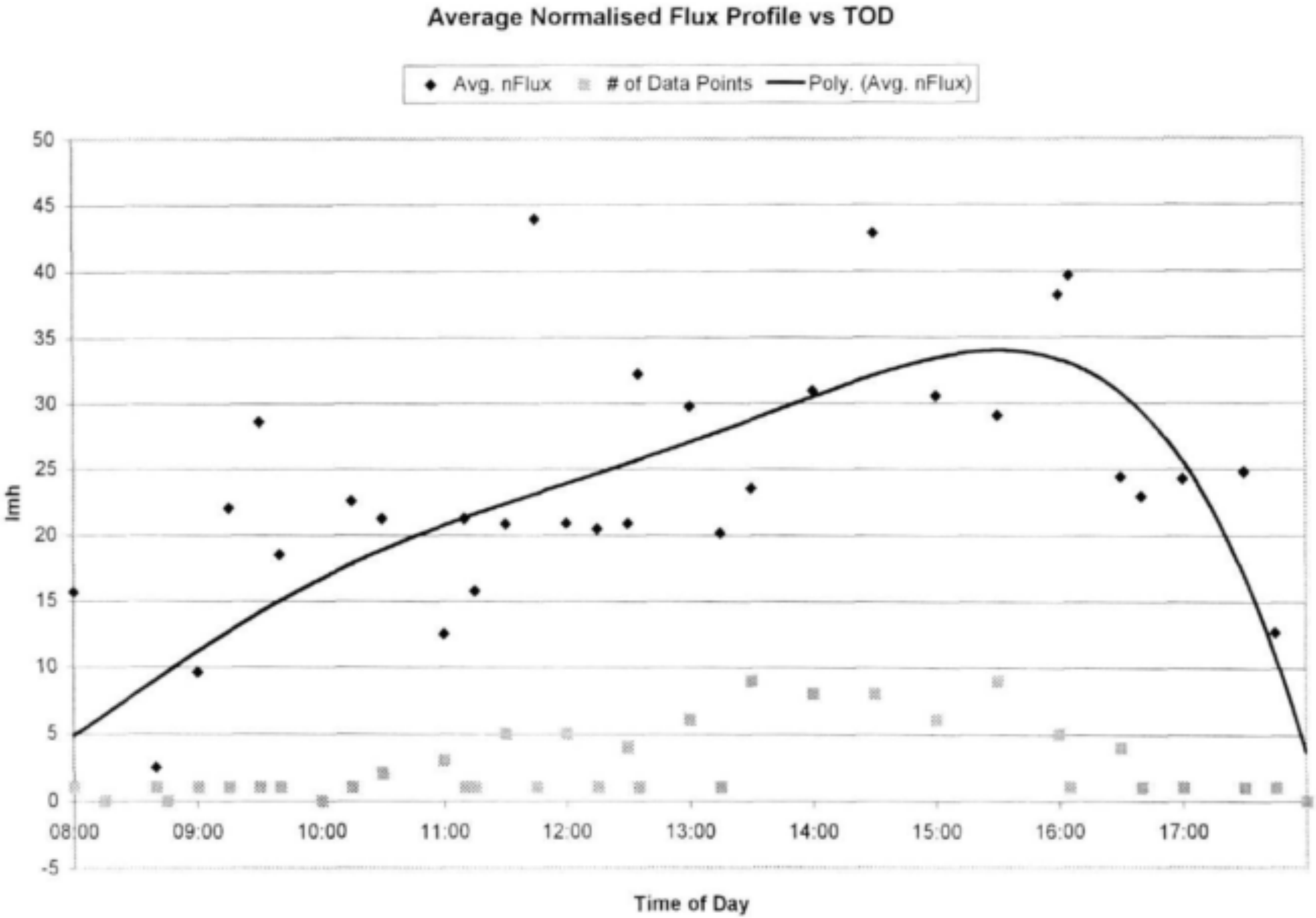
Time	Avg. nFlux	# of Data Points
07:00	0	0
08:00	16	1
08:15	0	0
08:40	2	1
08:45	0	0
09:00	10	1
09:15	22	1
09:30	29	1
09:40	19	1
10:00	0	0
10:15	23	1
10:30	21	2
11:00	13	3
11:10	21	1
11:15	16	1
11:30	21	5
11:45	44	1
12:00	21	5
12:15	20	1
12:30	21	4
12:35	32	1
13:00	30	6
13:15	20	1
13:30	24	9
14:00	31	8
14:30	43	8
15:00	31	6
15:30	29	9
16:00	38	5
16:05	40	1
16:30	24	4
16:40	23	1
17:00	24	1
17:30	25	1
17:45	13	1
18:00	0	0

Normalised Flux vs Time of Day



Appendix F

Summary of Continuous Operation Data


Average Normalised Flux Profile vs TOD
◆ Avg. nFlux
▨ # of Data Points
— Poly. (Avg. nFlux)
lmh
50
45
40
35
30
25
20
15
10
5
0
-5
08:00
09:00
10:00
11:00
12:00
13:00
14:00
15:00
16:00
17:00
Time of Day

Appendix G

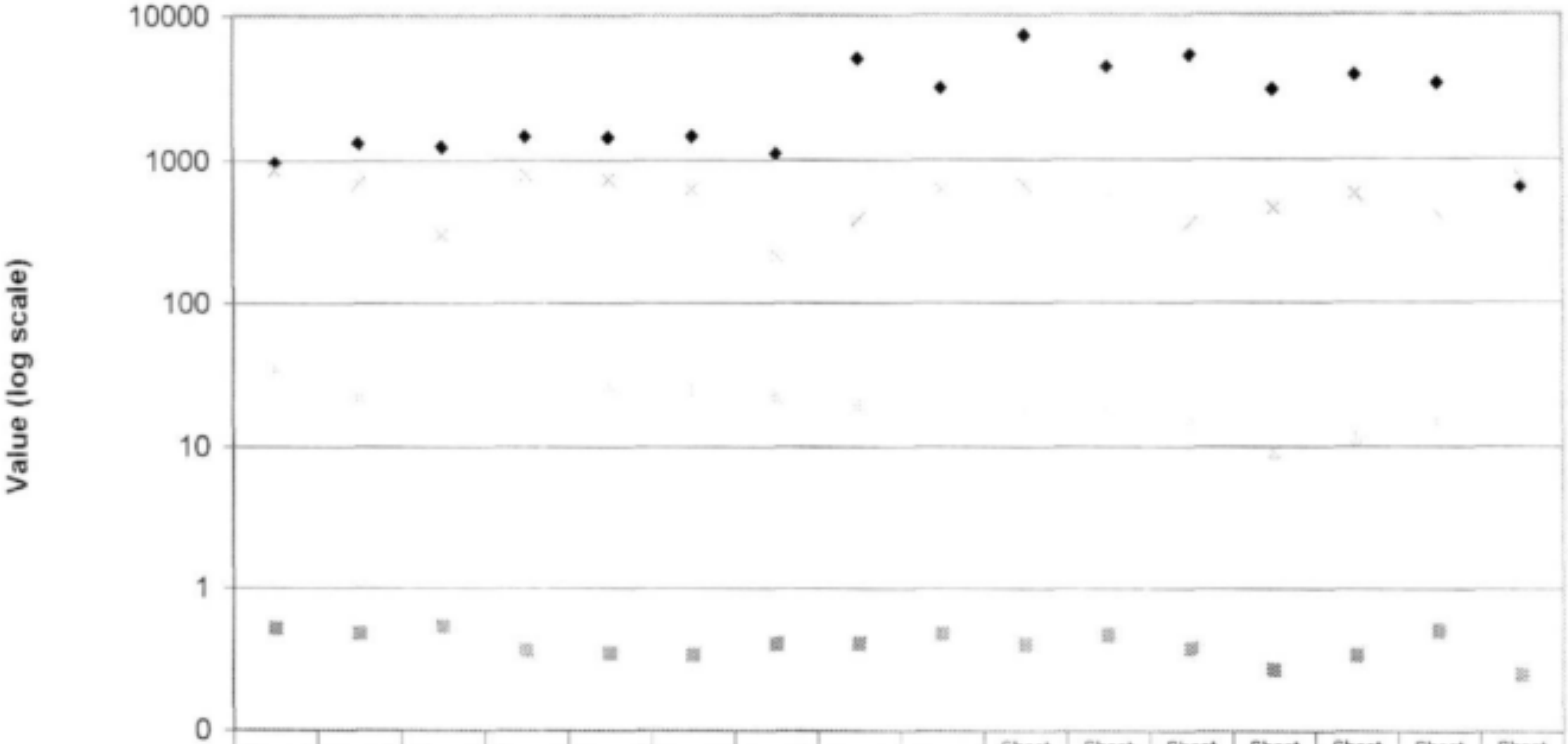
Summary of All Averaged Data

Summary of Continuous Operation Test Results

- Springbok March to May 1999

Sunlight	Data	Total	Units
sun	Count of Sunhours	39.0	
	Average of Sunhours	9.7	h
	Max of Sunhours	11.3	h
	Min of Sunhours	2.9	h
	Average of Feed	107.6	litres/h
	Max of Feed	197.9	litres/h
	Min of Feed	23.8	litres/h
	StdDev of Feed	58.4	litres/h
overcast	Count of Sunhours	9.0	
	Average of Sunhours	8.6	h
	Max of Sunhours	10.9	h
	Min of Sunhours	5.3	h
	Average of Feed	84.0	litres/h
	Max of Feed	174.4	litres/h
	Min of Feed	29.1	litres/h
	StdDev of Feed	56.3	litres/h
slight o/c	Count of Sunhours	3.0	
	Average of Sunhours	10.8	h
	Max of Sunhours	11.1	h
	Min of Sunhours	10.6	h
	Average of Feed	172.0	litres/h
	Max of Feed	179.0	litres/h
	Min of Feed	159.4	litres/h
	StdDev of Feed	10.9	litres/h
Total Count of Sunhours		51.0	
Total Average of Sunhours		9.5	h
Total Max of Sunhours		11.3	h
Total Min of Sunhours		2.9	h
Total Average of Feed		107.2	litres/h
Total Max of Feed		197.9	litres/h
Total Min of Feed		23.8	litres/h
Total StdDev of Feed		58.8	litres/h

Average Test Data



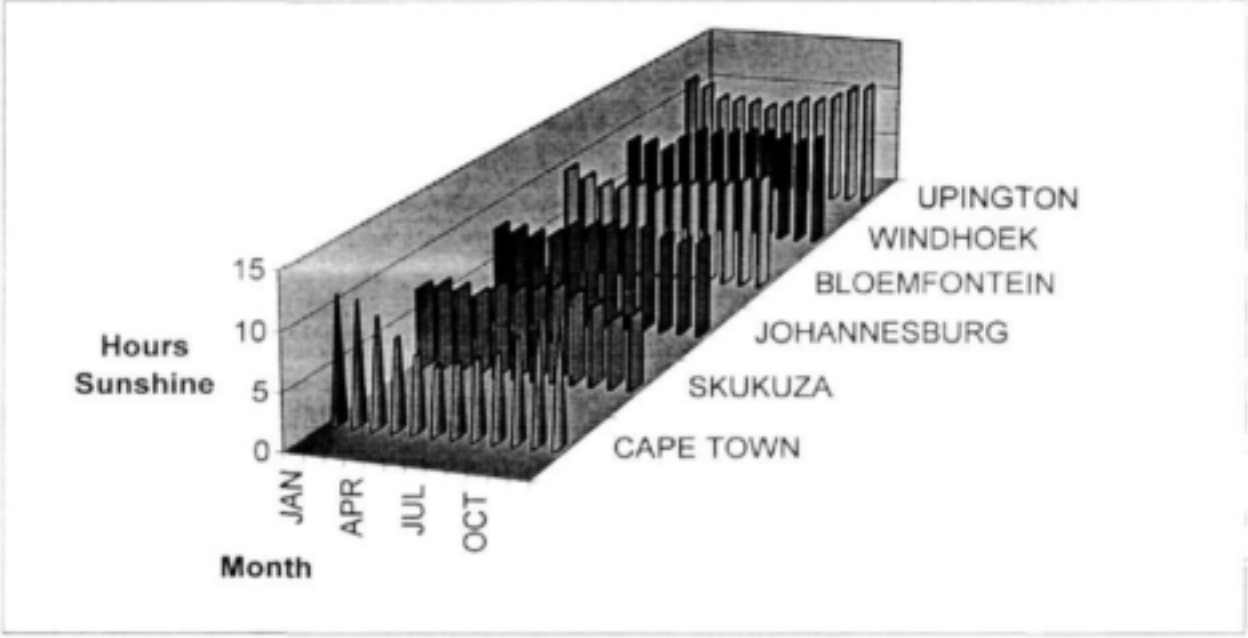
	Sheet 1	Sheet 2	Sheet 3	Sheet 4	Sheet 5	Sheet 6	Sheet 7	Sheet 8	Sheet 9	Sheet 10	Sheet 11	Sheet 12	Sheet 13-14	Sheet 15-16	Sheet 17	Sheet 18-23
◆ Avg. Conductivity	953	1305	1232	1451	1427	1446	1099	4984	3116	7231	4373	5239	3037	3810	3348	632
▨ Avg. Recovery	52%	48%	53%	36%	34%	33%	40%	40%	47%	40%	46%	37%	27%	34%	50%	25%
Avg. Flux	35	22	25	26	26	25	22	20	28	18	20	15	9	11	15	7
× PPD	856	681	301	790	717	624	211	379	602	654	573	354	461	569	418	727

Test Sheet

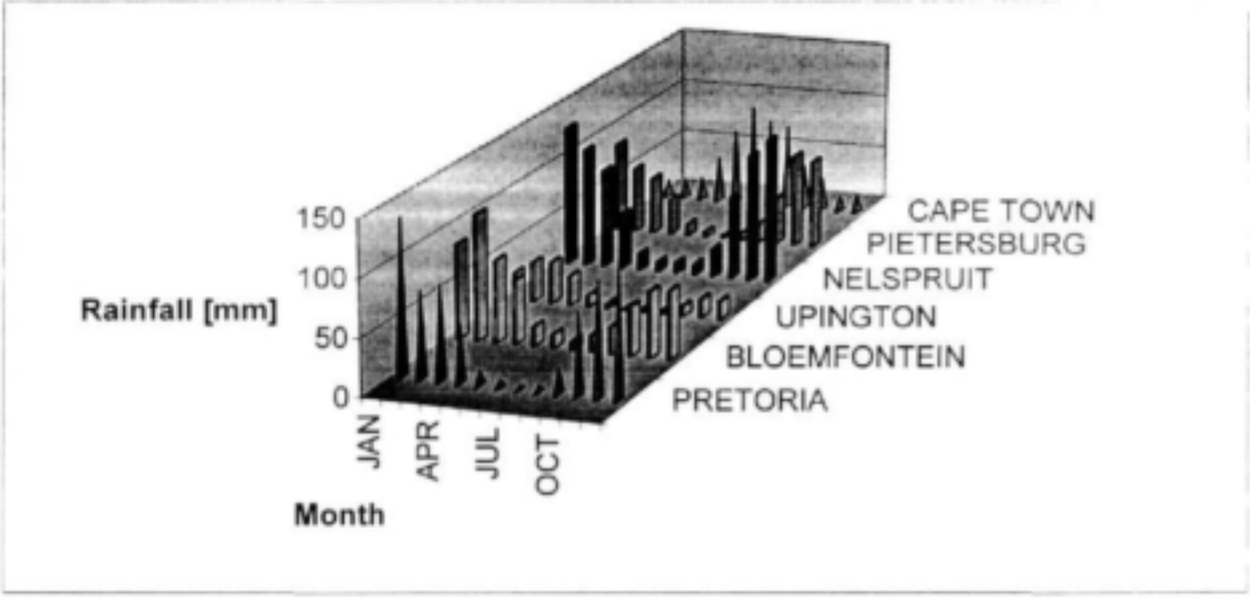
Appendix H

Sunshine and Rainfall Data for South African Towns

AVERAGE DAILY NUMBER OF SUNSHINE HOURS
1961-1990



AVERAGE RAINFALL
1961-1990



Appendix I

Calculation of Normalised Flux

The calculation of the normalised flux for a membrane system takes into consideration temperature and pressure fluctuations and normalises these for standard conditions.

To estimate the effect of temperature alone (constant pressure) on the permeate flow rate of an element or group of elements, the following equation may be used(13):

$$\mathbf{T_{cor} = Q_{25} / Q_T = e^x}$$

$\mathbf{T_{cor}}$ = Temperature correction factor
$\mathbf{Q_{25}}$ = The permeate flow rate at 25°C
$\mathbf{Q_T}$ = The permeate flow rate at temperature T

$$\mathbf{x = U\,(1/(T+273) - 1/298)}$$

T = the temperature in °C
U = a constant which depends on the element being used
(For all TFC models U = 2600)

To estimate $\mathbf{Q_{25}}$, the permeate flow rate at 25°C, multiply $\mathbf{Q_T}$, the observed permeate flow rate, by $\mathbf{T_{cor}}$

To estimate the effect of pressure alone (constant temperature) on the permeate flow rate of an element or group of elements, the following equation may be used:

$$\mathbf{P_{cor} = Q_{Ref} / Q_P = P_{Ref} / \mu}$$

$\mathbf{P_{cor}}$ = Pressure correction factor
$\mathbf{Q_{Ref}}$ = The permeate flow rate at the reference pressure.
$\mathbf{Q_P}$ = The permeate flow rate at pressure P
μ = Average Osmotic Pressure

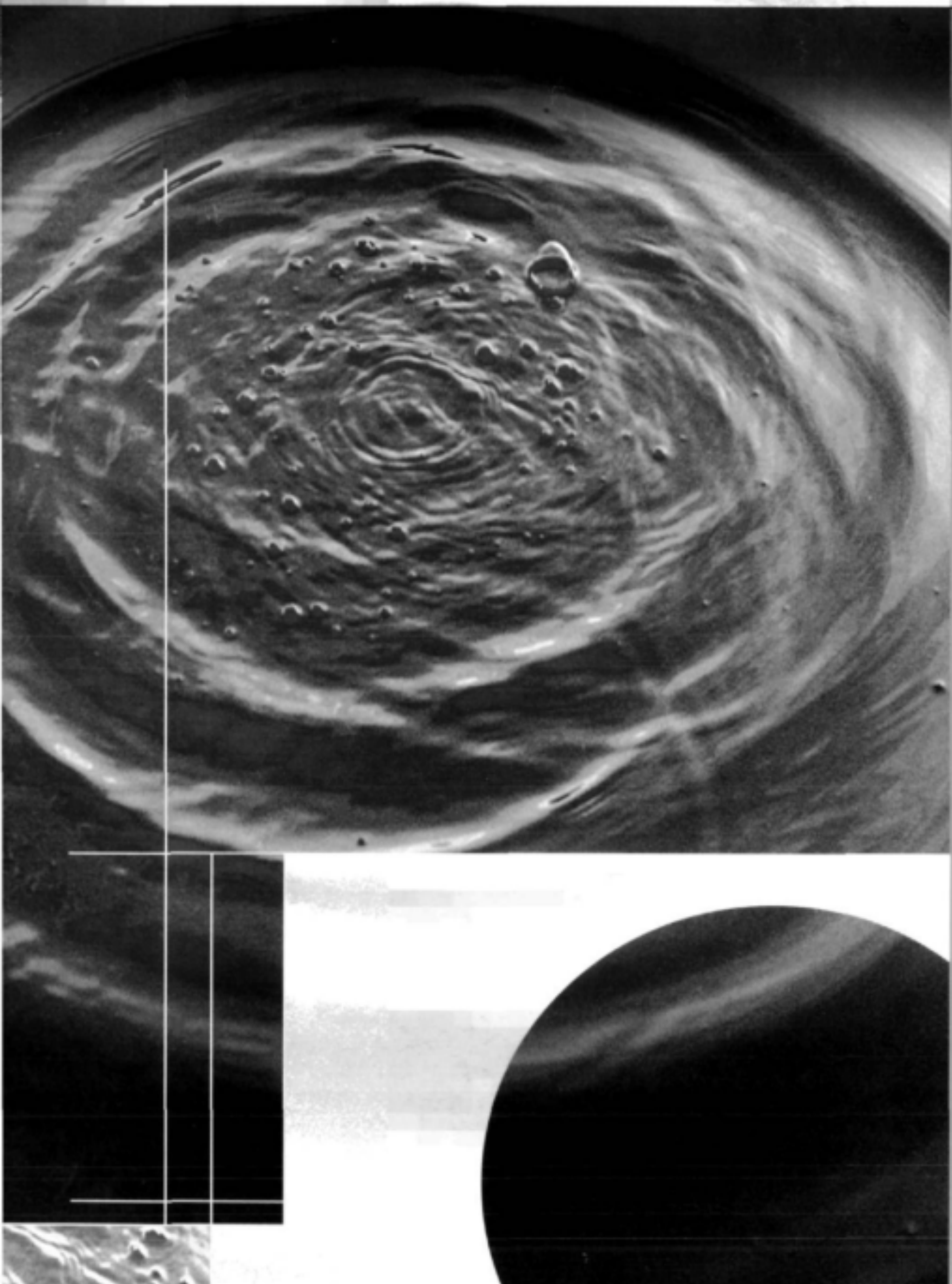
$$\mathbf{\mu = (P_{in} - P_{out})/2 - P_p - C_F/C_{Ref}.\ln(1/(1\text{-}R))/R}$$

$\mathbf{P_{in}}$ = Membrane Inlet Pressure
$\mathbf{P_{out}}$ = Membrane Outlet Pressure
$\mathbf{P_p}$ = Permeate Backpressure
$\mathbf{C_F}$ = Feed conductivity for pressure P
$\mathbf{C_{Ref.}}$ = Reference conductivity
R = Recovery

Therefore the normalised system flux (lmh) is:

$$\mathbf{F_N = Q_{PT}/n_m A_m \,.\, P_{cor} \,.\, T_{cor}}$$

$\mathbf{A_m}$ = Membrane surface area. = 2.4 m^2 for 2 ½" LP membrane
$\mathbf{n_m}$ = Number of membranes



Water Research Commission

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Appendix H

Sunshine and Rainfall Data for South African Towns

Appendix I

Calculation of Normalised Flux

The calculation of the normalised flux for a membrane system takes into consideration temperature and pressure fluctuations and normalises these for standard conditions.

To estimate the effect of temperature alone (constant pressure) on the permeate flow rate of an element or group of elements, the following equation may be used(13):

$$T_{cor} = Q_{25} / Q_T = e^x$$

T_{cor} = Temperature correction factor
Q_{25} = The permeate flow rate at 25°C
Q_T = The permeate flow rate at temperature T

$$x = U\,(1/(T+273) - 1/298)$$

T = the temperature in °C
U = a constant which depends on the element being used
(For all TFC models U = 2600)

To estimate Q_{25}, the permeate flow rate at 25°C, multiply Q_T, the observed permeate flow rate, by T_{cor}

To estimate the effect of pressure alone (constant temperature) on the permeate flow rate of an element or group of elements, the following equation may be used:

$$P_{cor} = Q_{Ref} / Q_P = P_{Ref} / \mu$$

P_{cor} = Pressure correction factor
Q_{Ref} = The permeate flow rate at the reference pressure.
Q_P = The permeate flow rate at pressure P
μ = Average Osmotic Pressure

$$\mu = (P_{in} - P_{out})/2 - P_p - C_F/C_{Ref}.\ln(1/(1-R))/R$$

P_{in} = Membrane Inlet Pressure
P_{out} = Membrane Outlet Pressure
P_p = Permeate Backpressure
C_F = Feed conductivity for pressure P
$C_{Ref.}$ = Reference conductivity
R = Recovery

Therefore the normalised system flux (lmh) is:

$$F_N = Q_{PT}/n_m A_m \;.\; P_{cor} \;.\; T_{cor}$$

A_m = Membrane surface area. = 2.4 m^2 for 2 ½” LP membrane
n_m = Number of membranes