SMALL SCALE DESALINATION IN SOUTH AFRICA WITH PARTICULAR REFERENCE TO SOLAR DISTILLATION

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SMALL SCALE DESALINATION IN SOUTH AFRICA WITH PARTICULAR REFERENCE TO SOLAR DISTILLATION

by

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BSc Eng (Civil) *Cape Town*

submitted in partial fulfillment of the requirements
for the degree of Master of Science in Engineering

September 1991

Declaration:

The work contained in this thesis is essentially my own work and has not been submitted to any other university for degree purposes.

Signed by candidate

Date: 30/9/91

To my loving wife, Lindi, and dear children, Sarah and Allen,
who have put up with this for far too long.
To Ian Pearson, who possesses not only the beard of Moses,
but also the faith of Abraham and the patience of Job.
To my parents and Creator, who got me here in the first place.
To my Lord and Saviour, who I trust will get me out again.

ACKNOWLEDGEMENTS

The preliminary investigations into the viability of Solar Distillation in South Africa were sponsored by the Department of National Health and Population Development. The remainder of the work behind this thesis was sponsored jointly by the National Energy Council and the CSIR. The Small Business Development Corporation, Cape Town Office, financed the Namaqualand field work. Thanks to Oom Karl Joseph, patriarch of Paulshoek. Thanks to Hans Pieterse for monitoring the still on his parents' farm, Buffelsdrif. At various times the following members of the Division of Water Technology, CSIR, have contributed in some way to the project: Annemarie du Plessis, Jackie Meeding, Baby Ramahotswa, Ian Pearson, Felipe Solsona, Cecile Thom, Timothy Motshoene and Cecil Chibi. Thanks are due to Manfred Krige, for regular loan of his workshop, and for valued practical advice.

ABSTRACT

Communities living in the remote, arid parts of South Africa are often reliant on brackish groundwater for their drinking water, sometimes to the detriment of their health. The quality of their drinking water is of concern to these communities and they are willing to pay for the means of improving their drinking water quality. A market survey indicated that an affordable price for a family desalination unit producing an average of 20 litres of drinking water per day would be R750. Conventional technologies such as Reverse Osmosis, Electrodialysis and Ion Exchange are generally too expensive and complex for application at demands of below 100 litres per day. Solar distillation, on the other hand, is well suited to such micro-scale applications. The technology has been widely reported on internationally, particularly since 1945, but is little known in South Africa. Experimental work was done on both a basin still and on inclined wick stills, single and multiple effect, in order to ascertain reliability and cost-effectiveness. The single effect inclined wick still was found to be the most promising and its design was investigated for the effect of parameters such as basin depth, feed rate, feed salinity and wick type. It was found that the inclined wick still is optimally 50 to 80 mm in depth, should have a black or nearly black cotton or polyester wick, should be fed at a rate of between 1 and 2 $\ell/m^2/hr$, and is not sensitive to the salinity of the feed water. Its winter and summer yield averaged 3 and 5 $\ell/m^2/d$ respectively. A promising prototype has been produced and tested with some success in the field. Lessons from field tests could be applied to producing a final prototype which is expected to be affordable and reliable. Its total annual cost (amortizing over the expected life of 10 years and including the cost of maintenance) is estimated at R90 per standard 1 m^2 panel, which leads to a distillate cost of R30/m^3, and a water supply cost of R15/m^3 when 1:1 blending is applied.

SYNOPSIS

Most communities living in the remote, arid regions of Southern Africa are dependent on brackish groundwater for their drinking water needs. Salinities of over 2000 mg dissolved salt per litre are common in borehole waters of Namibia, the Kalahari, Namaqualand, the Karroo and parts of the Northern Transvaal. The recommended upper salinity limit for healthy drinking water is 2000 mg/ℓ, beyond which point heart disease and arthritis become more marked. In particular, high levels of nitrate and fluoride are responsible for the diseases methaemoglobinaemia and fluorosis.

For these communities there is a need for an affordable, reliable means of desalinating their daily drinking water. Of the various desalination technologies available the only one that seemed likely to be economically viable at household scale was *solar distillation.* Solar stills rely on the sun's energy to desalinate water, operate at relatively high efficiencies (30-50%, being the enthalpy of vaporisation of the distilled water as a fraction of the incident solar energy), and are very simple in concept and operation. The two most competitive alternatives are the Reverse Osmosis and Electrodialysis processes, but these are not simple, require electric power, and only become economically viable when upwards of several thousand litres of water per day need to be purified. Thus the question that needed to be answered was: could a simple, rugged, reliable, and efficient still be built for a price that is affordable?

The objectives of this research project were thus to do the following:

- Determine the need for small scale (20 litres/day) desalination technology and the price end users may be prepared to pay for it.
- Evaluate the current state-of-the-art of solar distillation through literature review and testing selected prototypes.
- Optimize the design of those prototypes showing the best potential. Optimization of, in particular, cost and reliability.
- Test the most promising prototypes in the field.
- Make recommendations for the implementation of this technology.

The potential market for small scale desalination was divided into the following logical segments: farmers, villages, hospitals and clinics, technikons and schools, the railways, black tribal areas and the military. For each segment the need for small scale desalination was defined and assessed. Most of the above market segments were assessed from the results of telephonic surveys, but for the black tribal areas a field survey was conducted in Lebowa.

The market survey concluded that there existed a market for household desalination units capable of producing 20 litres of drinking water per day and costing less than R750. The market size was estimated at between 3 000 and 20 000 units.

Energy and Water literature databases residing at the National Energy Council and the CSIR were searched for references to solar distillation and solar energy. Over 100 publications spanning the last three decades were traced and obtained. From the literature survey two promising designs, the inclined wick still and the multi-effect inclined wick still, were selected and constructed. A fibreglass still of the basin or greenhouse type was also obtained from the Rural Industries Innovation Centre in Botswana. These stills were set up on the roof of the Appropriate Technology Group's building at the CSIR in Pretoria, and operated over a period of time. Global radiation and still production were measured at least on a daily basis, and sometimes more often. With the inclined wick stills feed water flux was measured, and with the basin still water and glass temperatures were recorded. Distillate quality was monitored, as well as the feed water salinity.

The following conclusions were drawn from this experimental work:

- Both inclined wick stills and basin stills are simple and reliable.
- The multi-effect inclined wick still is not rugged and reliable in operation, and is not more cost-effective than the simpler single effect inclined wick still.
- The inclined wick still is the optimum design because its yield is not so much reduced during the winter months. Its winter yield averages over 3 $l/m^2/d$, and its summer yield exceeds 5 $l/m^2/d$ on clear days. The basin still, on the other hand, produces a similar volume of distillate on summer days, but in the winter the yield reduces to an average of only 1,7 $l/m^2/d$.

The inclined wick still having proved the most likely to succeed in the field, four identical wick stills of area 0,35 m^2 each were constructed and tested side by side over a period of seven months. This enabled the effect of certain parameters such as basin depth[a], feed water flux, wick type and feed water salinity to be assessed. It was found that the inclined wick still:

- is optimally 50 to 80 mm in depth;
- should have a cotton/polyester fabric wick which should be absorbent (absorbency being not significantly affected by the mix of fibres chosen, only the weave) and

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[a] When referring to an inclined wick still *basin depth* refers to the spacing between the wick and the glass cover, not to be confused with the depth of water in the basin type still.

black in colour, although up to six months fading of the wick can be tolerated before inversion or redyeing of the wick is required;

- ☐ should optimally be fed at a rate of between 1 and 2 ℓ/m2/hr; and
- ☐ is not sensitive to the salinity of the feed water in the range 300 to 70 000 mg/ℓ TDS (tap water strength to double seawater strength).

Field tests on 2 m^2 household scale inclined wick stills were carried out at two locations, one on a farm in the Northern Transvaal, and the other at the small Namaqualand village of Paulshoek. The tests commenced in May in both areas. From these tests it was possible to learn how best to implement the technology in practice, and an impression was gained of how they might be received by potential users. While the stills have been well received and have performed satisfactorily for the time of year, with the benefit of hindsight it would be better to make the standard still panel 1 m^2 in area. Users can then buy as many panels as are required to meet their daily needs. A 1 m^2 panel is the more convenient, practical size in terms of transport, erection, feed water distribution through the wick, and glass support.

Prices have been obtained from various producers and distributors of the principal components of the inclined wick stills. Different materials have been compared for cost and durability, and estimates have been made of the final cost of drinking water desalinated in this way. The recommended standard 1 m^2 inclined wick still panel should be able to be retailed for under R300 (material cost R100, labour R70, balance to marketing and mark-up). The standard panels' total annual cost (amortizing over the expected life of 10 years and including the cost of maintenance) was estimated at R90, which leads to a distillate cost of R30/m^3, and a water supply cost of R15/m^3 when 1:1 blending is applied. Two of these panels would be necessary to provide the average household with its drinking water throughout the year (assuming 1:1 blending). This is not only cheaper (at this scale of production) than any of the alternative desalination technologies available, but according to the market survey it should be affordable to a large share of those dependent on brackish groundwater.

Drawings are provided of the recommended prototype. Several of these should be manufactured and tested in the field in the high salinity areas of South Africa before a final decision can be taken about the commercial prospects of this design.

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LIST OF SYMBOLS

c_{pa} = specific heat of air at constant pressure (J/kg°C)
D = angle of declination of the sun (°)
g = gravitational acceleration (9,81 m/s^2)
h = heat transfer coefficient ($W/m^2{}^\circ C$)
h_c = heat transfer coefficient due to convection ($W/m^2{}^\circ C$)
h_{fg} = enthalpy of vapourisation of water at the temperature of evaporation (J/kg)
H_g = global radiation (J/m^2)
H_L = long wave thermal atmospheric radiation (J/m^2)
k = thermal conductivity (W/m°C)
L = angle of latitude (°)
M_a = molecular weight of dry air (≈29 kg/mole)
m_e = mass of water transferred by evaporation per unit area (kg/m^2)
M_w = molecular weight of water vapour (18 kg/mole)
m_{wg} = mass of water vapour transferred per unit area from the glass surface (kg/m^2)
n_a = number of moles of dry air
n_w = number of moles of water vapour
P_g = vapour pressure at temperature T_g (Pa)
P_T = total pressure (Pa)
P_w = vapour pressure at temperature T_w (Pa)
q = rate of heat transfer (W/m^2)
q_c = rate of heat transfer due to convection (W/m^2)
q_e = rate of heat transfer due to evaporation (W/m^2)
q_r = rate of heat transfer due to radiation (W/m^2)
T = temperature (°C or K)
T_g = glass temperature (°C or K)
T_w = water temperature (°C or K)
α = absorptivity
β = coefficient of volumetric thermal expansion (K^{-1})
ΔT = temperature difference (°C or K)
ϵ = emissivity
η = efficiency
ρ = density (kg/m^3)
μ = dynamic viscosity (kg/ms)
υ = kinematic viscosity (μ/ρ) (m^2/s)
σ = Stefan-Boltzmann's constant = $5{,}67 \cdot 10^{-8}$ W/m^2K^4
τ = transmittance
θ_{opt} = optimum inclination of a still to the horisontal plane for maximum radiation to be received
X = characteristic length of a system (m)

Dimensionless numbers:

Nu = hX/k (Nusselt number)
Gr = $(X^3\rho^2 g\beta\Delta T/\mu^2)$ (Grashof number)
Pr = $(C_p\mu/k)$ (Prandtl number)
Re = $(\rho\upsilon X/\mu)$ (Reynolds number)

CHAPTER 1

INTRODUCTION

1.1 Rainfall and evaporation variation in South Africa

Rainfall over Southern Africa varies widely geographically, from season to season and from year to year. While the eastern seaboard receives up to 1000 mm of rain per year on average, as one moves over the escarpment and westwards the mean annual precipitation decreases dramatically (Figure 1.1). In the more arid west the reliability of the rain is also reduced, with the Karroo and Namaqualand typically experiencing over 30% deviation from their average annual rainfall (Figure 1.2). In the Kalahari and Namibia the deviation about the mean of the already sparse rainfall is over 40%. In these areas the evaporation potential is many times higher than the average rainfall (Figure 1.3), and the groundwater is consequently rich in salts. In other areas with more substantial rainfall the geology contributes towards the high salinity in the groundwater.

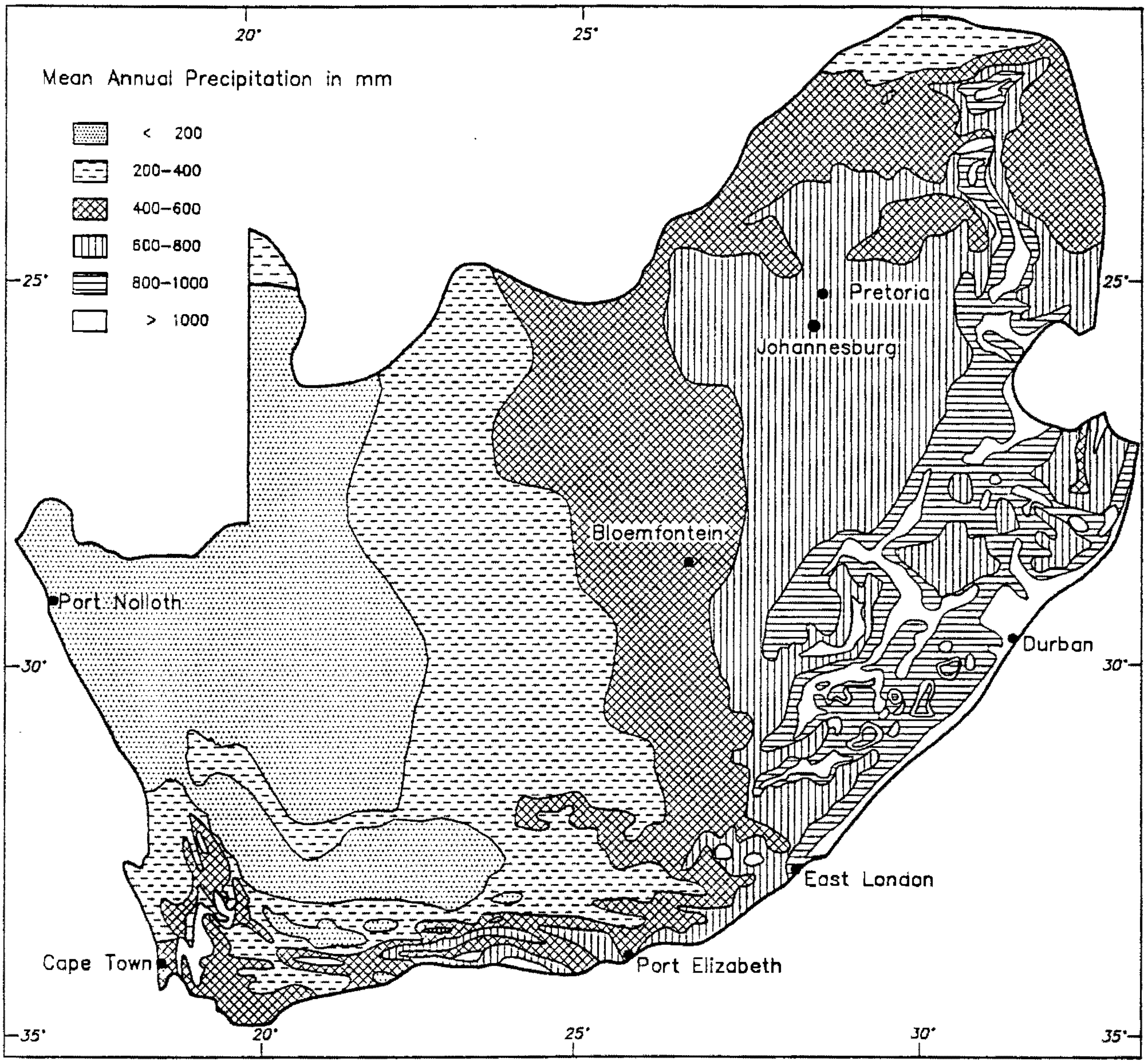

Figure 1.1: Mean annual precipitation over South Africa (Department of Water Affairs, 1986)

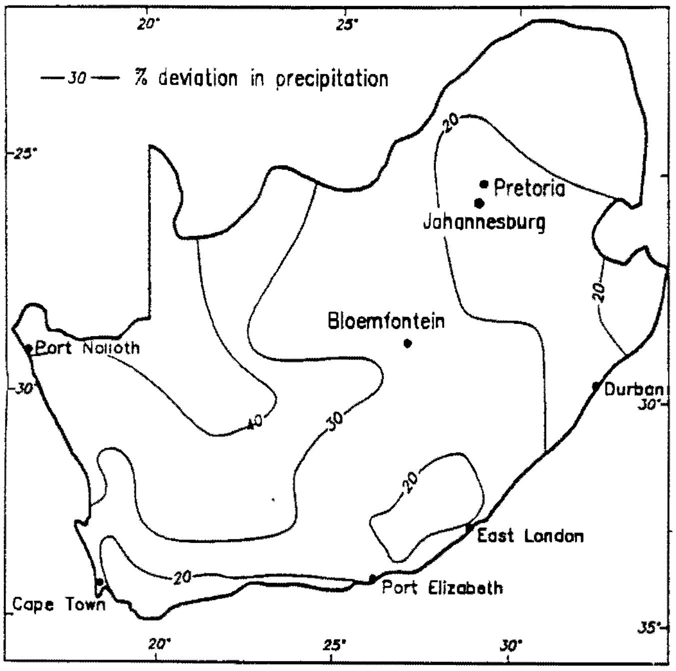

Figure 1.2: **Percentage deviation from mean annual rainfall**
(Department of Water Affairs, 1986)

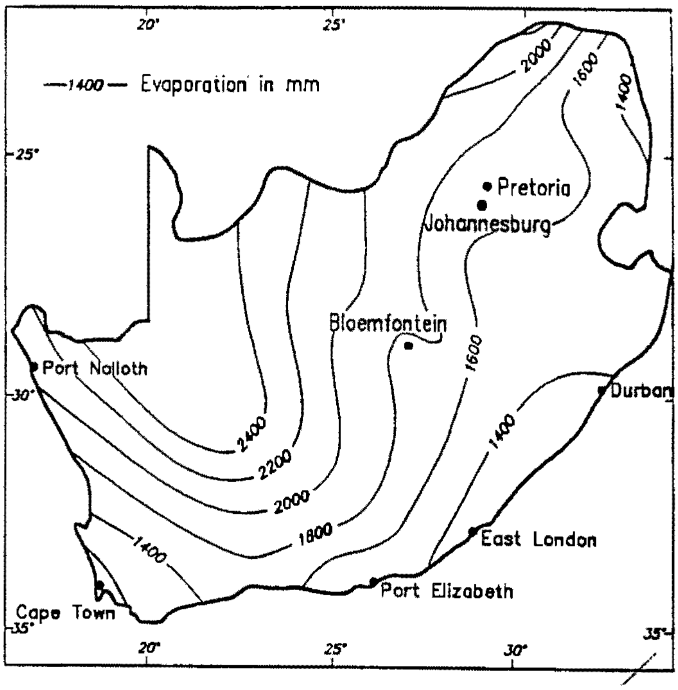

Figure 1.3: Mean annual evaporation from an open water surface
(Department of Water Affairs, 1986)

1.2 The problem of water supply in arid areas

Communities that live in the remote, arid regions of Southern Africa, of which there are several, are dependent on brackish groundwater for their drinking water needs. Salinities of over 2000 mg dissolved salt per litre are common in borehole waters of Namibia, the Kalahari, Namaqualand, the Karroo and the Northern Transvaal. The upper limit for healthy drinking water is 2000 mg/ℓ[a], beyond which point heart disease and arthritis become more marked (Hattingh, 1985). Two constituents of the total salinity which have a significant affect on health are fluoride and nitrate. *Fluoride* is beneficial in preventing dental caries in low concentrations (between 0,7 and 1,0 mg/ℓ), but becomes toxic at levels only slightly above the recommended level. One effect is the disease known as dental fluorosis, which is recognised by the severe discolouration and crumbling of teeth; another is osteoporosis, which is a crumbling of the bones. The recommended limit for fluoride is 1,5 mg/ℓ. Figures 1.4 and 1.5 are based on maps of the total dissolved solids and fluoride content of borehole waters of South Africa, produced in 1958 by van Noort and MacVicar of the Division of Chemical Services of the Geological Survey[b]. *Nitrate* at concentrations above 20 mg/ℓ (as nitrogen, equivalent to 90 mg/ℓ as NO$_3$) causes a disease known as methaemoglobinaemia, where the ingestion of excess nitrate reduces the blood's oxygen carrying ability. The disease can be fatal to infants and foetuses (whence comes the common name "blue baby disease"),

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[a] The SABS recommendation (SABS 241-1984) is that the conductivity of drinking water should not exceed 70 mS/m, but conductivities of up to 300 mS/m can be tolerated if there is no alternative (these conductivities approximate salinities of 500 mg/l and 2000 mg/l respectively - see Appendix G).

[b] The complete review and redrafting of these maps forms part of a major research effort recently initiated by the Water Research Commission. Groundwater quality determinands will be plotted for the entire country on 1:250 000 scale. The first maps are, however, not expected to become available before 1993.

and for this reason the safe level of nitrate and nitrite combined should ideally not exceed 10 mg/ℓ (as Nitrogen). Nitrates at levels above 50 mg/ℓ (as Nitrogen) are common in borehole and well waters of Namibia, Botswana and the Northern Transvaal (Super *et al*, 1981; Palmer, 1981; Muller, 1990).

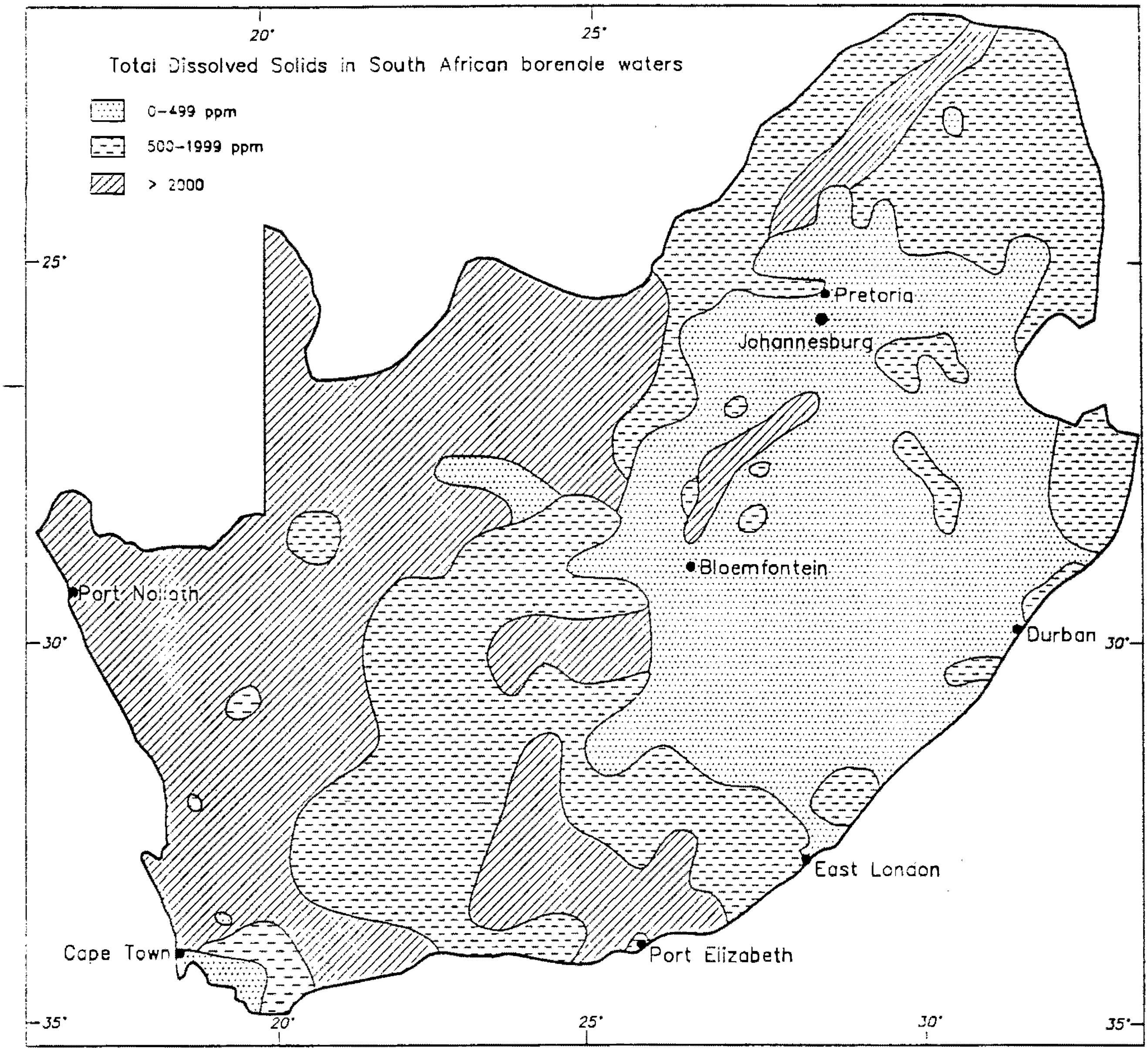

Figure 1.4: Map of the total dissolved solids content of South African borehole waters (after van Noort and MacVicar, 1958)

1.3 Survey of demand for small scale desalination

Quite apart from health aspects, salty water is unpleasant to the taste and is poorly suited for washing. Over the years the CSIR has been approached by farmers and spokespersons for rural communities to develop an affordable household scale desalination device which could provide at least for daily drinking water needs, and possibly washing needs. A review of the available technology indicated that it would be possible to develop a low cost solar still which would meet the requirements of simplicity and affordability, but there was some doubt as to whether the market for such a product was large enough to justify the costs of developing it. Consequently a market survey was carried out and extracts from it are included in Appendix A.

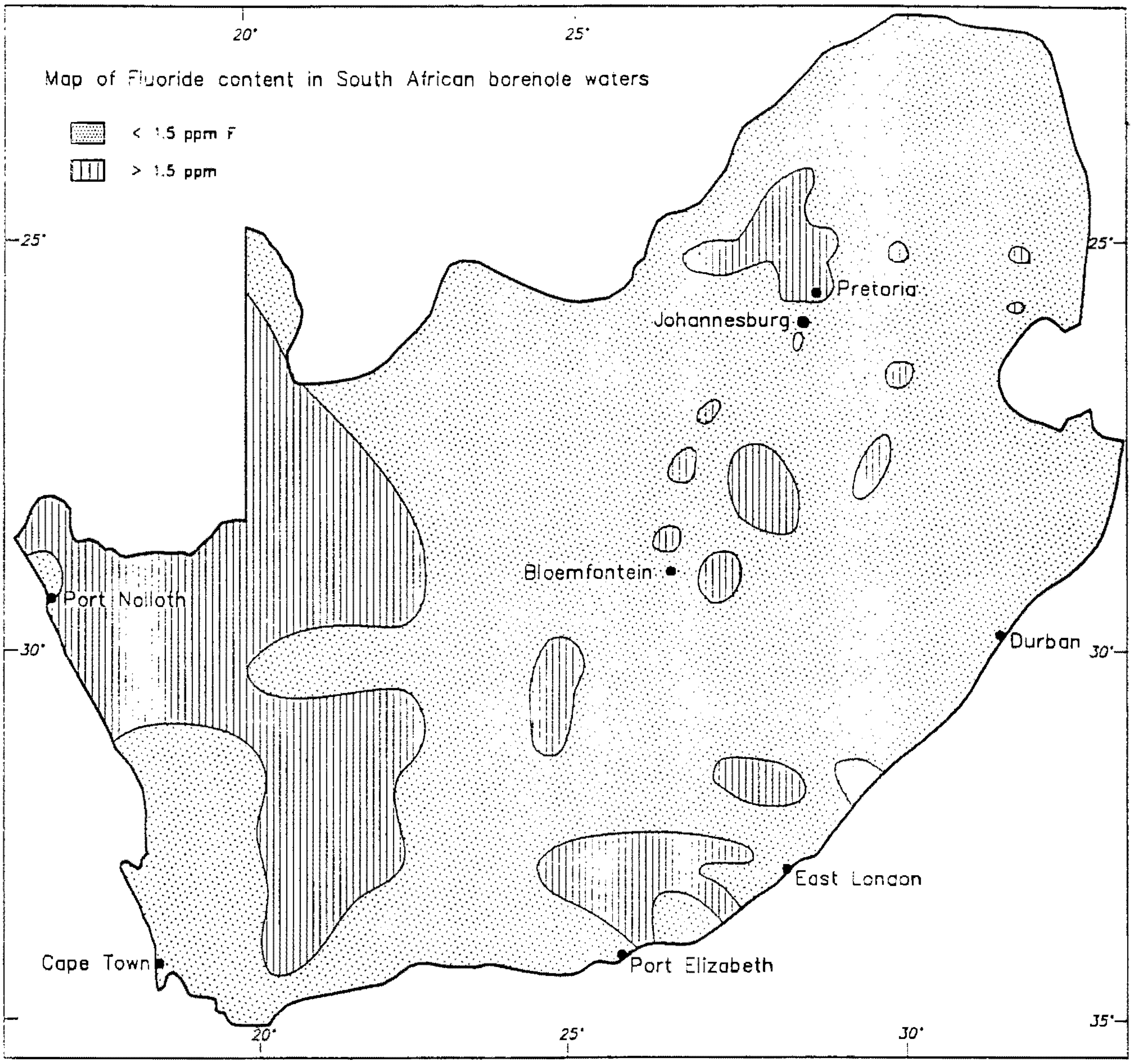

Figure 1.5: Map of the fluoride content of South African borehole waters (after van Noort and MacVicar, 1958)

One area that suffers from poor ground water quality is the Matlabas valley in the North-western Transvaal. A survey of ten of the farmers in this valley indicated that half of them would be prepared to pay over R500 (1989, equivalent to R750 in 1991 rands) for a household scale desalination unit which would supply their families daily drinking water needs (estimated at 20 litres/day). Another survey, this time of a tribal area in Lebowa which is beset by severe salinity problems, indicated that even relatively impoverished communities would be prepared to pay the costs of desalinating water, based on R500 per household (although in this case some kind of finance would need to be arranged). The market survey concluded:

"Many people in South Africa and her neighbouring countries rely on brackish boreholes for their domestic water supply needs. Should these people wish to desalinate small quantities of water for drinking (< 50 ℓ/day) Solar Distillation is the most economical option they have.

"In a survey of the possible market for small scale desalination equipment with a view to developing an improved low cost, more efficient unit which requires low maintenance even if neglected for a period, it appears that the demand for such units will fall in the range of 3 000 to 20 000 units. Although this is a wide range, even the lower figure is quite substantial."

1.4 Objectives of this investigation

With this positive indication of the need for the development of an affordable, simple desalination device it was decided to go ahead with this research.

At the outset the following objectives were defined:

☐ Review the alternative desalination technologies in terms of cost, complexity and reliability in order to define more exactly where solar distillation should most appropriately be applied.

☐ Evaluate the current state-of-the-art of solar distillation through literature review and testing selected prototypes.

☐ Optimize the design of that prototypes showing the best potential. Optimization of, in particular, cost and reliability.

☐ Test the most promising prototype in the field.

☐ Make recommendations for the implementation of solar distillation on a wider scale.

1.5 Scope of this thesis

In the following chapter the alternative desalination technologies are briefly described, and their application at small scale is assessed. Solar distillation, being the only technology of relevance for a household installation, is reviewed in some detail in Chapter 3. In Chapter 4 the experimental program followed in the course of this research is described, and in Chapter 5 the results of the experiments are discussed. Chapter 6 deals with the field tests that were carried out on two prototypes, one in Namaqualand and the other in the Northwestern Transvaal. In Chapter 7 the final prototype is presented with a set of drawings for manufacture and installation, with a discussion of maintenance requirements, and with projections of the likely costs of water produced by this means. The conclusions and recommendations of this work are summarised in the concluding chapter.

CHAPTER 2

REVIEW OF ALTERNATIVE DESALINATION TECHNOLOGIES AND ASSESSMENT OF THEIR APPLICATION AT SMALL SCALE

2.1 Large scale desalination

Installed desalination capacity worldwide has been escalating steadily this century (Figure 2.1). The bulk of this capacity (92%) is based on two processes, multistage flash distillation (69%) and reverse osmosis (23%), the rest being divided among several other processes including other distillation processes (e.g. vertical tube, vapor compression) and electrodialysis. Reverse Osmosis is the coming technology, with only 2% of the market in 1970 but 23% by 1987.

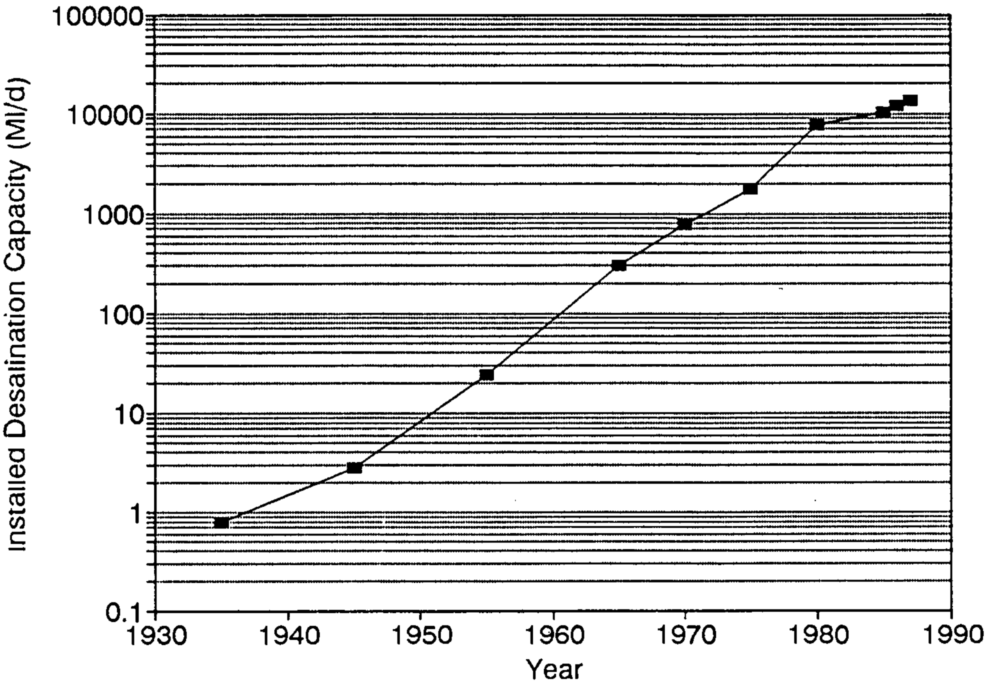

Figure 2.1: Growth in worldwide installed desalination capacity (data from Kharbanda, 1990)

The heart of the multistage flash distillation (MSF) process is the flash distillation chamber, where heated brine[a] is introduced to a semi-evacuated chamber so that it rapidly boils, the vapour thus produced condensing on the outer walls of the tubes bringing fresh (cool) brine into the process. For increased efficiency the process incorporates many flash chambers, each one being fed by the waste brine from the chamber before it. Figure 2.2 illustrates the concept of the MSF process.

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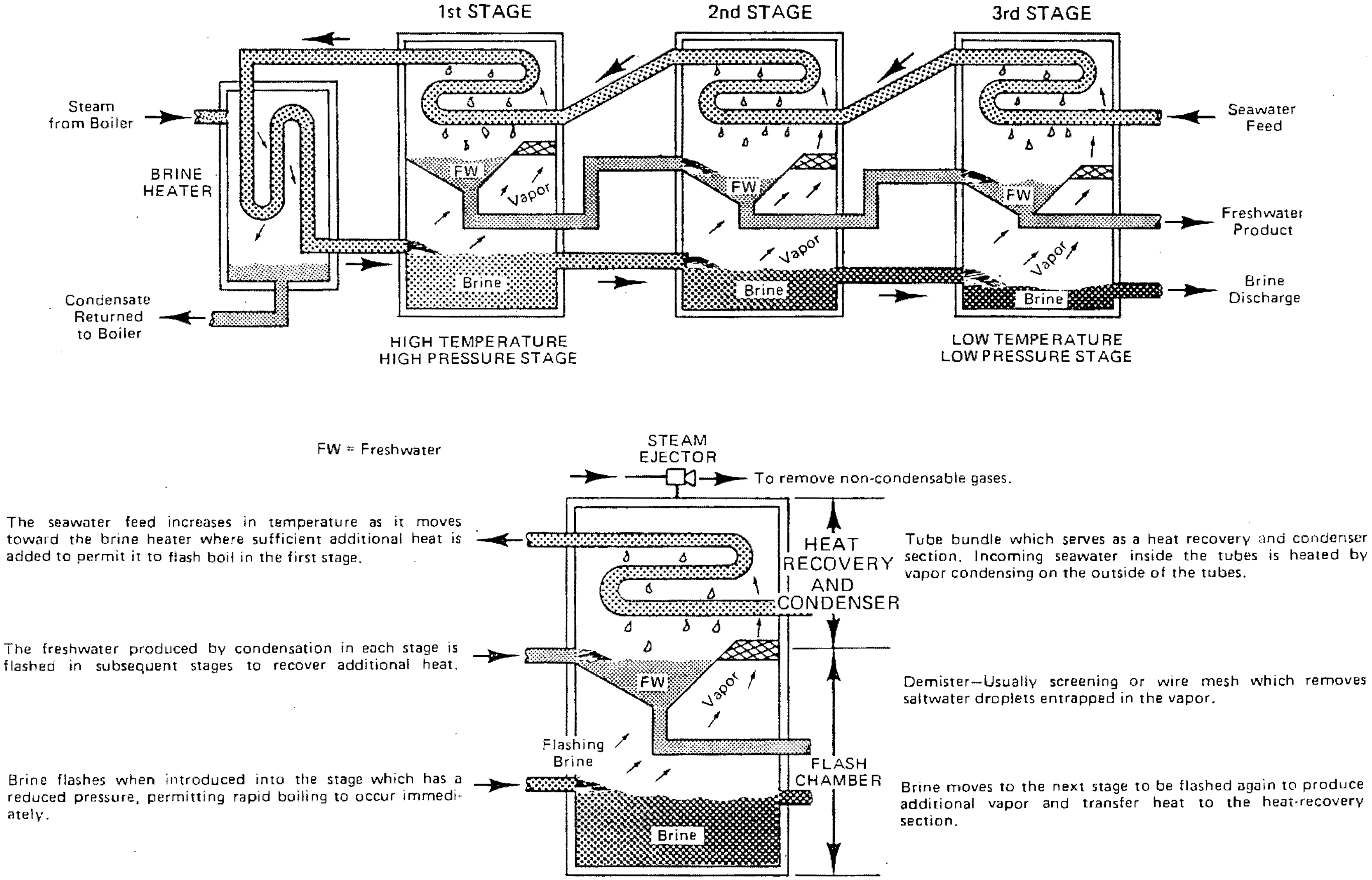
[a] The term *brine* is often used to denote salty water, particularly when dealing with sea water. In this thesis it has also been used to describe that water which remains after distillation has taken place, i.e the waste or reject water from a continuous flow process, or the water in the basin of a basin still.



The seawater feed increases in temperature as it moves toward the brine heater where sufficient additional heat is added to permit it to flash boil in the first stage.

The freshwater produced by condensation in each stage is flashed in subsequent stages to recover additional heat.

Brine flashes when introduced into the stage which has a reduced pressure, permitting rapid boiling to occur immediately.

Tube bundle which serves as a heat recovery and condenser section. Incoming seawater inside the tubes is heated by vapor condensing on the outside of the tubes.

Demister—Usually screening or wire mesh which removes saltwater droplets entrapped in the vapor.

Brine moves to the next stage to be flashed again to produce additional vapor and transfer heat to the heat-recovery section.

Figure 2.2: Conceptual diagram of the multistage flash (MSF) process (Buros, 1980)

Multistage flash distillation is mentioned because it is such an important part of desalination worldwide. It is however a large scale industrial process involving sophisticated heat exchangers and pumps. The average MSF plant size today is over 2 Mℓ/d, or 2000 m^3 per day, enough to supply a town of some 20 000 people with all their domestic water requirements. The process has proved economically viable particularly where it has been coupled with a thermal or nuclear power station, whose waste heat energy is sufficient to provide the primary heat input to the MSF process at no cost.

2.2 Small scale desalination

For the small scale desalination that is likely to be applied in Southern Africa for some time to come, Reverse Osmosis, Electrodialysis, Ion Exchange and Solar Distillation are the technologies which offer the best chance of success.

Before going on to describe these technologies it is appropriate to define more exactly what is meant by "small scale". What would be the typical water requirements of a family, of a farm, and of a small municipality?

2.2.1 Daily Water Requirements

The minimum amount of fresh water required per day for drinking, cooking and oral hygiene is 2 to 4 litres per person (saline water may be used for most other purposes). Thus a family of six or seven will require up to 20 litres of fresh water per day. Fresh water is also desirable for bathing and washing clothes due to the additional detergents and soap required when using saline waters (especially hard waters). In such cases some 100 to 200 litres of fresh water will be required by the family each day. Typical domestic water consumption figures (according to convenience of supply) are given in Table 2.1.

In the case of farms a substantial amount of water is required for stock watering (Table 2.2), although the acceptable limits for quality would be more relaxed than those for water intended for human consumption. In fact the recommended *maximum* conductivity limit for livestock watering according to Kempster et. al (1980), is 1980 mS/m. This equates to a salinity of approximately 13 000 mg/ℓ TDS. Most groundwaters in Southern Africa are well within this limit, but the limit is set for survival as opposed to optimum health and productivity. The recommended salinity limit for routine stock watering is approximately 3 250 mg/ℓ TDS (Kempster, 1980).

Typical water requirements for livestock watering are given in Table 2.2 below.

Table 2.1: Typical Domestic Water Usage (Hofkes et. al 1981)

Type of water supply	Typical water consumption (ℓ/capita/day)	Range (ℓ/capita/d)
Communal water point (e.g. village well, public standpost)		
distance > 1000 m	7	5 - 10
500 < distance < 1000 m	12	10 - 15
Village well		
distance < 250 m	20	15 - 25
Communal standpipe		
distance < 250 m	30	20 - 50
Yard connection (tap placed in house yard)	40	20 - 80
House connection		
single tap	50	30 - 60
multiple tap	150	70 - 250

Table 2.2: Water requirements for institutions and livestock watering (Hofkes et al 1981)

Category	Typical Water Use (ℓ/d)	Unit for Estimation
Livestock		
cattle	25 - 35	head
horses and mules	20 - 25	head
sheep	15 - 25	head
pigs	10 - 15	head
Poultry		
chickens	15 - 25	100 fowl

From the above it is possible to estimate the required daily production for small scale desalination plant as laid out in Table 2.3. To aid definition, the plant sizes have been classified in three sizes: minimum, small and medium. Demands falling between the ranges defined in the table could be defined as minimum to small and small to medium. The available technologies for desalinating water in these ranges are detailed in the remainder of this chapter.

Table 2.3: Required daily production for small scale desalination plant

Classification of Installation	Areas of Application	Daily Capacity litres/day
Minimum	Households - essential requirements for family	10 to 20
Small	Households - essential requirements, also washing water	100 to 200
Medium	Farms, small institutions, small municipalities[a] for drinking water only	3 000 to 15 000

2.2.2 Reverse Osmosis (RO)

□ Operating Principle

Natural osmosis (Figure 2.3a) is a diffusion process in which two solutions of unequal concentration are separated by a semi-permeable membrane through which water is capable of passing. As a result of a natural tendency to equalise the concentration of dissolved solids on either side of the membrane, water passes through the membrane from the weaker to the stronger solution until molecular concentrations are equal on both sides of the membrane.

The process of reverse osmosis (Figure 2.3b) involves overcoming the osmotic pressure of the solution. Feed water is desalinated by a semi-permeable membrane through which water is forced by applied pressure which is greater than the osmotic pressure of the solution. Table 2.4 lists the natural osmotic pressures of waters of different salinities. The solvent moves through the membrane in one direction only. The water is thereby divided into two streams - a pure water stream called the permeate, and the concentrate or brine. The membrane also acts as a molecular filter to retain bacteria, viruses and most organic material found in natural waters.

Commercial membranes are typically formed from cellulose acetate which is permeable to water molecules, but impermeable to most dissolved impurities. In the 1960s a technique was discovered for forming the membrane in an asymmetric layered structure - a semi-permeable skin just a few Ångstroms thick , supported by a porous layer several μm thick.

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[a] Typical population sizes of small municipalities in high salinity areas in South Africa are in the range 1 000 to 5 000 (see the list in appendix A).

This dual structure combined the hitherto elusive properties of high water flux with structural strength, and the modern Reverse Osmosis (RO) industry was born.

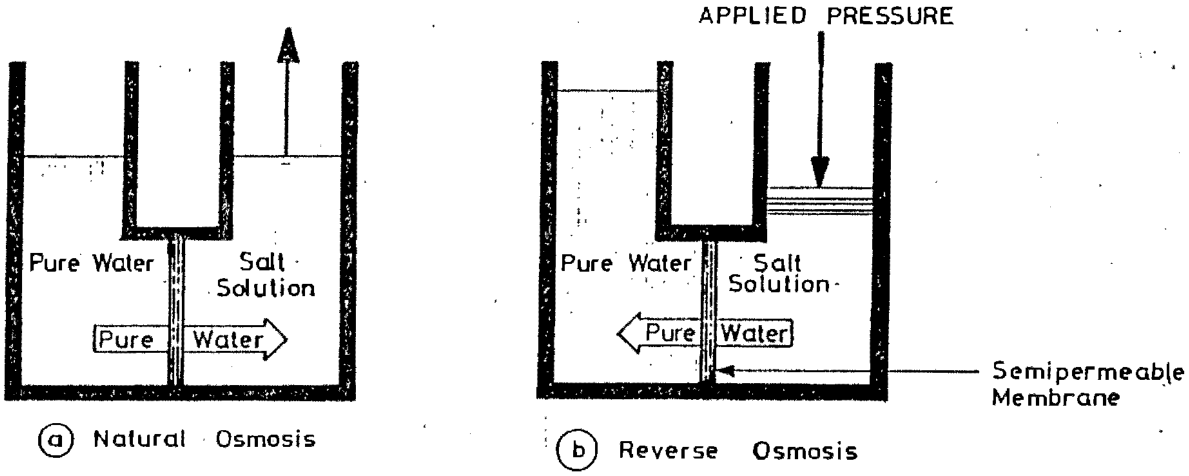
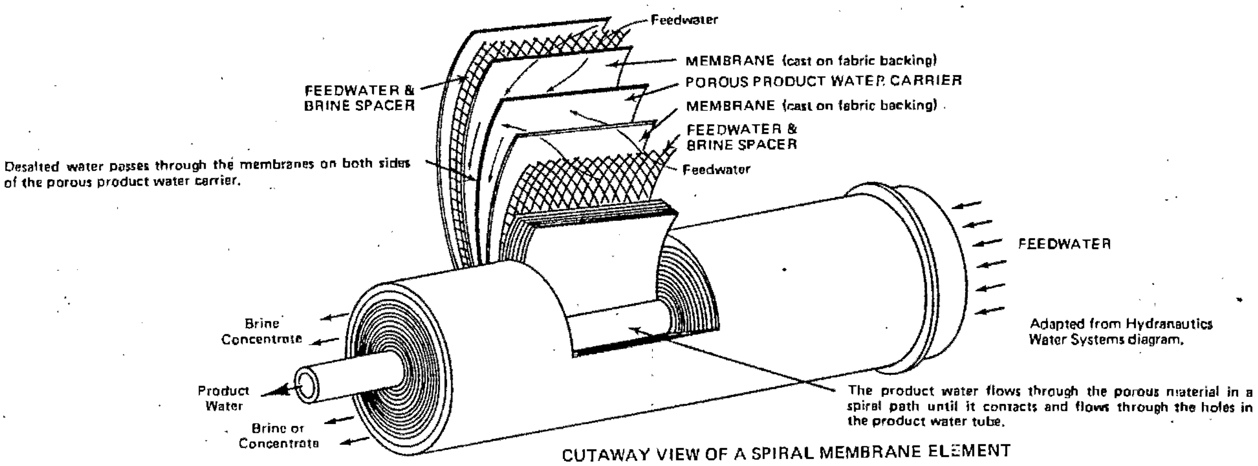


Figure 2.3: Natural osmosis and reverse osmosis

Table 2.4: Approximate natural osmotic pressures of waters of different salinities

Type of Water	Total Dissolved Solids (TDS) (mg/ℓ)	Osmotic Pressure (bar or 100 Kpa)
Brackish water	1 500	1
Brackish water	5 000	3
Very brackish water	12 000	7
Sea water	35 000	23
Brine	50 000	37

There are several ways in which the membrane are configured in practice. They were initially clamped as flat sheets, with alternating porous spacer sheets, into stacks. A later development was to wind the membranes with the spacer sheets into rolls, which are more compact. These are known as spiral wound membranes and are the most commonly used membrane type today. Other types are tubular membranes (where the membranes are cast as tubes, almost like straws, and packed closely together), and hollow fine fibre membranes, consisting of aromatic polyamide fibres no thicker than a human hair. In the case of tubular membranes permeation is from the inside to the outside of the tube, while the reverse holds for hollow fine fibre membranes. The latter can withstand very high operating pressures and are also compact. Figure 2.4 shows details of a spiral wound membrane and its use in a pressure vessel.

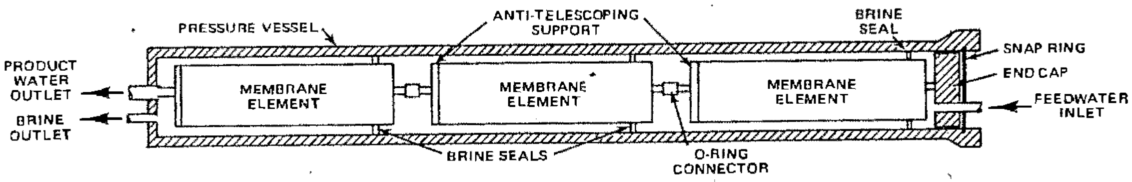


Desalted water passes through the membranes on both sides of the porous product water carrier.

Adapted from Hydranautics Water Systems diagram.

The product water flows through the porous material in a spiral path until it contacts and flows through the holes in the product water tube.

CUTAWAY VIEW OF A SPIRAL MEMBRANE ELEMENT



CROSS SECTION OF PRESSURE VESSEL WITH 3-MEMBRANE ELEMENT

Figure 2.4: **Spiral wound membrane cut-away view and application in a pressure vessel**

□ Minimum installation

Reverse Osmosis membranes are highly sensitive to clogging, so the minimum pretreatment that is required for feed water to the process is 10 μm microfiltration. If the water has any scaling potential (waters containing calcium sulphate, or calcium and magnesium bicarbonate) chemical addition is required. Only high clarity borehole waters can be treated without additional pretreatment. Most waters will require sand filtration ahead of the microfiltration. More turbid waters will require coagulation, flocculation and sedimentation ahead of the sand filtration.

To apply the pressures required for filtration, a high pressure pump with a sophisticated hydraulics system is required. The pressure required depends on the water being treated (cf. Table 2.4) with most commercial plants starting at about 14 bar. The pressure required for a given flow with a given salt concentration will increase with membrane age (membrane performance decreases with time) until the membranes are replaced. To compensate for this, plants have to be designed to deliver the minimum requirement just before membrane replacement i.e. surplus capacity must be built in to allow for membrane performance reduction.

The membranes themselves are generally housed in stainless steel pressure vessels. The tubular membrane stack at the heart of the state-subsidised Bitterfontein/Nuwerus Reverse Osmosis Plant, the first municipal desalination plant in South Africa, can be seen in Figure 2.5.

A typical process layout for a small RO installation is illustrated in Figure 2.6.

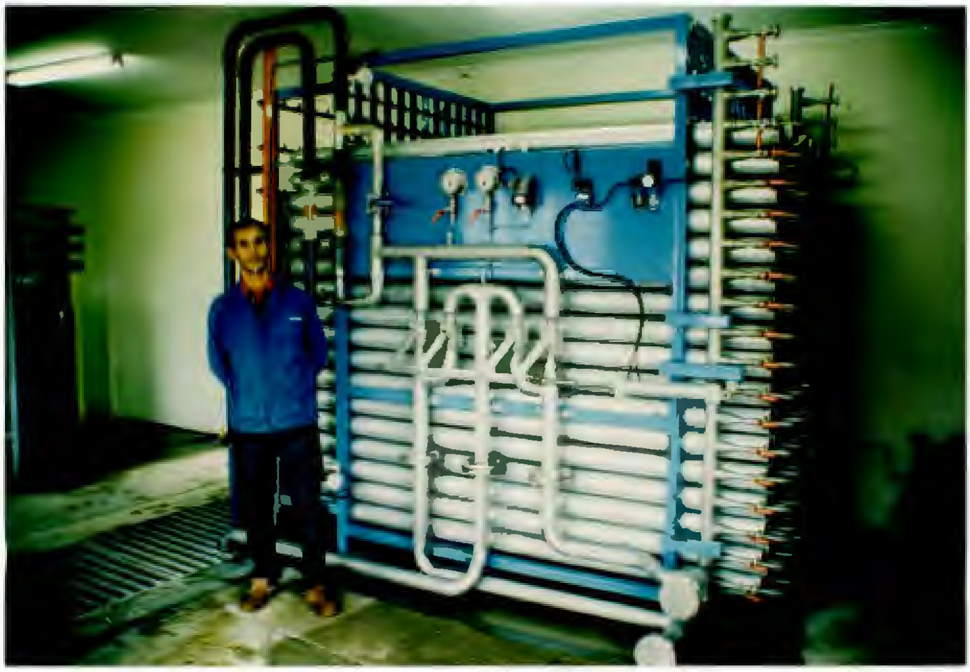
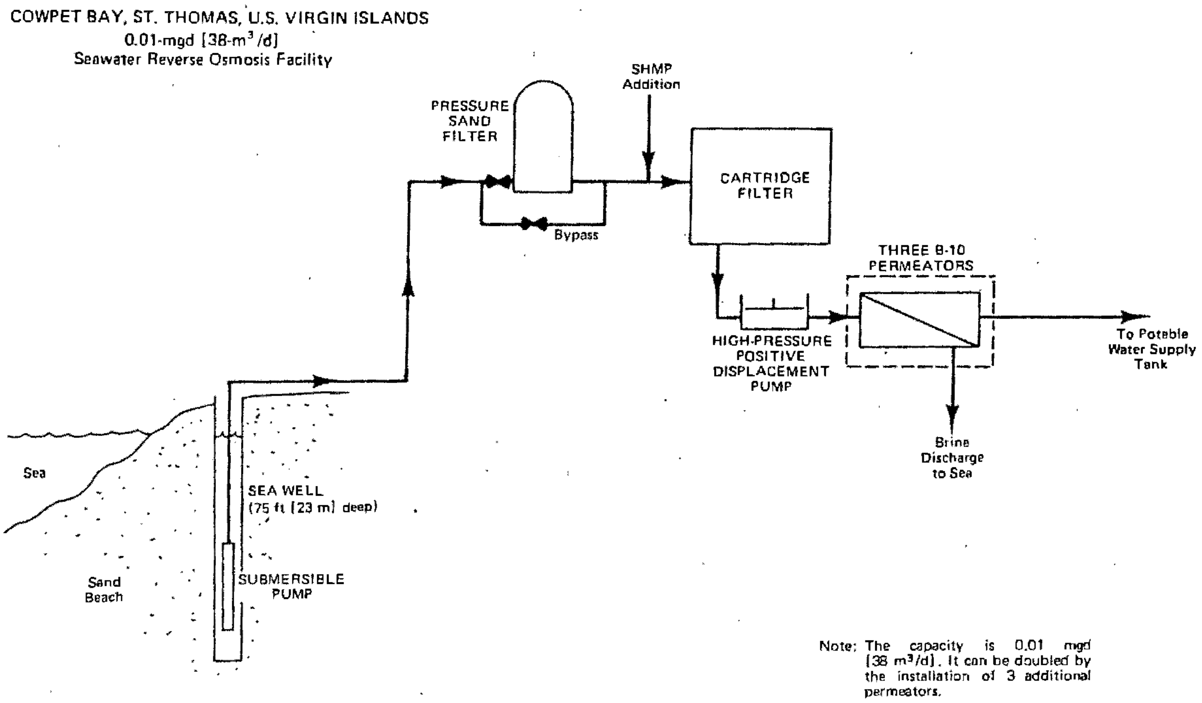


Figure 2.5: Tubular membrane stack at Bitterfontein, Cape Province, capacity 150 m^3/d



Note: The capacity is 0.01 mgd [38 m³/d]. It can be doubled by the installation of 3 additional permeators.

Figure 2.6: Typical process diagram for minimum-type RO installation
(SHMP = sodium hexametaphosphate, a precipitation inhibitor which discourages the deposition of problem salts, typically dosed at 1 to 10 mg/ℓ depending on feed water characteristics)

☐ Operation and Maintenance Requirements

Operation and maintenance requirements will vary according to the size and complexity of the installation. The very minimum requirements would be regular renewal of microfilters, chemical addition, replacement of membranes and pump care. More complex plants might require additional maintenance on the pretreatment side, e.g. backwashing of sand filters. The Bitterfontein plant (current production 100 m^3/d) has two full time operators.

☐ Costs

The Bitterfontein plant is producing water at a cost of R26/m^3, including amortization, operation and maintenance (all costs quoted here were supplied by the Department of Water Affairs, Western Cape Region, who are responsible for the scheme). This price also includes the cost of the borehole network supplying water to the plant, and the pipeline delivery to Bitterfontein and Nuwerus, 15 km distant. The actual cost of the desalination plant itself is R12-05/m^3 for capital amortization at 17,25%, and R6-97 for operation and maintenance, for a total of R19-03/m^3. These prices are quite high in comparison to the figures generally quoted for RO desalination at this scale, but it must be noted that the plant is not yet operating at its full capacity, which will be nearly double the current figure. Although this higher capacity will only be achieved at the cost of an additional membrane stack, the bulk of the balance of the scheme is already in place, so the final cost per m^3 can be expected to be not much more than half the current price (it should also be realised that the Bitterfontein scheme is something of a showcase project, being the first of its kind in the country, which has tended to increase the costs beyond the norm).

Commercial RO plants in South Africa start at about 5 m^3/d capacity. Manufacturers have found it impossible to scale their plant down from that level economically. These units start at ± R40 000, assuming electricity is available for powering the pump. If no electricity is available, a further R5 000 will be required for the diesel pump. Operation and maintenance costs quoted are in the order of R3 per m^3, excluding labour (Danie Nel, Membratek, Martin Slabber, AEC and Mitchell, Seabrak, pers. comms).

Research is currently being done at the Division of Water Technology, CSIR, on low pressure (6 to 7 bar) small scale RO units. It is believed that such a unit producing from 200 l/d could be marketed for ±R5 000 (Dr J.J. Schoeman, CSIR, pers.comm). Confirmation of this is not expected until 1992.

Attempts have been made to market small hand pump powered reverse osmosis units. With a production of only 1 ℓ/hr the unit's cost of R2 000 to R3 000 proved too high for successful commercialization. (Martin Slabber , AEC, pers. comm)

Summarising the available cost information on Reverse Osmosis, it appears that the minimum capital outlay, given products currently available, is not less than R40 000. This will provide a unit that can produce from 5 m^3/d to 10 m^3/d of product water at a TDS of below 500 mg/ℓ, assuming feed salinity of between 2000 and 6000 mg/ℓ. Including maintenance and labour, the cost per m^3 of product water will be in the order of R13, assuming that the full capacity of the system is used. If, say, only *0,5* m^3 of product water is produced daily from a system of this capacity, that water will still bear the full capital cost of the installation, and will cost in the order of R70/m^3.

If the current attempts to produce a R4 000 to R5 000 RO unit with a product water capacity of 0,5 m^3/d are successful, then it will be possible to achieve product water costs of ± R13/m^3 at this low scale. Operating such a unit at a scale of 100 ℓ/d would lead to a product water cost in the order of R30/m^3.

2.2.2 Ion Exchange

□ Operating Principle

Unlike other desalination processes described here, ion exchange does not remove all salts in equal, or roughly equal, proportions. Ion exchange is used to target and remove a particular problem ion in a water e.g. Ca^{2+} in the case of an excessively hard water (cation exchange), or NO_3^- in the case of a water having too much nitrate (anion exchange). The removed ion changes places with an ion from the ion exchange *resin*, often Na^+ or Cl^-. After all the sacrificial ions in the resin column have been swopped out of the resin, the resin is regenerated by passing through it, in the reverse direction to the normal flow direction, a concentrated solution of the sacrificial salt (e.g. NaCl).

McRae (1976) describes the difference between anionic and cationic selective resins:

Modern ***cation selective*** *[resins] typically consist of polystyrene having negatively charged sulphonate groups (SO_3H) chemically bonded to most of the phenyl groups in the polystyrene. The negative charges of the sulphonate groups are electrically balanced by positively charged cations ('counter-ions') [e.g.H^+ or Na^+]. The sulphonate groups impart hydrophilicity to the polymer . . . The positively charged counter-ions are appreciably dissociated from the bound, negatively charged sulphonate groups into the absorbed water and are mobile therein. They may be exchanged for other cations from a solution bathing the [resin]. Such exchange does not alter the electroneutrality of the [resin].* ***Anion selective*** *[resins] typically consist of insolubilized polystyrene having positively charged quaternary ammonium groups ($R_4N^+OH^-$) chemically bonded to most of the phenyl groups in the polystyrene. In this case the counter-ions [e.g. OH^- or Cl^-] are negatively charged.*

□ Minimum installation

Pumping may be required to get the feed water to an elevation, or pressure, to enable it to pass through the ion exchange column. The column itself will typically contain a sand layer before the resin to filter out colloidal matter and organics, and where there is a likelihood of iron precipitation it may contain an anthracite layer as well.

In the context of drinking water supply on a small scale, a good example of a minimum type ion exchange process is given by the following case study:

Drinking water supply to the Seaparankweh Makapan Health Centre, Bophuthatswana: (CSIR, Watertek Report Ref. W24/25/3/11, 1991)

The clinic is supplied by a borehole yielding water containing over 50 mg/ℓ NO_3^- (as N). An ion exchange column was installed by a commercial firm to reduce the nitrate in the water to 1 mg/ℓ. For this nitrate reduction the column would have to be regenerated after the passage of every 36 m^3, requiring 30 kg of NaCl and taking 36 minutes. The column was charged with 80 litres of a proprietary anion exchange resin. The flow rate through the column when operational was between 1 and 3 m^3. Assuming a consumption of 100 ℓ/d of drinking water at the clinic, the column would need to be regenerated about once per year. The layout of the installation is illustrated in Figure 2.7.

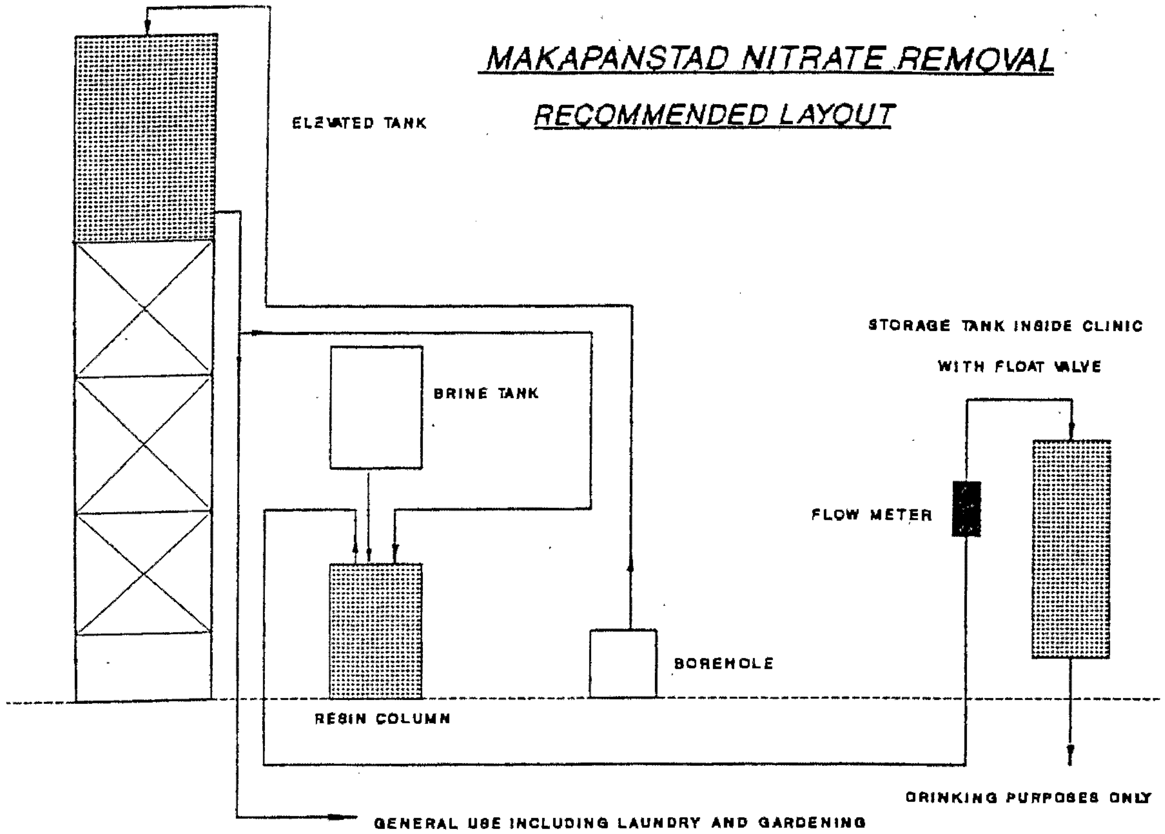


Figure 2.7: Process layout for Makapanstad ion exchange plant (100ℓ/d)

□ Operation and maintenance requirements

In an installation such as the one described above, the principle maintenance that has to be done is the regeneration and rinsing of the resin column. To do this requires the operator to be competent to mix the required regenerant salt to the specified concentration, and to operate the pump that drives the regeneration process. The operator should also be competent to know when the process is working properly, and when the resin is in need of regeneration.

After a number of backwash cycles, the resin becomes exhausted and needs to be renewed. A rule of thumb often applied is that 10 to 20 % of the resin will need to be replaced every year, given that the process operates continuously. In the case of the installation at Makapanstad the demand is so much lower than the capacity that the resin will not have to be renewed for several decades, unless other factors cause it to deteriorate.

□ Costs

The Makapanstad clinic's water problem is a good example of the kind of need that this thesis attempts to address. Unfortunately the ion exchange plant installed there is substantially over designed for that need. This illustrates the universal problem that commercial desalination plants do not tend to be produced for very small demands (20 to 200 ℓ/d).

The cost of this installation at 1991 prices would be approximately:

Tank:	R1400	
Pump:	R1000	
100 ℓ Resin:	R2500	(R25 per litre)
Other:	R 500	
TOTAL:	**R5400**	

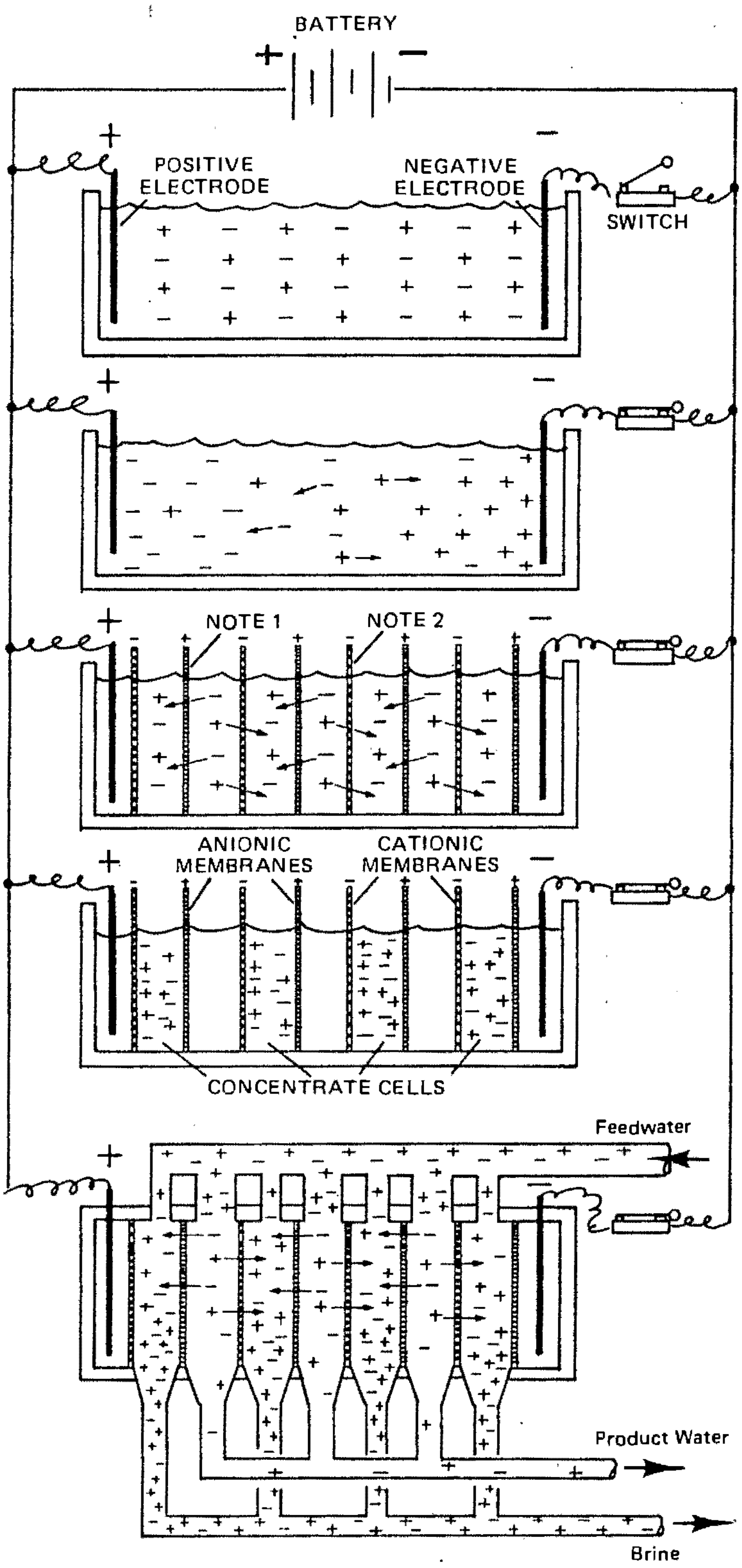
The regenerant would cost ± R1/m^3 water processed.

For a production of 100 ℓ/d the treatment cost is ± R30/m^3, excluding the cost of skilled supervision, which is necessary for the viability of this process. Including the cost of skilled supervision the water cost would be more than double, but this unit could have been built for half the price (probably not less) if it had been sized for the actual demand.

2.2.3 Electrodialysis

□ Operating principle

Electrodialysis (ED) transports ions through membranes from one solution to another by means of direct electric current. The membranes are essentially ion-exchange resins in sheet form. An important difference is that being thin (≈0,3 mm) the ED membranes do not permanently retain the ions removed from solution, but function by their exclusion of ions in the solution of like charge to the fixed charged groups in the resin. For example a cation selective membrane may consist of polystyrene with negatively charged bound groups (eg sulphonate groups) and mobile H$^+$ counter-ions. Cations in the solution being acted on by the electric current will be able to move into this membrane, not being repelled by the negative fixed groups in the membrane. As the cations move into the membrane the original H^+ counter ions are displaced out of the other side of the membrane, and the membrane maintains its overall electroneutrality. Such a cation selective membrane would be impermeable to anions. The cation selective membrane's mechanism is mirrored in the anion selective membrane. Figure 2.8 (after Buros, 1980) gives a clear step by step explanation of the electrodialysis principle.



Many of the substances which make up the total dissolved solids in brackish water are strong electrolytes. When dissolved in water they ionize; that is, the compounds dissociate into ions which carry an electric charge. Typical of the ions in brackish water are Cl^{-1}, Na^{+1}, HCO_3^{-1}, Mg^{+2}, SO_4^{-2}, and Ca^{+2}. These ions tend to attract the dipolar water molecules and to be diffused in times, fairly evenly throughout a solution.

If two electrodes are placed in a solution of ions, and energized by a battery or other direct current source, the current is carried through the solution by the charged particles and the ions tend to migrate to the electrode of the opposite charge.

If alternately fixed charged membranes (which are selectively permeable to ions of the opposite charge) are placed in the path of the migrating ions, the ions will be trapped between the alternate cells formed.

Note 1: A positively fixed charge (anionic) membrane will allow negative ions to pass, but will repel positive ions.

Note 2: A negatively fixed charge (cationic) membrane will allow positive ions to pass, but will repel negative ions.

If this continued, almost all the ions would become trapped in the alternate cells (concentrate cells). The other cells, which lack ions, would have a lower level of dissolved constituents and would have a high resistance to current flow.

The phenomenon illustrated above is used in electrodialysis to remove ions from incoming saline water on a continuous basis. Feedwater enters both the concentrate and product cells. Up to about half of the ions in the product cells migrate and are trapped in the concentrate cells. Two streams emerge from the device: one of concentrated brine and the other with a much lower concentration of TDS (product water).

Figure 2.8: The principle of electrodialysis derived step by step (after Buros, 1980)

□ Minimum installation

Figure 2.9 shows the essential elements of the electrodialysis process. As in the case of RO, prefiltration to micron scale is required to prevent rapid loss of service of the membranes. Unlike RO, pressure is not required, only circulation. Also similar to RO is the sophistication of the hydraulic circuitry, but the fittings do not have to be rated for high pressures. A DC power source is a key element in the process. Acid and/or polyphosphate must be continuously added to prevent the excessive build up of scale and other deposits on the membrane walls. More sophisticated units will have electrical and hydraulic circuitry to enable the product cells and brine cells to be switched several times per hour, allowing the flushing out of scale, slimes and other deposits from the cells.

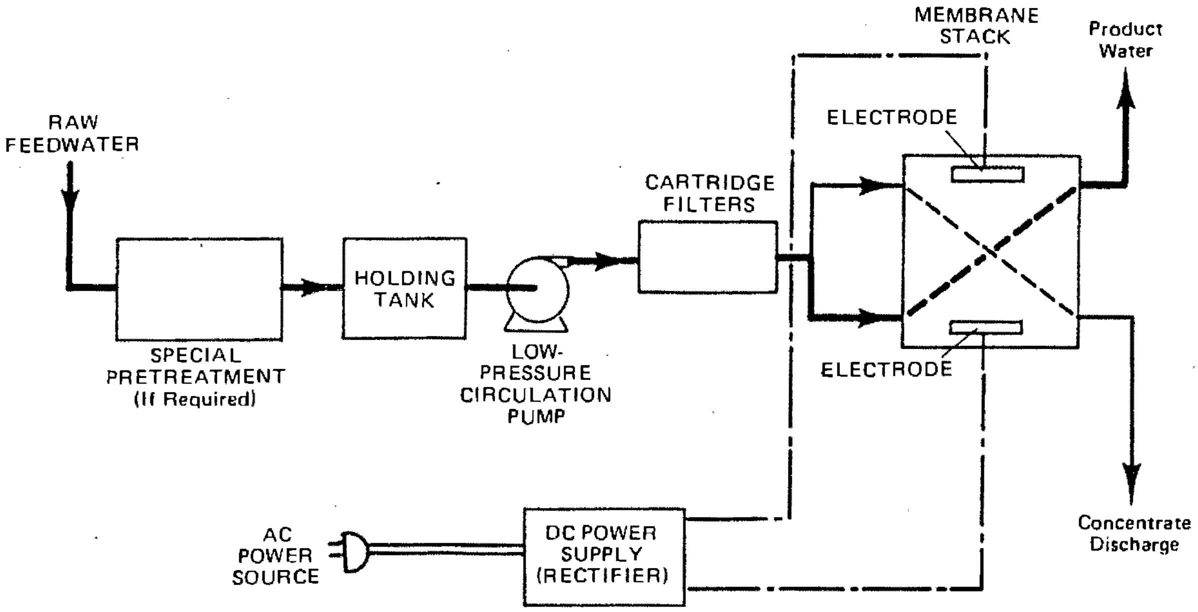


Figure 2.9: Basic components of an electrodialysis unit (Buros, 1980)

□ Costs

ED might be cheaper than RO in terms of the hydraulics of the process, but the membranes are more expensive. Thus at scales of several cubic metres per day the processes are similar in cost. ED does not enjoy such economies of scale as RO because the membrane cost constitutes a much higher fraction of the total cost, so at demands greater than this RO will generally be preferable. ED is however more suited than RO to downscaling to capacities of several hundred litres per day because the low pressure hydraulic system does not have such a high threshold cost as in the case of RO (in RO a 20 bar fitting is a 20 bar fitting, and there is a practical limit to how small you can reduce your pipe sizes, regardless of flow).

While RO membranes need replacement about every three years on average, ED membranes are more robust and generally last for about 10 years. With ED membranes more expensive, the cost of membrane replacement in the two processes is comparable.

It is probable that an ED unit with a capacity of, say, 200 ℓ/day can be produced for R2000 to R3000 (J.J. Schoeman, CSIR, pers. comm). Allowing for an energy cost of ± $50^c/m^3$, and a few rands for chemical addition, supervision and filter maintenance, the final cost of the water so produced would be in the order of $R10/m^3$. It would be impractical to build an ED unit any smaller than this because of the basic outlay (circulation pump, hydraulics, DC power supply).

Being dependent on a DC power supply, electrodialysis lends itself to the utilisation of photovoltaics. Photovoltaics are a capital intensive, but they do pay for themselves in an area remote from the electrical grid.

No commercial ED units are available in South Africa to this writer's knowledge.

2.2.5 Solar Distillation

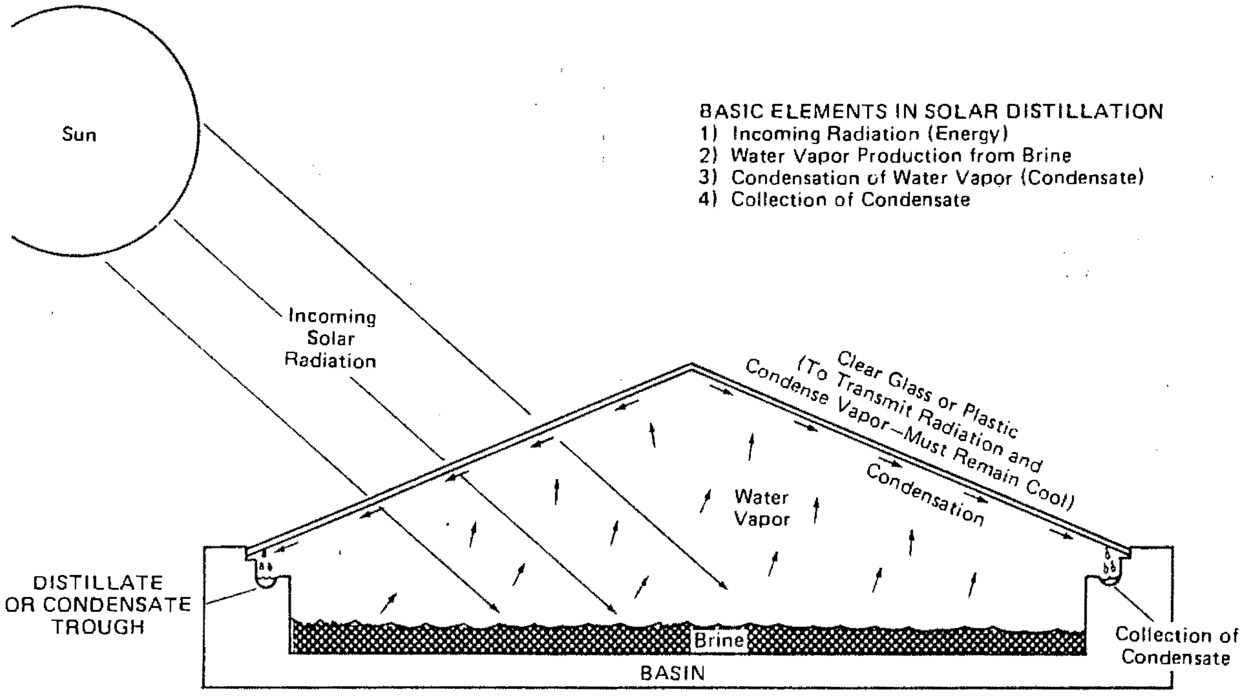
□ Operating principle

The sun's energy is used to heat the saline water, some of which evaporates. The vapour circulates by convection to a cooler surface where it condenses and is collected. Distilled water is produced in this way. Usually the whole process of evaporation and condensation is integrated into one container, typically a basin with a pitched glass cover. Figure 2.10 shows the basic elements of a basin solar still. Other still types have the water not in a horizontal basin, but flowing or cascading down an incline.

Typically 20 to 50 % of the daily solar radiation is utilized for evaporation of distillate, the balance being lost through reflection and radiation from the water and glass cover, and through losses to the ground beneath the still.

Maximum production is reached in mid summer, when the daily solar radiation is at its greatest. On clear days 5,0 ℓ per m^2 of still area can be produced. In winter time, depending on latitude, production in horizontal basin stills decreases to below 2,0 $\ell/m^2/d$ on average. Inclined stills make better use of winter time radiation, and their winter time production can stay as high as 3,0 $\ell/m^2/d$.

Unlike other desalination processes, solar distillation is insensitive to the salinity of the feed water.



The inside of the basin is usually black to efficiently absorb radiation and insulated on the bottom to retain heat.

Figure 2.10: Basic elements in a solar still

☐ Minimum installation

Solar stills can be built from a variety of commercially available materials such as common window glass, aluminium sheeting, polystyrene, bricks and mortar. Provided that standard sizes of these components are used in the design, there is practically no economy of scale in moving from a 1 m^2 still to, say, a 1000 m^2 still. There are some savings at larger scales in terms of the water supply and collection systems, but these can be offset by the increased structural complexity of the larger stills.

Solar stills can be built for capacities of as little as 2,0 ℓ/d without loss of economy.

☐ Operation and maintenance

Apart from of course supplying water to the still, operation and maintenance is limited to the cleaning of the cover and the occasional removal of scale buildup. Scale deposition will gradually decrease the absorbency of the still base, but on the whole solar distillation is much more tolerant of scale than other desalination processes.

□ Costs

While solar stills have no economic barrier of scale as capacity decreases towards just a few litres of water per day, they also do not enjoy any significant economy of scale as capacity increases. The unit cost of water produced from solar distillation is thus essentially linear.

Maintenance costs are low, limited to the repair of occasional breakages. There is, however, a step in operational costs as one moves from a household installation, where labour can be assumed to be free, to large community stills, where it cannot be assumed free.

A range of construction costs quoted in the literature are given in Table 2.5 below. These costs have been converted to 1991 rands using the conversion chart given in Appendix F.

Table 2.5: Construction costs of solar stills*

Author and date	Still construction cost 1991 Rands/m^2
Frick (1973)	120
Ahmed (1967)	80
Morse (1970)	70
Delannis (1977)	90
Maber (1988)	110
El-Sayed (1976)	260
Lawand (1973)	170
van Steenderen (1972)	120
AVERAGE	**128**

* These prices generally only account for material cost.

Depending on labour costs for construction and maintenance, efficiency of the still, and amount of sunshine at the place of installation of the still, the cost of the distillate produced by solar stills will be in the order of R30 to R60 per m^3.

The cost of drinking water from solar stills will be less than the cost of distillate, according to the amount of blending of the feed water with the distillate that can be tolerated.

Assuming 1:1 blending and distillate cost of R30/m^3, drinking water would cost R15/m^3. This is the cheapest that drinking water can be supplied from solar distillation.

2.2.6 Evaluation of small scale desalination technologies

In evaluating which of the alternative small scale desalination technologies to use in a given situation, it is helpful to compare their performance under different headings: salinity of water source; availability of electricity; product quality; costs; and minimum operator skills.

☐ **Salinity of water source**

The level and type of dissolved salts contributing to the salinity of the water source will have a marked effect on the choice of technology. As previously stated, salinity levels of between 1,5 g/l and 35 g/l total dissolved solids may be encountered. In certain situations waters with lower salinities may also require desalination (e.g. for the removal of specific ions - fluoride, nitrate, or hardness, or for the production of distilled water for batteries or laboratory use).

Generally, solar distillation and reverse osmosis are more suited than electrodialysis or ion exchange for treating waters with high salinities.

The nature of the dissolved salts must also be taken into consideration. Generally RO is not suitable for treating wasters which are scaling in nature (i.e. close to saturation w.r.t. $CaSO_4$ or $CaCO_3$), have high levels of iron, or require the removal of a specific ion only (e.g. fluoride). RO may, however, be well suited to removing hardness from water when this is non-scaling in nature. Ion Exchange is also not well suited for treating scale forming waters, although in industry special processes have been developed to deal with such problems.

☐ **Availability of electricity**

Both RO and ED require electrical power for their operation. In remote areas where electrical power is not available, or where costs are high (e.g. from a diesel generating set), these technologies may not be suitable.

The primary power requirement for RO is for pumping to high pressures. This could be accomplished with a diesel engine driven pump, but the important aspects of system protection by high and low pressure cutouts etc. would require some source of electric supply.

Solar distillation and ion exchange technologies do not require electrical energy.

☐ Product Quality

The desired product quality may also affect the choice of technology. Table 2.6 compares the suitability of the different desalination processes for different product water types:

Table 2.6: Desalination technology suitability compared with product water required

Desalination product	Technology Choice			
	Solar distillation	Reverse Osmosis	Electrodialysis	Ion Exchange
Drinking Water (from brackish water)	+++	+++	+++	+
Drinking Water (specific iron removal)	++	+	++	+++
Pure water (e.g. for batteries)	+++	-	-	++
Softened Water	++	+++	++	+++
LEGEND: +++ well suited, ++ suitable, + may be used, - not suitable				

☐ Level of skills to operate and maintain

The operation and maintenance levels required by the system may influence the choice of technology. In areas where a system is required which must operate on its own with minimal attention, the technology selected must match these requirements. where a level of technical skills are available, alternative systems may be more easily considered. The skills levels required for the different systems are:

solar distillation:	unskilled, minimum time
reverse osmosis:	technical skills, significant time
electrodialysis:	technical skills, medium time
ion exchange:	low skills, medium time

☐ Costs

The costs associated with each technology may be divided into capital, running and maintenance costs. The source of funding and the ability to pay for ongoing costs will influence the choice of technology. For each technology, the associated costs are summarized qualitatively in Table 2.7.

Table 2.7: Qualitative comparison of costs for alternative desalination technologies

	Capital	Running	Maintenance
Solar distillation	High for all capacities	Low (filling and cleaning)	Low: Some glass and seal replacement, periodic descaling, or wick replacement
Reverse Osmosis	Very high for small quantities, medium for larger capacity plants	high in terms of pumping and chemicals, as well as skilled manpower for supervision	High: Periodic membrane replacement, some mechanical component replacement
Electrodialysis	Very high for small quantities, medium for larger capacity plants	High in terms of electrical energy, chemicals and skilled supervision	Medium: Membrane replacement and mechanical components
Ion Exchange	High, reducing slightly for larger capacities	High, chemicals,	High: resin replacement and mechanical components

Conclusion of evaluation of alternatives for small scale desalination

Hard cost information on the competing desalination alternatives is hard to come by without embarking on an exhaustive investigation. It is clear from the above, however, that neither reverse osmosis, electrodialysis nor ion exchange can be economically applied at the minimum household demand level of 10 to 20 ℓ per day as specified in Table 2.3. At this level, solar distillation is the only option that is economically applicable, and viable from a maintenance point of view.

At demands above this minimum level, the decision about when to switch over to an alternative technology will depend on the type of feed water, the type of product water required, the availability of electricity and the types of skills available amongst those expected to operate the plant. Table 2.8 suggests demand ranges at which the various technologies might best apply. Between 200 ℓ/d and 500 ℓ/d solar distillation could only be justified if the community being served were dependent on very saline water (e.g. sea water), if electricity was unavailable, and if the skills base in the community was low. It is hard to see how solar distillation could be justified at demands of above 500 ℓ/d, under any circumstances.

Table 2.8: Suggested economic capacity ranges for competing desalination technologies, depending on circumstances

Desalination technology	Suggested Capacity Range (ℓ/d)	Favourable indicators for use
Solar Distillation	2 - 200	No electricity supply, very salty water (e.g. sea water), high sunshine levels, low skills base
Electrodialysis	100 - 5 000	Feed water TDS < 5 000 mg/ℓ high skills base, availability of electricity
Reverse Osmosis	> 3 000	Availability of electricity, medium skills base, feed water TDS < 10 000 mg/ℓ
Ion Exchange	> 100	Specific problem (e.g. NO_3^-) as opposed to overall TDS problem, high skills base

Finally, in support of the above discussion about the relative merits of the various desalination technologies at small scale, the field experience of Mr A.S. Strydom has relevance (extract from letter to CSIR dated 3/4/1989):

During November 1985 to April 1986 I was involved in an Army project on border farms from Swartklip (Western-Transvaal) to Pafuri in the East.

One of the problems which struck me from the outset was the lack of drinking water on a large number of farms. Farmers use various methods to try to solve the problem, including:

1) *de-ionisers*
2) *electric distillers*
3) *chemicals etc.*

with all the problems that are involved with these methods, most of them very quickly fall into disuse.

I tried myself to sell Reverse Osmosis systems but was not successful because the capital and maintenance costs were not at all economically justifiable.

Therefore, in my opinion, a system will only work if it can meet the following requirements:

1) *capital cost reasonably low;*
2) *rugged;*
3) *reliable;*
4) *little maintenance work;*
5) *simple, so that unskilled labour can maintain it without any problem.*

CHAPTER 3

SOLAR DISTILLATION - SOME BACKGROUND AND A BRIEF REVIEW OF SOME STILL DESIGNS

3.1 Availability of Solar Radiation in Southern Africa

Solar radiation is a freely available but low intensity source of energy. In Southern Africa the global radiation average, measured in kWh/m^2/d, varies from 4,5 on the Natal coast to 6,5 in the Namib desert (Eberhard, 1990). The intensity of the sun varies through the day and the year according to its position in the sky. The sun's position in the sky at noon i.e. the angle between the sun and a horizontal plane, h_N, at latitude[a] L is given by the relation:

$$h_N = 90° - (L + D) \qquad 3.1$$

where D is the declination of the sun[b]. Thus at Pretoria, latitude 26°S, h_N is 87,5° at the summer solstice, and 40,5° at the winter solstice. To receive maximum solar radiation a surface should be perpendicular to the sun's rays. Algebraically

$$\theta_{opt} = L + D \qquad 3.2$$

where θ_{opt} is the inclination to the horizontal plane at which a surface will receive maximum radiation.

For example, at Pretoria θ_{opt} is 2,5° at midsummer and 49,5° at midwinter. These angles are illustrated in Figures 3.1 and 3.2 below. In practice it is seldom economically possible to vary the angle of a collector through the year, so the optimum angle would be one that gives the best year round average radiation. Cawood and Johnson have plotted the annual variation of total solar radiation on horizontal and tilted surfaces for Cape Town and Pretoria (Figure 3.3). From their plot it can be seen that a collector would receive the most steady level of radiation year round if it was inclined at 35° in Pretoria, and 53° in Cape Town.

While a still should ideally be oriented due north for optimum efficiency (if it was economically possible to have it track the sun through the day that would be better yet), it will not lose more than 5% efficiency if it is oriented within 30° of true north. The effect of orientation on efficiency is given in Figure 3.4, which is due to Balcomb, et al (1975).

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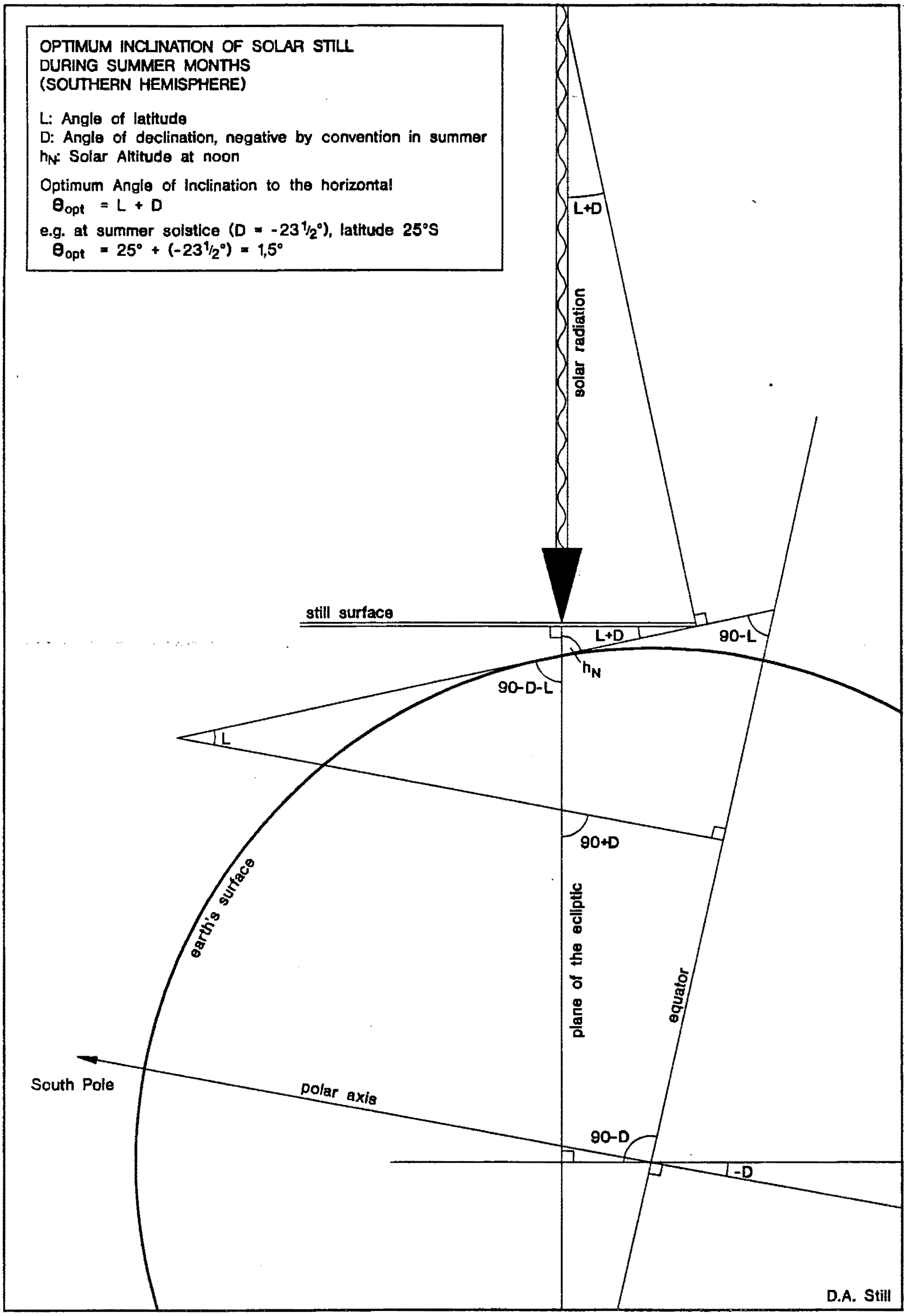
[a] The angle of latitude at a point on the earth's surface is defined as the angular distance of that point from the equator measured upon the curved surface of the earth, and is equal to the angle contained between the line tangential to the polar circumference of the earth at that point and the polar axis.

[b] The earth's rotates about its polar axis to give us night and day, and it orbits the sun once a year. The polar axis is tilted at an angle of 23,5° to the plane of the earth's orbit around the sun, called the plane of the ecliptic. This tilt means that a hemisphere is tilted towards the sun during part of the earth's orbit, and away from the sun at the opposite point of its orbit. These two extremes cause the change of the seasons. *The declination is the angle between the polar axis and the normal to the plane of the ecliptic, and it varies through the year from + 23,5° at the summer solstice to -23,5° at the winter solstice.* By convention declination is defined for the northern hemisphere, so that in South Africa the sun's declination is negative in summer and positive in winter. A table of declination through the calendar year appears in Maaren, 1976.



OPTIMUM INCLINATION OF SOLAR STILL
DURING SUMMER MONTHS
(SOUTHERN HEMISPHERE)

L: Angle of latitude
D: Angle of declination, negative by convention in summer
h_N: Solar Altitude at noon

Optimum Angle of Inclination to the horizontal
$\theta_{opt} = L + D$

e.g. at summer solstice ($D = -23\frac{1}{2}°$), latitude 25°S
$\theta_{opt} = 25° + (-23\frac{1}{2}°) = 1{,}5°$

Figure 3.1: θ_{opt} during summer in the southern hemisphere

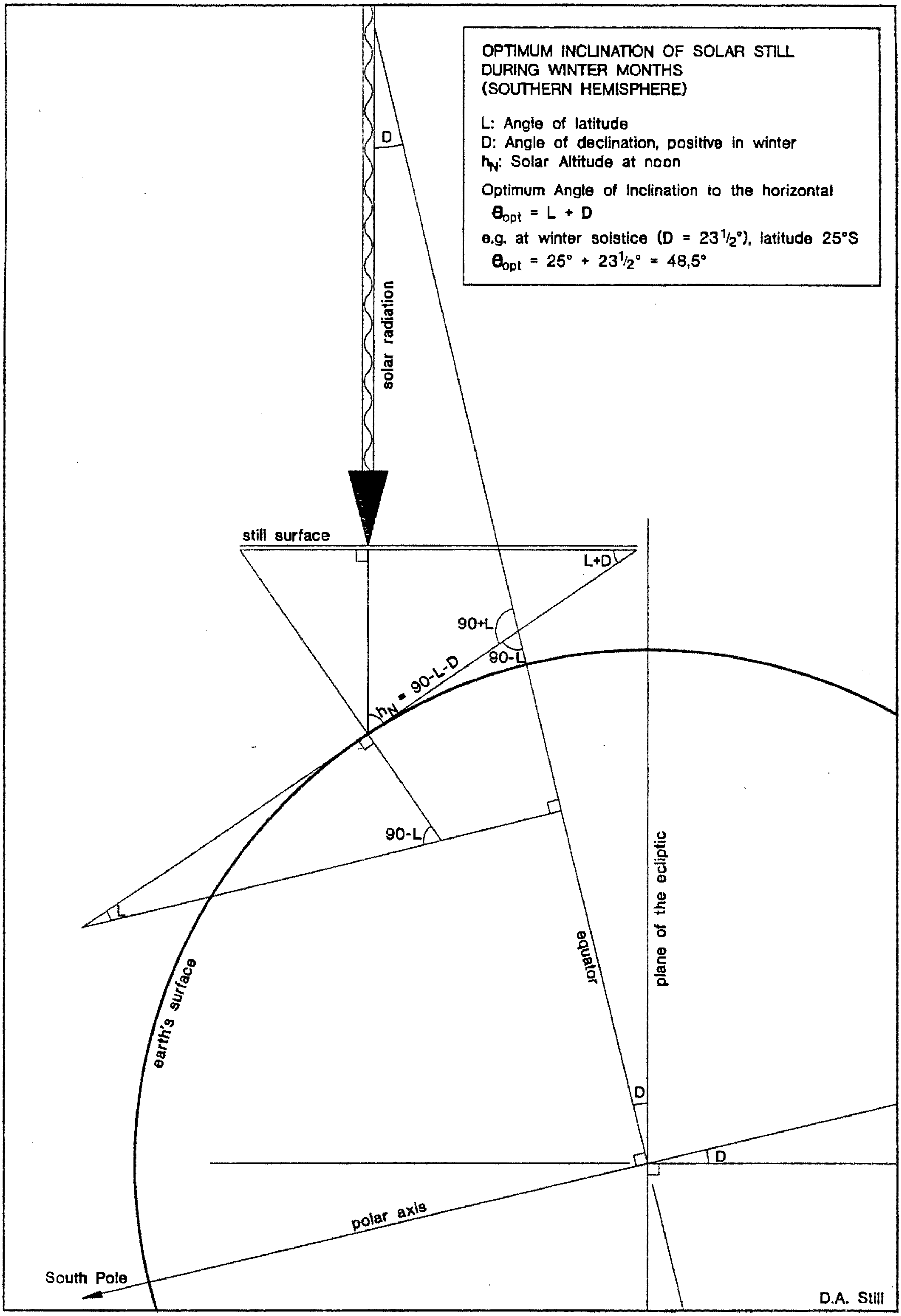


Figure 3.2: θ_{opt} during winter in the southern hemisphere

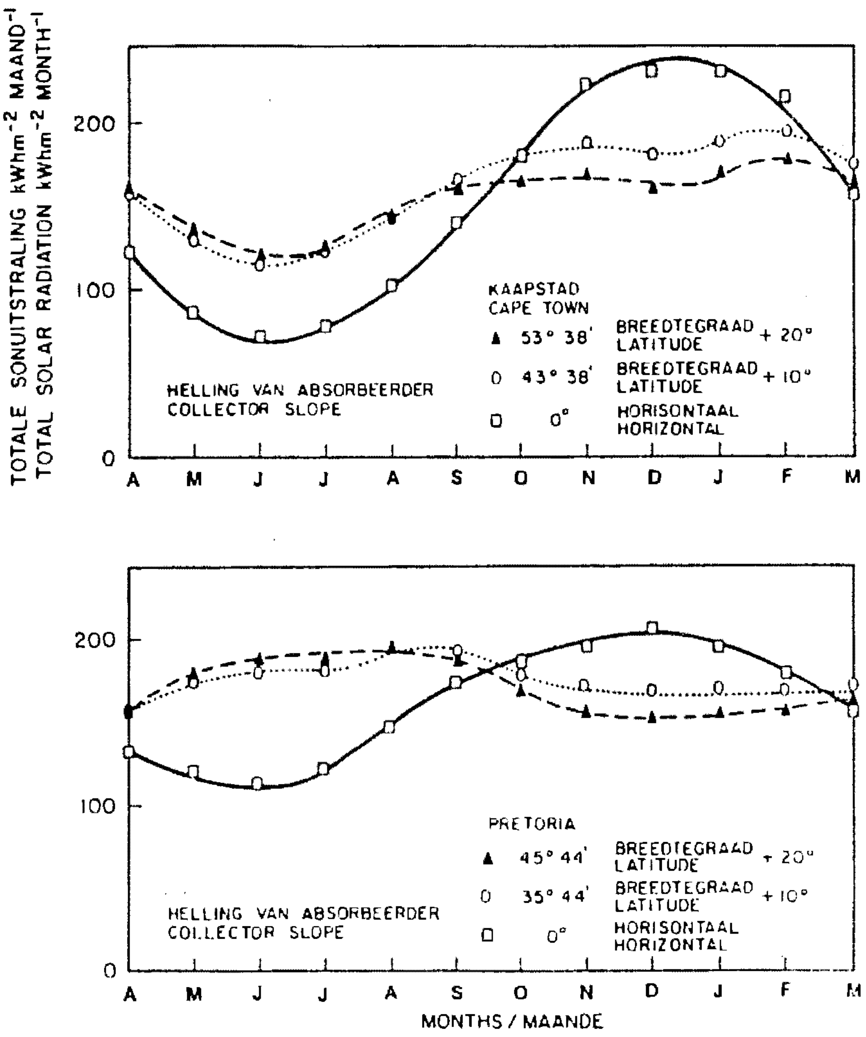


Figure 3.3: **Annual variation of total solar radiation on horizontal and tilted surfaces for Cape Town and Pretoria (Cawood and Johnson, 1977)**

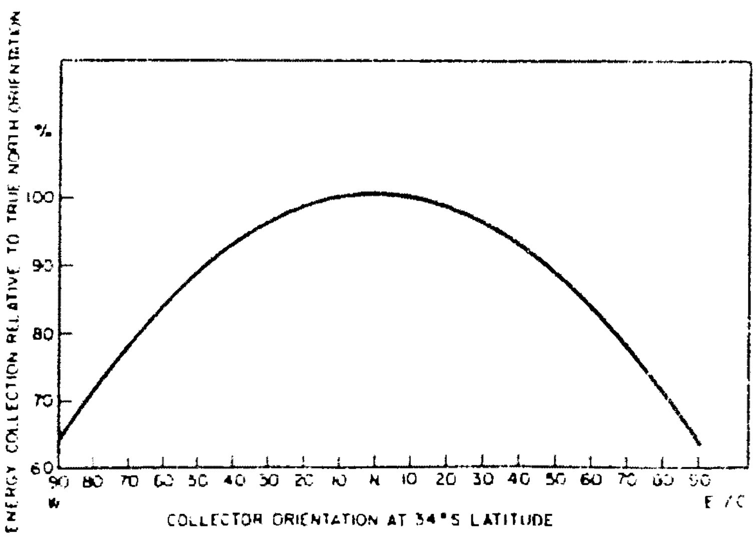


Figure 3.4: **Effect of orientation of collector on energy collection (Balcomb et al, 1975)**

Global solar radiation can be separated into two components: the direct component which beams directly down from the sun, and the diffuse component which is scattered by the atmosphere, tall objects, clouds etc. and which approaches a surface from virtually all angles. Yellott (1963) has shown that glass transmittance falls off dramatically for angles of incidence of greater than 50° (Figure 3.5). Since nearly all solar stills use a glass cover, the diffuse component of the total radiation is not efficiently utilized. The diffuse fraction of global radiation varies according to season and location, but in Southern Africa it lies in the range 15 to 45%. Fortunately in the more arid regions where solar distillation is likely to be of benefit the diffuse fraction is generally below 25% of average global radiation figures (Chinnery, 1971).

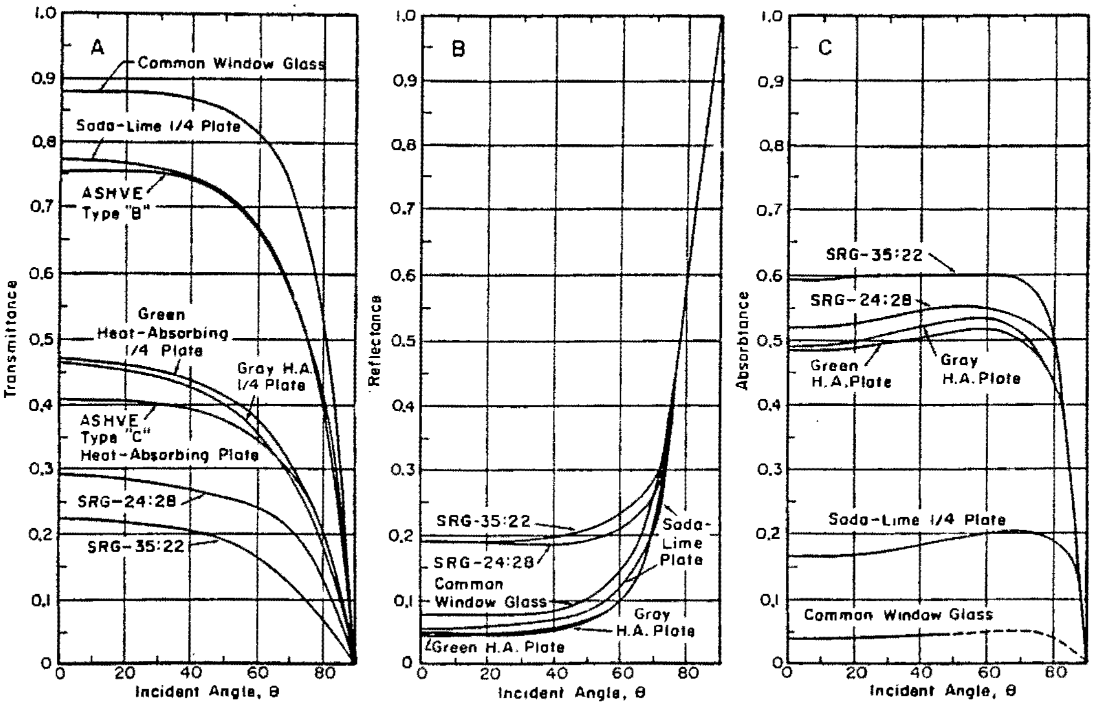


Figure 3.5: Solar transmittance, reflectance and absorbtance of common glasses according to Yellott (1963)

Solar radiation in Southern Africa has been monitored by the Weather Bureau since 1951 (Chinnery, 1971). Sunshine duration and hourly diffuse and total radiation are measured at twelve sites around the country, and sunshine duration only is recorded at a further hundred odd sites. Using standard equations for relating sunshine hours to global radiation, and correlating with sites where radiation figures are available, Eberhard has produced a solar radiation data handbook for Southern Africa. Included in this handbook are tables with the calculated radiation values for inclined surfaces at each of the twelve main Weather Bureau stations, as well as radiation maps for the region for each month of the year. Figures 3.6 and 3.7 are reproductions of Eberhard's radiation maps for December and June, while 3.1 and 3.2 are his tables for radiation incident on inclined surfaces at Pretoria and Cape Town respectively.

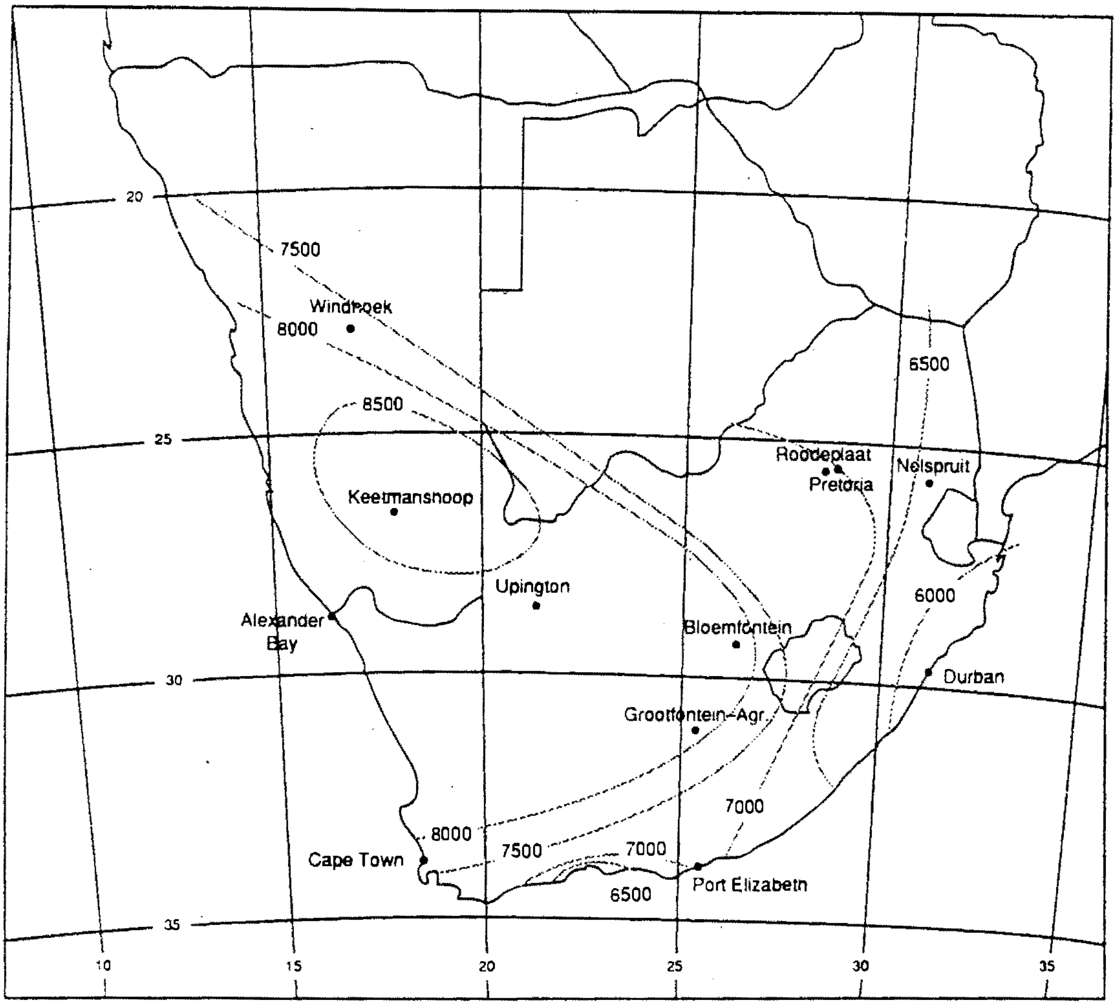


Figure 3.6: **Global radiation for Southern Africa for December measured in Wh/m²/d, according to Eberhard (1990).**

Table 3.1: **Mean daily global radiation on tilted surfaces, calculated for Pretoria (Wh/m²/d) (Eberhard 1990)**

Degrees	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	Annual Mean
5	6288	6029	5435	4835	4528	4310	4540	5277	5969	6329	6367	6812	5560
10	6232	6052	5566	5085	4877	4712	4934	5633	6183	6403	6335	6717	5727
15	6142	6037	5661	5302	5195	5083	5297	5953	6357	6436	6263	6590	5860
20	6014	5986	5721	5485	5479	5421	5624	6234	6489	6428	6152	6421	5954
25	5850	5898	5744	5632	5726	5722	5913	6472	6578	6379	6003	6213	6011
30	5652	5774	5732	5742	5934	5984	6163	6668	6624	6289	5818	5967	6029
35	5420	5617	5683	5815	6103	6206	6370	6818	6627	6159	5597	5685	6008
40	5157	5431	5599	5849	6230	6385	6534	6923	6585	5989	5343	5370	5950
45	4868	5212	5480	5846	6315	6519	6653	6980	6501	5782	5057	5035	5854
50	4566	4962	5326	5803	6357	6609	6726	6990	6373	5540	4754	4683	5724
55	4241	4685	5140	5722	6355	6653	6753	6952	6204	5263	4430	4306	5559
60	3895	4392	4922	5604	6310	6651	6733	6868	5994	4953	4083	3908	5359
65	3531	4075	4675	5449	6223	6603	6666	6736	5746	4618	3714	3493	5128
70	3155	3738	4399	5259	6092	6509	6554	6560	5461	4264	3331	3088	4867
75	2803	3384	4099	5035	5921	6370	6396	6338	5141	3886	2946	2698	4585
80	2453	3018	3776	4778	5709	6188	6195	6075	4788	3489	2583	2307	4280
85	2123	2653	3433	4492	5459	5962	5951	5771	4407	3078	2218	1974	3960
90	1834	2309	3075	4177	5172	5696	5667	5428	4000	2661	1899	1697	3635

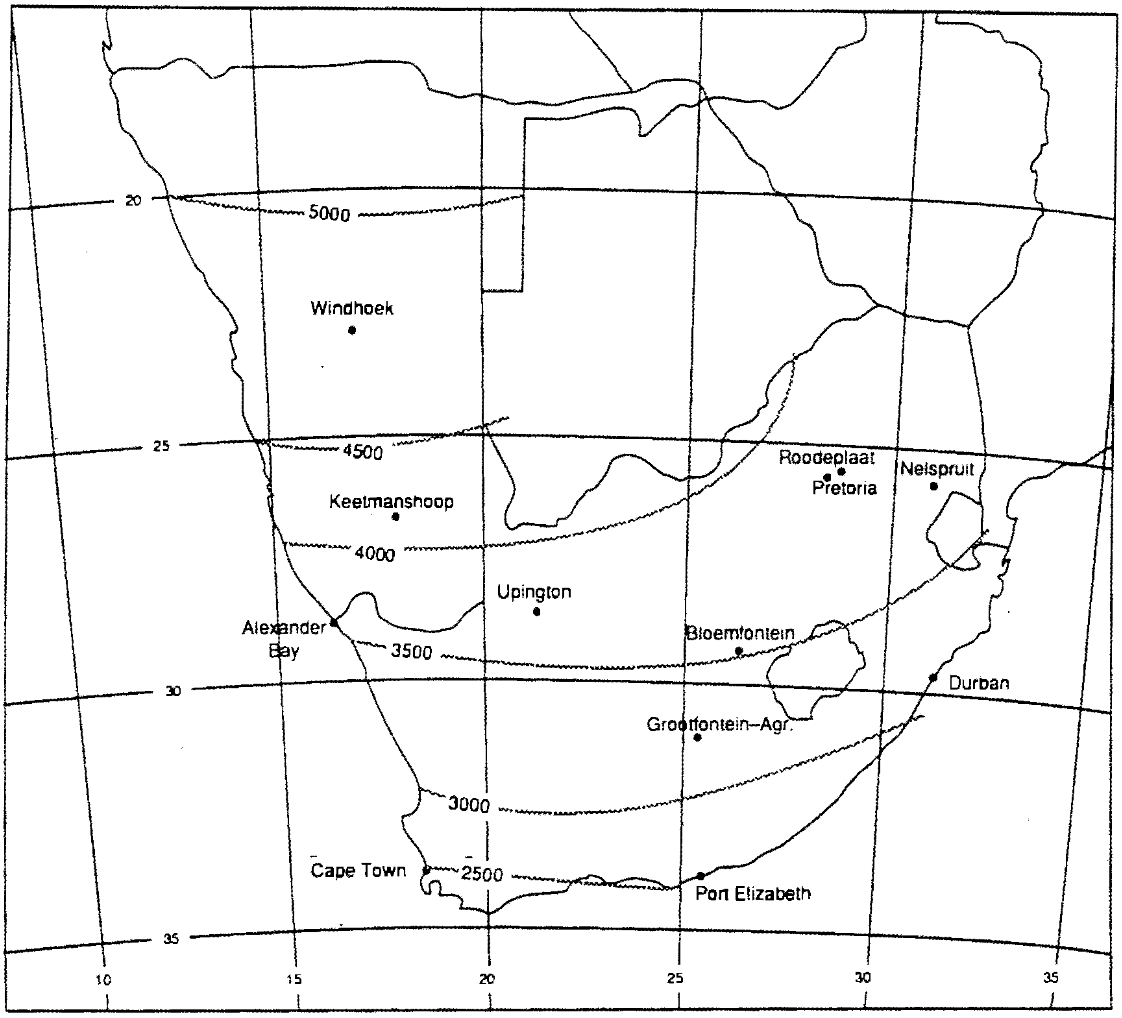


Figure 3.7: Global radiation for Southern Africa for June measured in $Wh/m^2/d$, according to Eberhard (1990)

Table 3.2: Mean daily global radiation on tilted surfaces, calculated for Cape Town ($Wh/m^2/d$) (Eberhard 1990)

Degrees	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	Annual Mean
5	7964	7297	6131	4536	3245	2684	2989	3742	4961	6443	7591	7927	5459
10	7948	7407	6363	4860	3554	2989	3304	4033	5198	6589	7611	7882	5645
15	7881	7470	6554	5152	3841	3276	3599	4298	5402	6693	7587	7786	5795
20	7780	7484	6702	5411	4103	3542	3871	4535	5572	6754	7523	7652	5911
25	7630	7450	6805	5635	4338	3785	4118	4743	5706	6771	7411	7477	5989
30	7432	7367	6864	5821	4545	4002	4337	4921	5803	6745	7252	7256	6029
35	7187	7237	6878	5969	4721	4193	4528	5066	5862	6676	7048	6989	6029
40	6896	7060	6846	6076	4866	4356	4688	5177	5884	6563	6800	6679	5991
45	6563	6837	6769	6143	4977	4489	4816	5254	5867	6410	6511	6330	5914
50	6190	6571	6648	6169	5056	4591	4912	5297	5812	6215	6181	5942	5799
55	5795	6264	6483	6153	5100	4662	4975	5304	5720	5981	5817	5548	5650
60	5383	5918	6275	6096	5109	4702	5003	5275	5591	5711	5442	5129	5469
65	4941	5544	6028	5997	5083	4708	4998	5211	5425	5405	5036	4682	5255
70	4473	5148	5741	5859	5024	4683	4958	5113	5225	5066	4604	4212	5009
75	3982	4723	5418	5681	4930	4626	4885	4981	4992	4706	4148	3723	4733
80	3491	4271	5061	5466	4802	4536	4778	4816	4728	4323	3674	3271	4435
85	3030	3798	4673	5215	4643	4416	4639	4619	4434	3917	3220	2819	4119
90	2563	3310	4258	4929	4452	4266	4469	4392	4114	3492	2777	2387	3784

3.2 Basic theory of Solar Distillation

3.2.1 Introduction

Stills powered directly by the sun generally consist of a water basin or wick, covered by sloping glass or plastic, on which water is condensed or collected. The classic basin distillation process is represented schematically in Figure 3.8 (after Löf, 1963). Saline water is fed either continuously or intermittently to the pool having depths typically ranging from 2 to 20 cm. The bottom of the pool has a black surface to absorb solar energy. A drain is provided for continuous or intermittent discarding of the brine. The condensate which forms on the inside surface of the cover runs down to collection troughs at its lower edges.

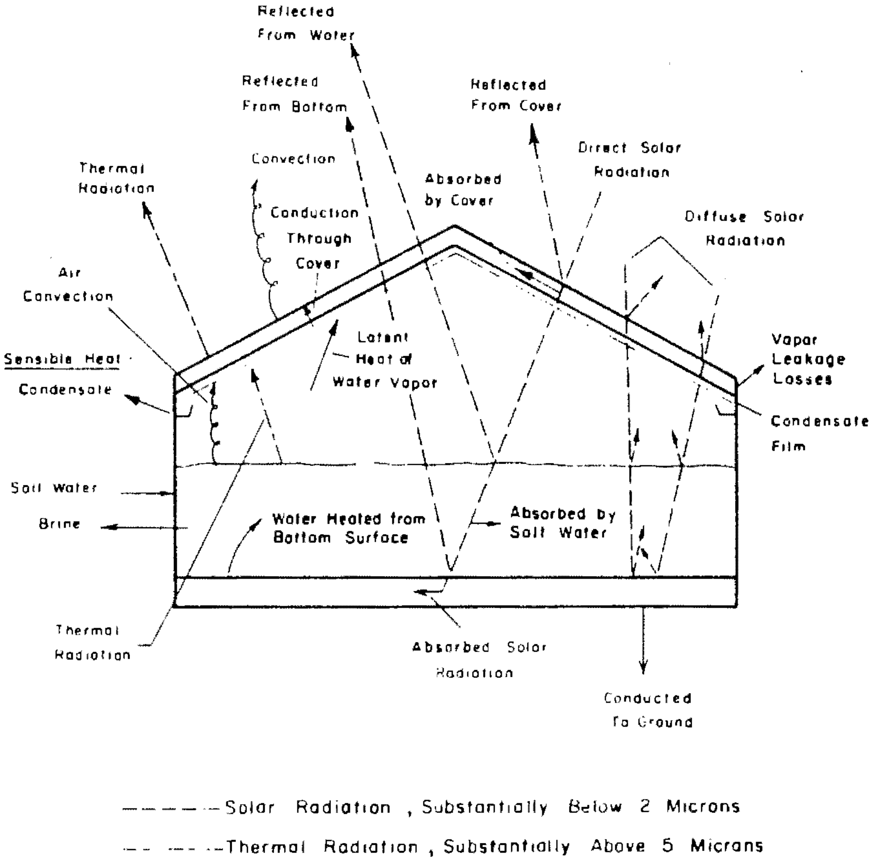


Figure 3.8: Schematic cross section of basin solar still and diagram of principal energy flows (after Löf, 1966)

The still receives direct and scattered (diffuse) solar radiation, and long wave thermal radiation from the atmosphere. A portion of both types of radiation is reflected, according to the angle of incidence of the radiation and the reflectivity of the surface, and a portion passes into the glass. Of the radiation that is not reflected, the long wave radiation is completely absorbed in the glass, the short wave solar radiation only partly, according to its angle of incidence and the type of glass (ref. Figure 3.5) .

A portion of the incident solar energy having been transmitted by the cover, Löf continues as follows:

Solar energy transmitted by the cover is partially absorbed in the salt water, the major portion being absorbed on the basin bottom. Heat is conducted from the bottom surface into the salt water, thereby increasing its temperature and vapour pressure; partial vaporization into the open air space then occurs. Convection currents carry the warm, vapour-laden air to the transparent cover, which is generally 10 to 30°F [6 to 17 °C] cooler than the brine. Moisture condenses on the underside of the cover, the heat of condensation being conducted through the cover to the surrounding atmosphere; the partially dehumidified air drifts back to the surface of the brine for further moisture addition. A thin film of condensate flows down the transparent cover to the collecting trough, from which it passes to storage. Unevaporated brine, typically about half the feed, is run to waste, thereby preventing salt deposition.

Before going on to describe the distillation mathematically, it is important to describe the modes of heat transfer operative in the process - conduction, convection, evaporation and radiation:

3.2.2 Conduction, Convection Evaporation and Radiation

☐ **Conduction:**

Thermal conduction is a process by which heat diffuses through solid bodies or through stagnant fluids. The Penguin *Dictionary of Science* (Fourth edition, 1971) describes thermal conduction as follows: *The transmission of heat from places of higher temperature to places of lower temperature in a substance, by the interaction of atoms or molecules possessing greater kinetic energy with those possessing less. In gases the heat energy is transmitted by collision of the gaseous molecules, those possessing the greater kinetic energy imparting, on collision, some of their energy to molecules having less. Conduction in liquids is mainly due to the same process. In solid electrical conductors, the chief contribution to thermal conduction arises from a similar process taking place between the free electrons present. The interaction of the molecules responsible for thermal conduction in solid electrical insulators arises from the elastic binding forces between the molecules, which are effectively fixed in space.* The law governing conductive heat transfer between two points at temperatures T_h and T_c (°C) respectively is

$$q = k \frac{T_h - T_c}{l} \qquad 3.3$$

where q = rate of heat transfer (W/m^2)
k = thermal conductivity of the material at that temperature (W/m°C)
and l = distance between the points (m)

The thermal conductivity of pure metals is a function of their electrical conductivity, and is thus easily determined. For other materials the value of k has to be determined experimentally.

□ **Convection:**

Again drawing from the Penguin *Dictionary of Science*, *convection is the transference of heat through a liquid or gas by the actual movement of the fluid. Portions in contact with the source of heat become hotter, expand, become less dense and rise; their place is taken by colder portions, thus setting up convection currents.*

When heat transfer occurs between a solid surface and its adjacent fluid, the rate of heat flow is described by Newton's law of cooling

$$q = h_c \Delta T \tag{3.4}$$

where q = rate of heat transfer (W/m^2)
h_c = heat transfer coefficient (W/m^2°C)
and ΔT = temperature difference between the surface and the fluid mass

While this in itself is a simple relation, the evaluation of the coefficient h_c is exceedingly complex. It is a function of the geometry of the surface, the flow characteristics and the physical properties of the fluid. In most practical cases the heat transfer coefficient is evaluated from empirical equations obtained by correlating experimental results using methods of dimensional analysis. These coefficients are generally given by a relationship between one dependent dimensionless group, the *Nusselt* number (*Nu*), and three other independent dimensionless groups, the *Reynolds* number (*Re*), the *Grashof* number (*Gr*) and the *Prandtl* number (*Pr*), depending on whether free or forced convection applies. These dimensionless numbers are given by the following expressions:

$$Nu = hX/k$$

$$Gr = (X^3 \rho^2 g \beta \Delta T/\mu^2)$$

$$Pr = (C_p \mu/k)$$

and

$$Re = (\rho v X/\mu)$$

where g = gravitational acceleration (9,81 m/s^2)
h = heat transfer coefficient (W/m^2°C)
k = thermal conductivity (W/m°C)
β = coefficient of volumetric thermal expansion (K^{-1})

ρ = density (kg/m^3)
μ = dynamic viscosity (kg/ms)
υ = kinematic viscosity (μ/ρ) (m^2/s)
X = characteristic length of a system (m)

In the case of solar stills, the characteristic length of the system, X, would be the distance between the surface of the water and the glass.

□ Evaporation

In distillation an important mechanism of heat transfer which is linked to convection is **evaporation**. When water evaporates it changes phase from liquid to gas, a change involving a significant step in the enthalpy, or heat content, of the water. For example, the enthalpy of 1 kg of water (as liquid) at 25 °C is 105 kJ. The enthalpy of water vapour at 25 °C is 2547 kJ. The difference is known as the *latent heat/enthalpy of vaporization* of water, h_{fg}. At 25°C h_{fg} is equal to 2442 kJ/kg. At 100°C it is equal to 2257 kJ/kg. When an air stream entrains water vapour at a warm surface and carries it to a cooler surface (which has a lower vapour pressure[a]) some of the water vapour will condense out of the air stream at the cooler surface until equilibrium is re-established. When convection currents are established between a warmer and a cooler surface, there will be a continuous transport of water vapour from the warmer to the cooler (assuming the availability of water at the warm surface). This mechanism transfers a substantial amount of heat, in that the enthalpy of vapourisation of the water mass being transported is taken up at the warm surface and released at the cool surface. The rate of heat transfer due to evaporation, q_e, is given by the simple equation

$$q_e = \dot{m}_e h_{fg} \tag{3.5}$$

where h_{fg} = the enthalpy of vapourisation of water at the temperature of evaporation (J/kg)
$\dot{m}_e$ = the mass of water transferred by evaporation per unit area (kg/m^2)
q_e = the rate of heat transfer due to evaporation (W/m^2)

The prediction of m_e is complex, and closely related to convective heat transfer.

---

[a] In a mixture of gases enclosed in a container of fixed volume, each gas will exert a pressure according to the number of moles of that gas present in the container. These individual pressures are termed the *partial pressures* of the gases, and the *total pressure* exerted on the container is their algebraic sum. *Vapour pressure* is the partial pressure of water vapour. If water in the liquid form is present in an enclosed space at a given temperature, the vapour pressure will adjust through evaporation (or condensation) until it stabilizes at the *saturation vapour pressure* of water vapour at that temperature. The saturation vapour pressure of water vapour is not linearly proportional to temperature e.g. at 1°C it is 656 Pa, at 10°C it is 1227 Pa, and it is 101350 Pa at 100°C (at which temperature boiling occurs because the vapour pressure within the liquid is equal to the atmospheric pressure without).

☐ **Radiation:**

Thermal radiation is a process of heat transfer from one body to another by electromagnetic wave motion. All bodies emit radiation and the transmission of the radiant energy does not require a carrying medium. Thermal radiation detected as heat occurs mainly in the visible and infra-red regions of the electromagnetic spectrum. The calculation of thermal radiation is based on the Stefan-Boltzmann law which describes the emissive power of a blackbody, e_b, to the fourth power of the surface *absolute* temperature, T

$$e_b = \sigma T^4$$

where σ = Stefan-Boltzmann's constant = 5,67 . 10^{-8} W/m^2K^4

This equation yields the heat flux emitted by a black surface. To compensate for the fact that the amount of heat flux emitted by a real surface is lower than that for a black surface, an emissivity factor, ϵ, is added to the above equation.[a] In addition there is a continuous exchange of energy between surfaces which can see each other, so that the net rate of heat transfer from a surface at absolute temperature T_1 to another surface at absolute temperature T_2, is given by the equation

$$q = \varepsilon\sigma(T_1^4 - T_2^4) \qquad 3.6$$

For specific situations, various correction factors are applied to the formula to take account of the body shapes, the viewing angles, the radiation properties of the surfaces and of the fluid media through which the thermal radiation passes.

3.2.3 Mathematical description of solar distillation

The solar distillation process has been mathematically described by Dunkle (1961), and Malik (1982) among others.

Dunkle proposed the use of a natural (free) convection[b] relationship within solar stills and proposed the model described in this section for understanding the basics of the thermodynamics of the distillation process.

---

[a] Common values of ϵ are: water at 100°C, 0,95; smooth glass at 22°C, 0,94; commercial aluminium sheet at 100°C, 0,09; polished precious metals at ambient temperatures, 0,02.

[b] Fluid motion due entirely to the action of gravitational forces is usually called natural flow. If natural flow is not confined within a space by solid boundaries, it is referred to as free convection (in general, however, no distinction is made between them). For free convection, therefore, it is taken commonly that the motion of the fluid is caused by the action of the bouyancy forces arising from the density variations in the fluid owing to the temperature difference between the fluid and the contacting surface. [Wong, 1976]

The still is irradiated with direct and scattered solar radiation, H_s, and long wave atmospheric radiation[a], H_L (Figure 3.9). Of the long wave radiation $\alpha_{gL}H_L$ is absorbed in the glass, $(1 - \alpha_{gL})H_L$ is reflected from the glass, and none passes through the glass (glass is opaque to long wave radiation). Of the short wave radiation $\alpha_{gs}H_s$ is absorbed in the glass, τH_s passes through the glass and $(1 - \alpha_{gs} - \tau)H_s$ is reflected from the glass. $\alpha_w \tau H_s$ represents the amount of solar radiation absorbed by the basin. $(1 - \alpha_w)\tau H_s$ is reflected back to the cover. A reasonable daily average value for the transmittance, τ, of window glass would be 0,8 (Figure 3.5). The glass is at temperature T_g, the water surface in the basin at temperature T_w, and the ambient temperature outside the still is T_a.

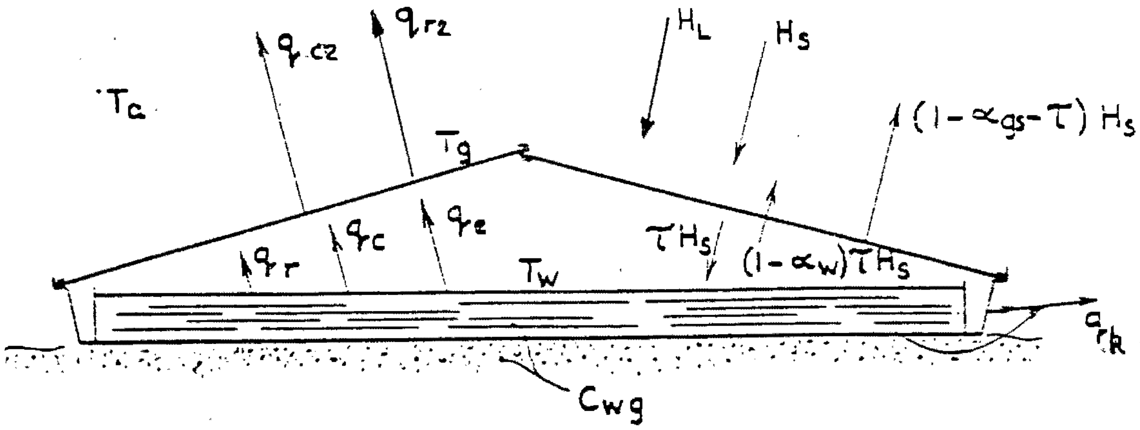


Figure 3.9: Heat fluxes for a solar still (modified from Morse, 1968)

Of the energy absorbed at the bottom of the still, a portion q_k, will be conducted away, part will go into heating the water, c_{wg}, and the remainder will be carried away from the water surface by convection, radiation and evaporation. This portion of absorbed heat is transferred to the lower surface of the glass, passes through the glass by conduction, and is carried away by convection and radiation from the upper surface of the glass. A simplified "thermal circuit" for this system is depicted in Figure 3.10.

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[a] Typically the atmospheric thermal radiation will be in the order of 5% of the solar radiation in magnitude (Maaren, 1976)

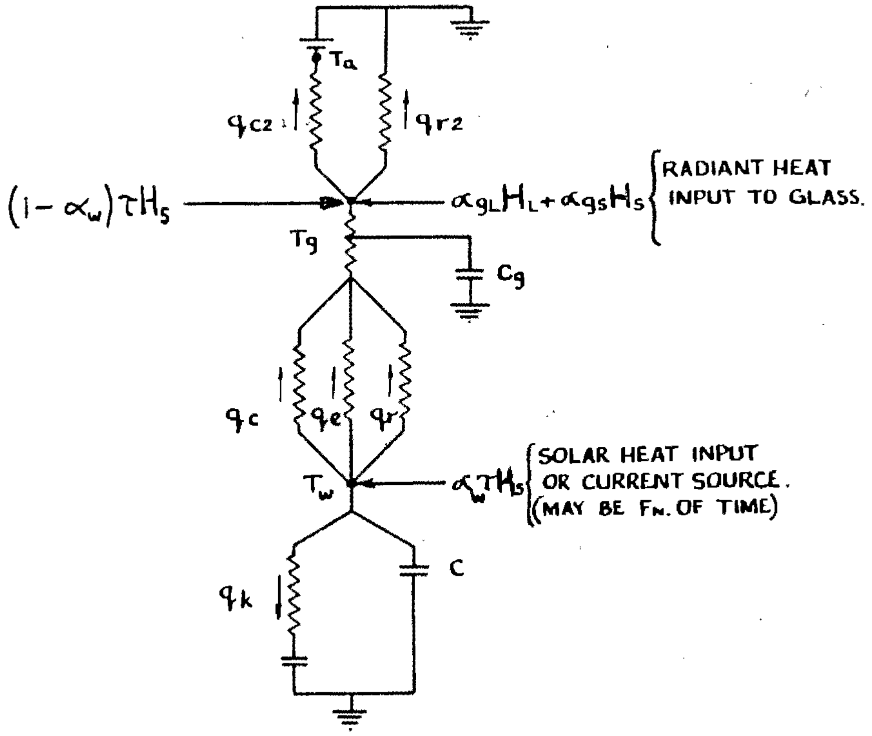


Figure 3.10: Thermal circuit of basin type solar still (modified from Dunkle, 1961)

Assuming steady state conditions[a] the equations for the various energy rates are:

Heat balance on the water:

$$\alpha_w \tau H_s - q_k + q_e + q_r + q_c \qquad 3.7$$

The heat balance on the glass cover:

$$q_e + q_r + q_c + \alpha_{gL} H_L + \alpha_{gs} H_s + (1 - \alpha_w)\tau H_s - q_{c2} + q_{r2} \qquad 3.8$$

Examining equations 3.7 and 3.8 it can be seen that in order to maximise q_e

a) the transmitted radiation, τH_s, should be maximised - this can be done by orienting the still perpendicular to the sun's rays;

b) the transmissivity of the cover should be high (most plastics have lower transmissivity than glass);

---

[a] In reality the radiation varies through the day as the sun moves through the sky, and according to cloud cover. This in turn means that the temperatures T_w, T_g and T_a vary through the day. Modelling the unsteady state conditions, or transient analysis, is beyond the scope of this text. The steady state analysis described here is sufficient for understanding the interplay of the operating parameters in the distillation process. For a fuller analysis, refer to Malik (1981).

c) the absorptivity of the base of the still, α_w, should be high, i.e it should be non-reflective;

d) the base losses, q_k, should be minimized - this can be done by insulating the still base;

e) the heat losses from the cover should be maximized - which can be done by artificially cooling the cover, or by wind;

f) the competing heat transfer mechanisms within the still, given by the terms q_r and q_c, should be minimized.

Except for *f)*, all of the above are quite easily achieved, though *e)* not economically (unless a large amount of cool water happens to be available and can be diverted to flow in a thin sheet over the cover from where it can be simply collected and sent on somewhere useful - to effect cooling a far greater volume of water is required than can be distilled in a day, so the coupling of the cooling of the cover to preheating the feed is not practical). *f)* is complicated by the fact that all three heat transfer terms, q_e, q_r and q_c are proportional to the difference in cover temperature between water and cover. To understand how the energy transfer is divided between these three mechanisms, it is necessary to express them in terms of the parameters of the solar distillation process. This is done in the ensuing section.

☐ Radiation term, q_r

The **radiation** exchange within the still between the salt water and the glass cover is given by equation 3.6, with the emissivity term in the equation, ϵ, replaced by the standard emissivity expression used for the case of two infinite parallel planes of emissivity ϵ_1 and ϵ_2 respectively.

$$q_r = \frac{1}{\frac{1}{\epsilon_1} + \frac{1}{\epsilon_2} - 1} \cdot \sigma \left(T_w^4 - T_g^4\right) \qquad 3.9$$

For glass and water ϵ_1 and ϵ_2 in the relevant temperature range are both ≈ 0,95, and the emissivity term in equation 3.9 reduces to 0,9.

☐ Convection term, q_c

In an enclosed space where heat and mass transfer occur simultaneously, the natural **convection** can be correlated in terms of special Nusselts and Grashof numbers (Dunkle, 1961; Malik 1981). The buoyancy term in the special Grashof number is modified by the density effect due to composition as well as temperature. In a horizontal enclosed air space for $3,2.10^5 < Gr < 10^7$ the relation between the Nusselt and Grashof numbers is

$$Nu = 0,075(Gr.Pr)^{1/3}$$

In the expression for the Grashof number in this case ΔT is an equivalent temperature difference which includes the molecular weight difference in evaluating the buoyancy effect, and for the air water system is given by:

$$\Delta T = (T_w - T_g) + \frac{(P_w - P_g)}{(269.10^3 - P_w)}.T_w \qquad 3.10$$

where P_w is the vapour pressure of water in N/m^2 at the temperature, T_w, of the water surface and P_g is the vapour pressure of water at the temperature T_g of the glass. In this range of Grashof's number the size of the space does not affect the *heat transfer coefficient*, which, from empirical correlations, over the normal range of still temperatures can be approximated by:

$$h_c = 8{,}84.10^{-4}\left[T_w - T_g + \frac{(P_w - P_g)}{(269.10^3 - P_w)}.T_w\right]^{1/3} \qquad 3.11$$

Substituting for h_c in equation 3.4 the convective heat transfer rate inside the still between the water in the base and the glass cover becomes:

$$q_c = 8{,}84.10^{-4}\left[(T_w - T_g) + \frac{(P_w - P_g)}{(269.10^3 - P_w)}.T_w\right]^{1/3}.(T_w - T_g) \qquad 3.12$$

☐ Evaporation term, q_e

The derivation of the **evaporative** heat transfer rate is described by Malik (1981).

The evaporative heat transfer derives from convection. The heat input from convection is q_c. The air that is being moved is being transferred from the water surface (temperature T_w), to the glass underside surface (temperature T_g). The mass of air transferred per unit area per unit time by free convection, $\dot{m}_a$, is thus given by the expression:

$$\begin{aligned}\dot{m}_a &= \frac{q_c}{c_{pa}.(T_w - T_g)} \\ &= \frac{h_c}{c_{pa}}\end{aligned} \qquad 3.13$$

where c_{pa} = specific heat[a] of air at constant pressure (J/kg°C)

---

[a] The specific heat of a substance is the energy required to raise the temperature of 1 kg of that substance by 1°C.

It is reasonable to assume that the air next to the water surface is saturated at the water temperature, and that the air and the water vapour observe the ideal gas law *(PV = nRT)*, therefore the specific humidity (or mass of water per unit mass of dry air) may be derived as follows:

$$\begin{aligned} \frac{P_a}{n_a} &= \frac{RT}{V} = \frac{P_w}{n_w} \\ \therefore \frac{M_a.P_a}{m_a} &= \frac{P_w.M_w}{m_w} \\ \therefore \frac{m_w}{m_a} &= \frac{M_w}{M_a}.\frac{P_w}{(P_T-P_w)} \end{aligned} \qquad \textbf{3.14}$$

Thus, the mass of water vapour transferred per unit area per unit time from the *water* surface, $\dot{m}_w$, is given by:

$$\dot{m}_w = \frac{M_w}{M_a} \cdot \frac{P_w}{(P_T - P_w)} \cdot \frac{h_c}{c_{pa}} \qquad \textbf{3.15}$$

where M_w = the molecular weight of water vapour (18 kg/mole)

M_a = the molecular weight of the dry air (≈29 kg/mole)

n_w = the number of moles of water vapour transferred

n_a = the number of moles of dry air transferred

P_T = the total pressure inside the still ($= P_a + P_w \approx 100$ kPa)

Similarly, the mass of water vapour transferred per unit area per unit time from the *glass* surface, $\dot{m}_{wg}$ is given by:

$$\dot{m}_{wg} = \frac{M_w}{M_a} \cdot \frac{P_g}{(P_T - P_g)} \cdot \frac{h_c}{c_{pa}} \qquad \textbf{3.16}$$

Then the net mass of water vapour transferred per unit area per unit time, $\dot{m}_e$, is given by the difference of the expressions 3.15 and 3.16, i.e.

$$\dot{m}_e = \dot{m}_w - \dot{m}_{wg} = \frac{M_w}{M_a} \cdot \frac{h_c}{c_{pa}} \left[\frac{P_w}{(P_T - P_w)} - \frac{P_g}{(P_T - P_g)} \right] \qquad \textbf{3.17}$$

The rate at which heat is transferred from the water surface to the glass cover on account of the mass transfer of water vapour, q_e is found by substituting for $\dot{m}_e$ in equation 3.5:

$$\begin{aligned} q_e &= h_{fg} \cdot \frac{M_w}{M_a} \cdot \frac{h_c}{c_{pa}} \cdot \frac{P_T.(P_w - P_g)}{(P_T - P_w)\,(P_T - P_g)} \\ &= h_e\,(P_w - P_g) \end{aligned} \qquad \textbf{3.18}$$

In a practical situation P_w and P_g are considerably smaller than P_T and therefore, one can simplify the expression for q_e (equation 3.18) by equating $(P_T\text{-}P_w).(P_T\text{-}P_g)$ to P_T^2)[a]. The equivalent mass transfer coefficient h_e may then be written in terms of the heat transfer coefficient h_c as:

$$h_e = \frac{h_{fg}}{c_{pa}} \cdot \frac{M_w}{M_a} \cdot \frac{1}{P_T} \cdot h_c \qquad 3.19$$

Substitution of the appropriate values for the different parameters yields:

$$h_e = 0{,}013 h_c \qquad 3.20$$

Malik also demonstrates an alternative derivation of equation 3.19, starting with a relation attributed to Lewis (1961)

$$\frac{h_c}{h_D \rho_a c_{pa}} = 1 \qquad 3.21$$

$$\text{where } h_D = \frac{\dot{m}}{A \cdot (\rho_w - \rho_a)}$$

where $\dot{m}$ = mass transfer rate (kg/hr)
h_D = mass transfer coefficient (kg/m^2)
ρ_a = density of dry air (kg/m^3)
ρ_w = density of water vapour (kg/m^3)
A = surface area over which transfer takes place (m^2)

and again assuming ideal gas conditions.

The ratio of h_e to h_c given by equation 3.20, 0,013, requires some correction for the simplifying assumption made in moving from 3.18 to 3.19, namely $(P_T\text{-}P_w).(P_T\text{-}P_g)$ is approximately equal to P_T^2. The value of this ratio that has been proven empirically to match test results most accurately is $16{,}273.10^{-3}$ (Dunkle, 1961; Talbert, 1970; Cooper 1974). Thus the heat transferred per unit area per unit time by evaporation from the water surface to the glass cover is best given by:

$$q_e = 16{,}273.10^{-3}.h_c.(P_w - P_g) \qquad 3.22$$

Each of the energy transfer modes found from equations 3.9, 3.12 and 3.22 can be expressed *as a fraction of the total energy transferred at the water surface* ($q_T = q_r + q_c + q_e$) *at given water surface and cover temperatures,* T_w *and* T_g, as shown in Figure 3.11.

---

[a] The full expansion of the term is $P_T^2 - P_wP_T - P_TP_g + P_wP_g$. The last term is << P_T^2, but the middle two do become quite significant at temperatures approaching 100°C, so this is a rough approximation in the normal operating range of stills (40 - 70 °C).

Figure 3.11 shows that, for a given glass/water temperature difference $T_w - T_g$, the fraction of the total energy transfer effected by evaporation, q_e, rises sharply with T_w, at the expense of q_c and q_r. This effect is unchanged right through the glass/water temperature difference range 2°C to 50°C. The figure is *not* saying that the *magnitude* of energy transferred by each of the modes does not increase monotonically with T_w, only that the energy *fraction* attributable to each term does not necessarily do so. It can be seen that by designing for high mean temperatures of operation the evaporative fraction predominates. In practice this is achieved by small water depths to reduce storage effects, high internal absorption and low conductive losses (i.e. good insulation). Preheating of the feed, where possible, is also advantageous.

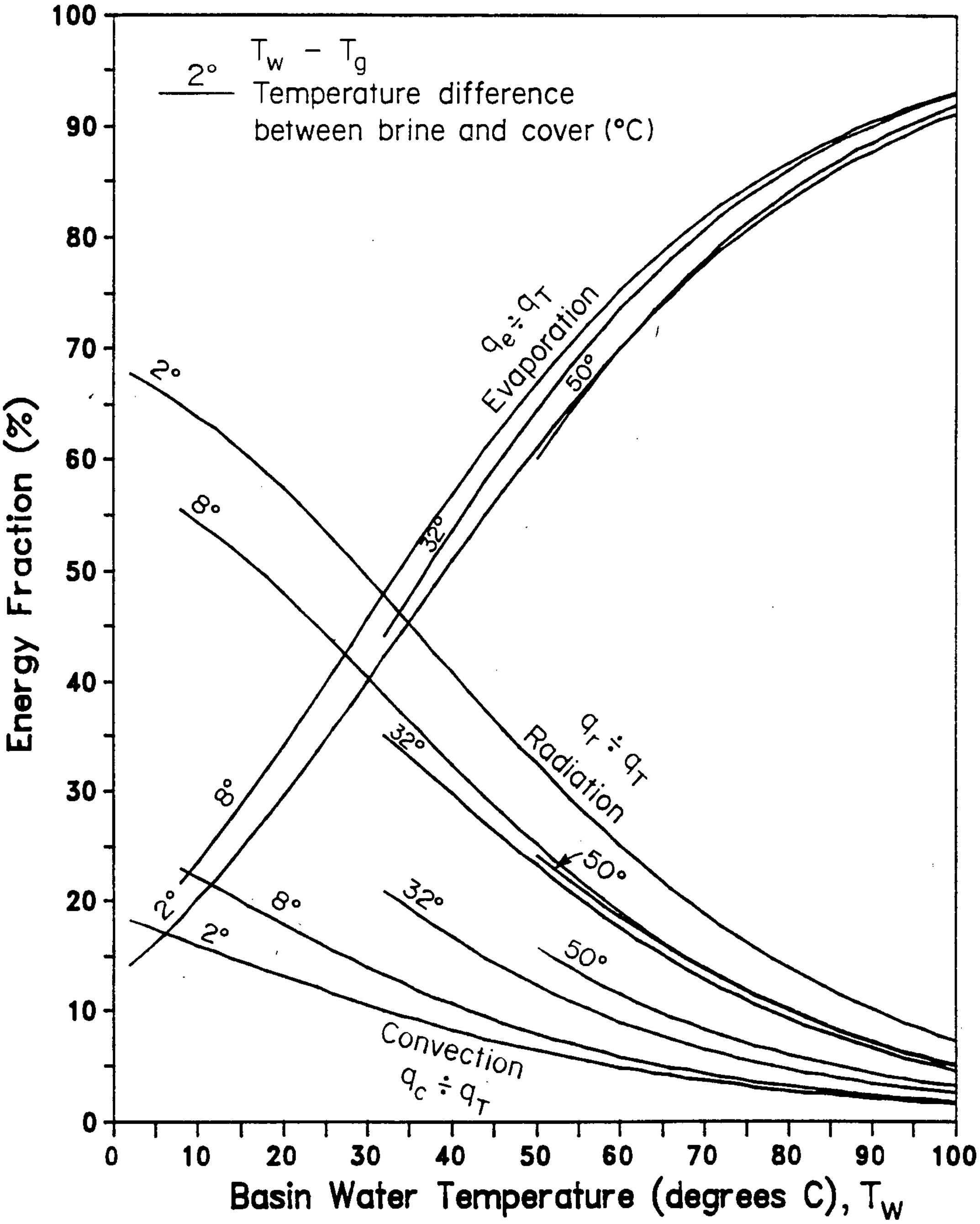


Figure 3.11: Energy transfer fractions due to evaporation, radiation and convection in a solar still at the water surface, as a function of water temperature T_w. $T_w - T_g$ = temperature difference between water and cover in °C.

3.2.4 Efficiency of a solar still

The **efficiency** of a solar still, η, is defined as that fraction of the incident global radiation which it is able to convert to useful work, in this case the distillation of water. Algebraically

$$\eta - \frac{\dot{m}_e . h_{fg}}{H_s} \tag{3.23}$$

where $\dot{m}_e$ = mass in kg of the water distilled per unit area (kg/m^2)

h_{fg} = enthalpy of vaporisation of the water at its feed temperature (J/kg) (η = 2442 kJ/kg at 25°C)

H_s = global radiation incident on the still area (J/m^2)

Efficiencies reported by authors range from 20% to 50% for conventional basin stills, with the variation largely attributable to the method of construction, and to the latitude of the place at which the measurements were made (by convention the radiation figure used is generally that for a horizontal surface, even though a still might be inclined).

The efficiency of a still is in fact a fairly meaningless parameter when quoted in isolation. Because the energy incident on the still is free, it does not matter how much of it is put to use. In contrast the collection apparatus is not free, and thus the only meaningful number to tag to a still is its capital cost per litre of daily output capacity.

Efficiency is useful, however, in enabling the comparison of essentially similar designs, where only one parameter is being varied (e.g. brine depth, glass thickness etc.).

3.3 History of Solar Distillation

The first significant scale solar distillation plant was commissioned in 1870 at Las Salinas in Chile (Frick and Hirschmann, 1973). This basin still produced 20 m^3/day to provide drinking water for a nitrate mining community, and it was in operation until 1910. Its production is reported as being 4 to 5 ℓ/m^2/d, as good as any basin-type still today.

Multistage flash (MSF) distillation technology eclipsed solar distillation early this century, and latterly reverse osmosis has been gaining market share from from MSF (see Chapter 2).

In spite of its inability to compete with modern industrial desalination processes at scale, solar distillation is still unchallenged in its applicability at small scale in remote areas. The most commercially successful use to date was the supply of 200 000 inflatable plastic stills to the U.S. Armed Forces during World War II (Malik, 1982). Since 1945 there has been sustained research in this field, and several fairly large community stills have been constructed in various parts of the world (Delyannis, 1973). Figure 3.12 lists the large scale stills that have been reported in the literature.

Country	Location	Date Built	Basin Size	Cover[a]	Purpose[b]
Australia[c]	Muresk I[d]	1963	4.000 ft^2	G	WS
	Muresk II[d]	1966	4,000 ft^2	G	WS
	Muresk IV	1971	2,513 ft^2	G	WS
	Muresk Mk VI	1973	1,960 ft^2	G	WS
	Coober Pedy[d]	1966	34.000 ft^2	G	WS
	Coober Pedy Mk VI[d]	1972	4.900 ft^2	G	WS
	Caiguna[d]	1966	4,000 ft^2	G	WS
	Caiguna Mk VII[e]	1972	400 ft^2	G	WS
	Hamelin Pool[d]	1966	6.000 ft^2	G	WS
	Griffith[d]	1967	4,450 ft^2	G	E
	Griffith Mk VI[d]	1970	2,513 ft^2	G	E
	Griffith Mk VII	1972	1,504 ft^2	G	E
	Townsville	1971	2,513 ft^2	G	E
	Darwin Mk VI	1972	980 ft^2	G	WS
	Mt. Derrimut Mk VI	1972	490 ft^2	G	WS
Cape Verde Islands	Santa Maria do Sal[d]	1965	8.000 ft^2	P	WS
Chile	Las Salinas[d]	~1872	48.000 ft^2	G	WS
	Quillagua	1968	1.076 ft^2	G	
Greece	Symi[d]	1964	28,920 ft^2	P	E,WS
	Symi II[d]	1968	27,924 ft^2	P	WS
	Aegina[d]	1965	16.040 ft^2	P	E,WS
	Aegina II[d]	1968	15,766 ft^2	P	WS
	Salamis[d]	1965	4.180 ft^2	P	E,WS
	Patmos	1967	93,000 ft^2	G	WS
	Kimolos	1967	27,000 ft^2	G	WS
	Nisyros	1969	22,000 ft^2	G	WS
	Fiskardo	1971	23.628 ft^2	G	WS
	Kionion	1971	25,776 ft^2	G	WS
	Megisti	1973	27,150 ft^2	G	WS
India	Bhavnagar	1965	4,050 ft^2	G	E
Mexico	Natividad Island, Baja California	1969	1,024 ft^2	G	WS
Pakistan	Gwadar I	1969	3,286 ft^2	G	WS
	Gwadar II	1972	97,433 ft^2	G	WS
Spain	Las Marinas[d]	1966	9,350 ft^2	G	WS
Tunisia	Chakmou	1967	4,730 ft^2	G	WS
	Mahdia	1968	14,000 ft^2	G	WS
USA	Daytona Beach, Florida				
	Original Deep Basin[d]	1959	2.450 ft^2	G	E
	Second Deep Basin[d]	1961	2.650 ft^2	G	E
	Large Inflated Plastic[d]	1959	2.330 ft^2	P	E
	Church World Service[d]	1963	1,600 ft^2	P	E
USSR	Bakharden, Turkmenia[d]	1969	6,450 ft^2	G	E,WS
	Bukhara region, Uzbek SSR[f]	1975	5425 ft^2	G	E
West Indies	Petit St. Vincent	1967	18,400 ft^2	P	WS
	Haiti	1969	2,400 ft^2	G	WS

[a] G = glass, P = plastic.

[b] E = experimental, WS = water supply.

[c] Australia stills of Mk VI and Mk VII types constructed with bottom insulation under part or all of stills.

[d] No longer operating.

[e] Waste heat also supplied.

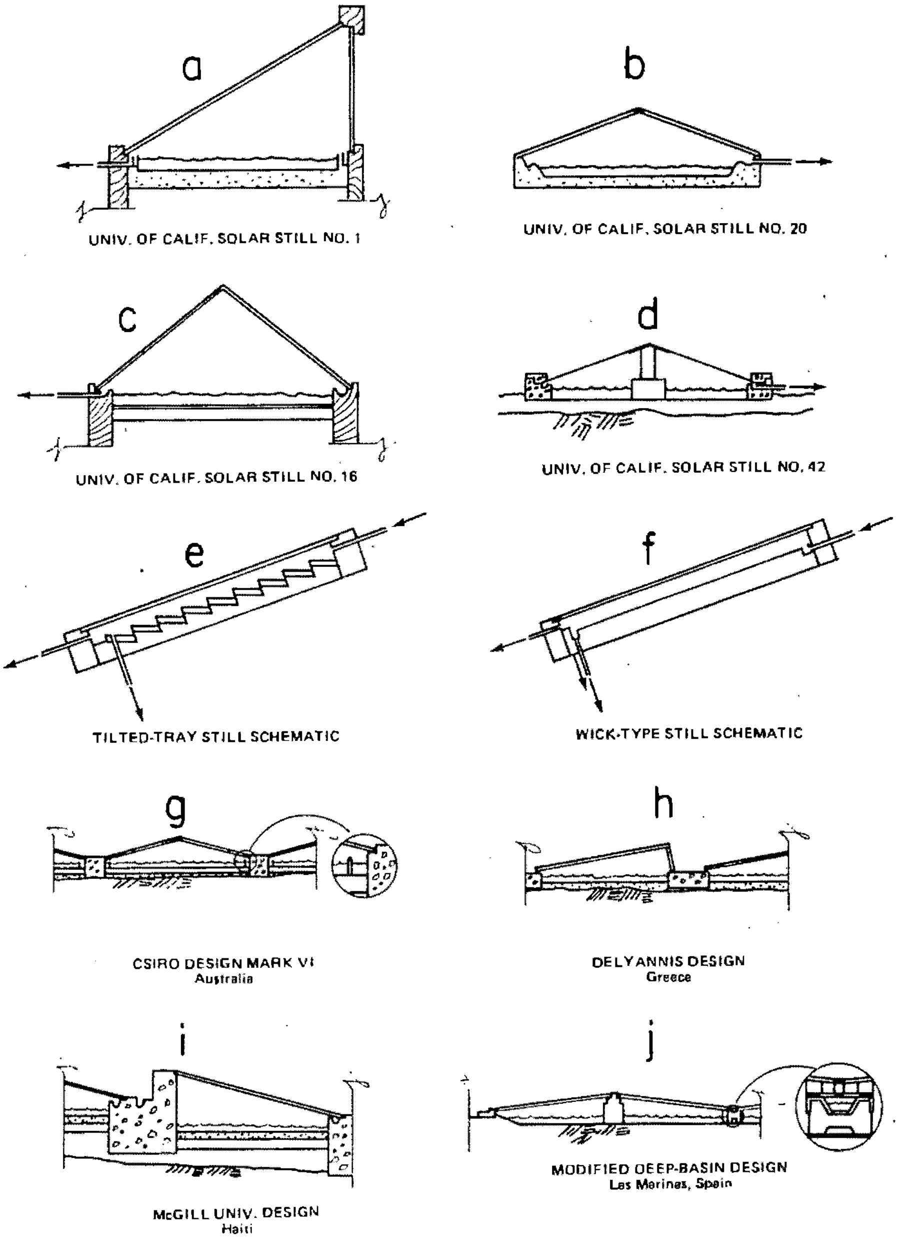
[f] Multiple-ledge tilted type.

Figure 3.12: Large stills listed by Delyannis (1973)

It is interesting to note the high proportion of discontinued stills. Large community stills have often proven difficult to maintain, and tend to fall into disrepair within a few years (Gomkale, 1988). With modern RO and ED technology now in competition with solar distillation, it is unlikely that such large stills will ever be built again.

3.4 Designs of Solar Still

Figure 3.13 illustrates some of the most common solar still designs. Stills *a, b, c, d, g, h, i* and *j* in the figure are all variations of the **basin still**, sometimes referred to as the greenhouse still because of its resemblance to a greenhouse. An alternative to the basin still is the **inclined wick still** (still *f* in the figure), which makes better use of the available solar energy during the winter months when the sun's elevation in the sky is lower, depending on latitude. Another design which makes better use of the sun in the winter months is the inclined tray, or **cascade still**, still *e* in the diagram. Of the two inclined stills, the wick still has the advantage of simplicity of construction. Another attractive feature of the inclined wick still is that it operates wih a very shallow water depth (as deep as the wick) which allows it to raeach a higher operating temperature than most basin stills. The inclined wick still was first described by Telkes in 1956, and is illustrated in more detail in Figure 3.14. In the 1960s it was considered too complex and the wick impractical because it could be expected to rot in situ (Löf, 1966).



UNIV. OF CALIF. SOLAR STILL NO. 1

UNIV. OF CALIF. SOLAR STILL NO. 20

UNIV. OF CALIF. SOLAR STILL NO. 16

UNIV. OF CALIF. SOLAR STILL NO. 42

TILTED-TRAY STILL SCHEMATIC

WICK-TYPE STILL SCHEMATIC

CSIRO DESIGN MARK VI
Australia

DELYANNIS DESIGN
Greece

McGILL UNIV. DESIGN
Haiti

MODIFIED DEEP-BASIN DESIGN
Las Marinas, Spain

Figure 3.13: Cross sections of some common types of solar stills

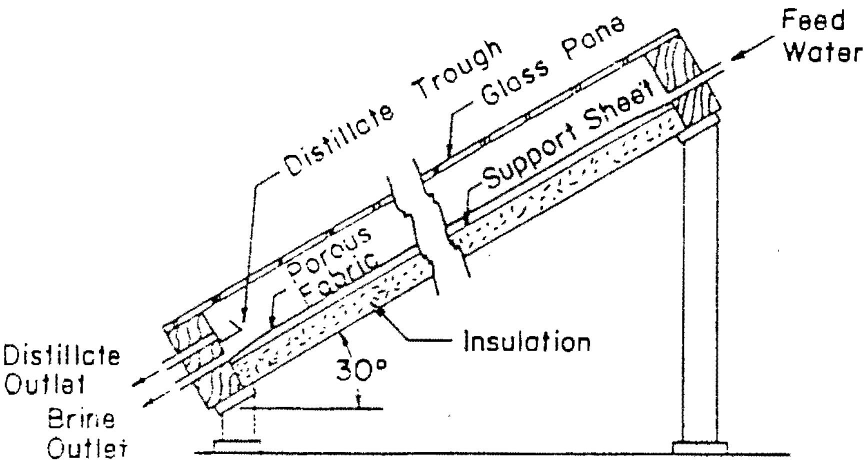


Figure 3.14: Inclined wick still

The **multiple effect inclined wick still**, illustrated in Figure 3.15, re-uses the enthalpy of vaporization/condensation of the distillate with each successive effect or cell, much as in the case of multistage flash distillation. This is very attractive because, as has been shown in section 3.2, this is the most significant energy fraction in the distillation process. The brack water is fed to a

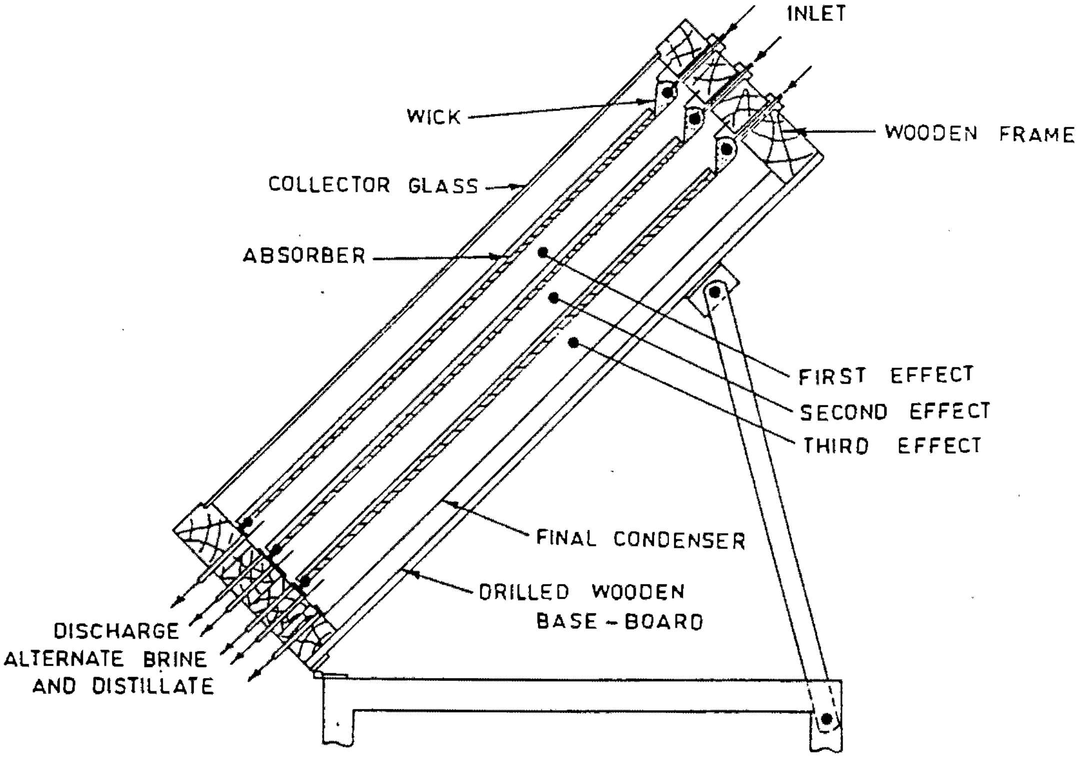


Figure 3.13: Multiple effect inclined wick still

wick which is fixed on the *back* of the metal cover plate of the still. The brack water is able to flow down the back of this plate without dripping down to the floor of the cell because of the capillary suction of the wick. The cover plate, which is insulated to maintain it at a high temperature, becomes hot and this heat passes by conduction through the plate to the brack water in the wick. The water is heated and some of it evaporates, to condense on the floor, or base of the cell, which is at a cooler temperature because it is not directly irradiated. In condensing this first effect distillate gives off its enthalpy of vaporization to the base plate, which is cooled by the brack water feed of cell number two, which is in turn heated by the heat of condensation being given off to that plate in cell 1. Cell, or effect, 2 then passes *its* distillate's enthalpy of vaporization on to cell 3 in the same way, and so on for as many cells as are economically justifiable. How many cells would be economically justified? This will depend on the efficiency. Assuming each cell operates with the same efficiency, η, the total mass of water produced by the combined cells, m_e (kg/m^2), will be the sum of the geometric series

$$\dot{m}_e = \frac{H_s\,(\eta + \eta^2 + \eta^3 + \ldots + \eta^n)}{h_{fg}} \tag{3.24}$$

where H_s = incident radiation (J/m^2)
h_{fg} = enthalpy of vaporization (J/kg)
n = the number of cells

Table 3.3: Progression of magnitudes of η^n terms in equation 3.24, showing economic number of cells for different values of η

η	η^2	η^3	η^4	Economic number of cells*
0,2	0,04	0,01	0,002	1
0,3	0,09	0,03	0,008	1
0,4	0,16	0,06	0,026	1
0,5	0,25	0,13	0,063	2
0,6	0,36	0,22	0,130	2
0,7	0,49	0,34	0,240	3
0,8	0,64	0,51	0,410	4

* On the assumption that each cell, after cell 1, is built for half the price of cell 1.

Table 3.3 above shows the magnitudes of the η^n terms of this series for increasing numbers of cells and for increasing magnitudes of η. If each cell added to the first cell costs only half as much to build as that first cell, then the economic number of cells for a given efficiency will be reached when the increase to the *total* efficiency to be gained by adding the *next* cell is less than half the efficency of the first cell. From Table 3.3 it can be seen that the economic number of cells for efficiencies of 30%, 50% and 70% is 1, 2 and 3 respectively. With a 3 cell unit operating with 70% cell efficiencies, the total of the efficiency term becomes 153%. Such a still will produce nearly four times as much per unit area as the typical basin still operating at 40 % efficiency, at a cost per unit area of about double that of the basin still. In other words, the water cost would be halved. If this were possible, as is claimed by Ouahes and le Goff (1987), this type of still would be very attractive. Other authors (Dunkle (1961), Yeh (1987, 1988, 1990)) claim efficiencies in the region of 50%. In this case a double effect still could be produced having an effective total efficiency of 75%, and costing 1,5 times as much per unit area. This is only marginally better than the basin still (typical efficiency 40%.)

Conclusion from review of designs:

The *basin still* is worth investigating bacause it is the best established design and appears to be very simple and reliable.

The *inclined wick still* shoulb be investigated because of its potential to yield a greater volume of distillate in the winter months when the sun is low in the sky (at Southern African latitudes).

The *multiple effect still* should be investigated to establish whether it is reliable, and whether it is more cost-effective than more conventional designs.

3.5 Southern African experience with solar distillation

While little research has been done on solar distillation in Southern Africa, in comparison with the rest of the world, two initiatives should be mentioned.

3.5.1 CSIR work in the 1960s in South West Africa

The CSIR researched several different still designs in the 1960s in South West Africa (van Steenderen, 1972). Their work eventually focussed on the basin still, and field units were built at five sites. The prototype selected was constructed on the ground, using bricks for the foundation, sand for insulation, butyl rubber for the lining, and square aluminium tubing for the frame (Figure 3.16). Figure 3.17 shows the full installation of the still. No provision has been made for cleaning the basin (it would necessitate removing a portion of the cover glass), but with the proposed continuous flow operation salt build up should not be too rapid. The daily production for the stills at these sites was monitored for a calendar year (1970) and these daily totals were then averaged over the calendar months to produce Figure 3.18. On this figure the production has been plotted per still, each still having a 5 m^2 area. The summer production is typically about 4 $\ell/m^2/d$, and in winter it drops to an average of about 1,6 $\ell/m^2/d$. The claimed average annual production for the prototype

3,4 ℓ/m²/d, which seems a little high in the light of Figure 3.18. Its material cost was R48 (1970 prices) for the full 5 m² still. Converting (see Appendix F) to 1991 prices this equates to R610, or R122 /m². The labour cost was estimated at R31 (1970 prices).

At the culmination of this work an excellent technical guide was produced, with full instructions for home manufacture of the prototype.

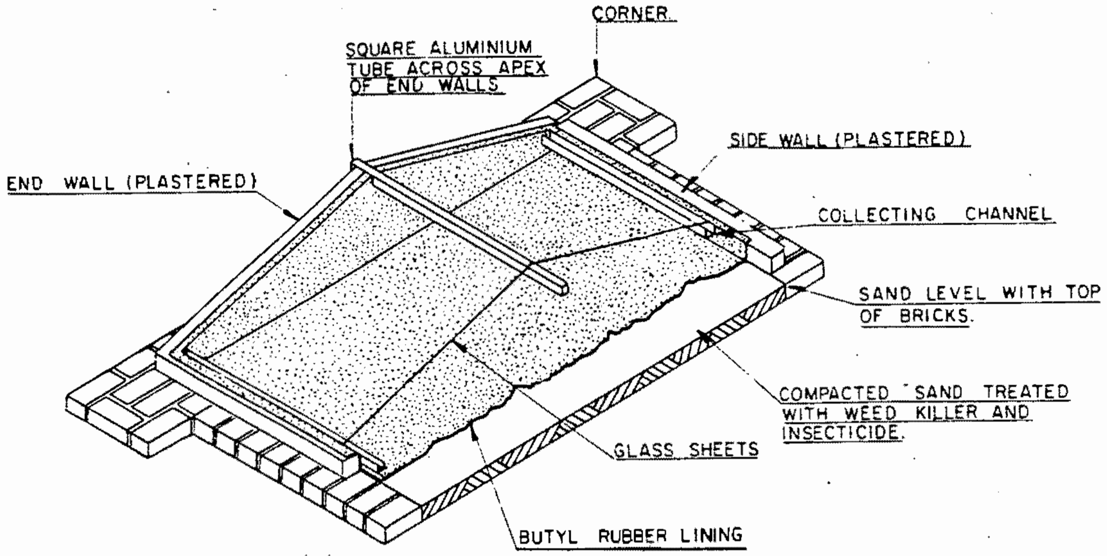


Figure 3.16: The 1960s CSIR basin still prototype, material details

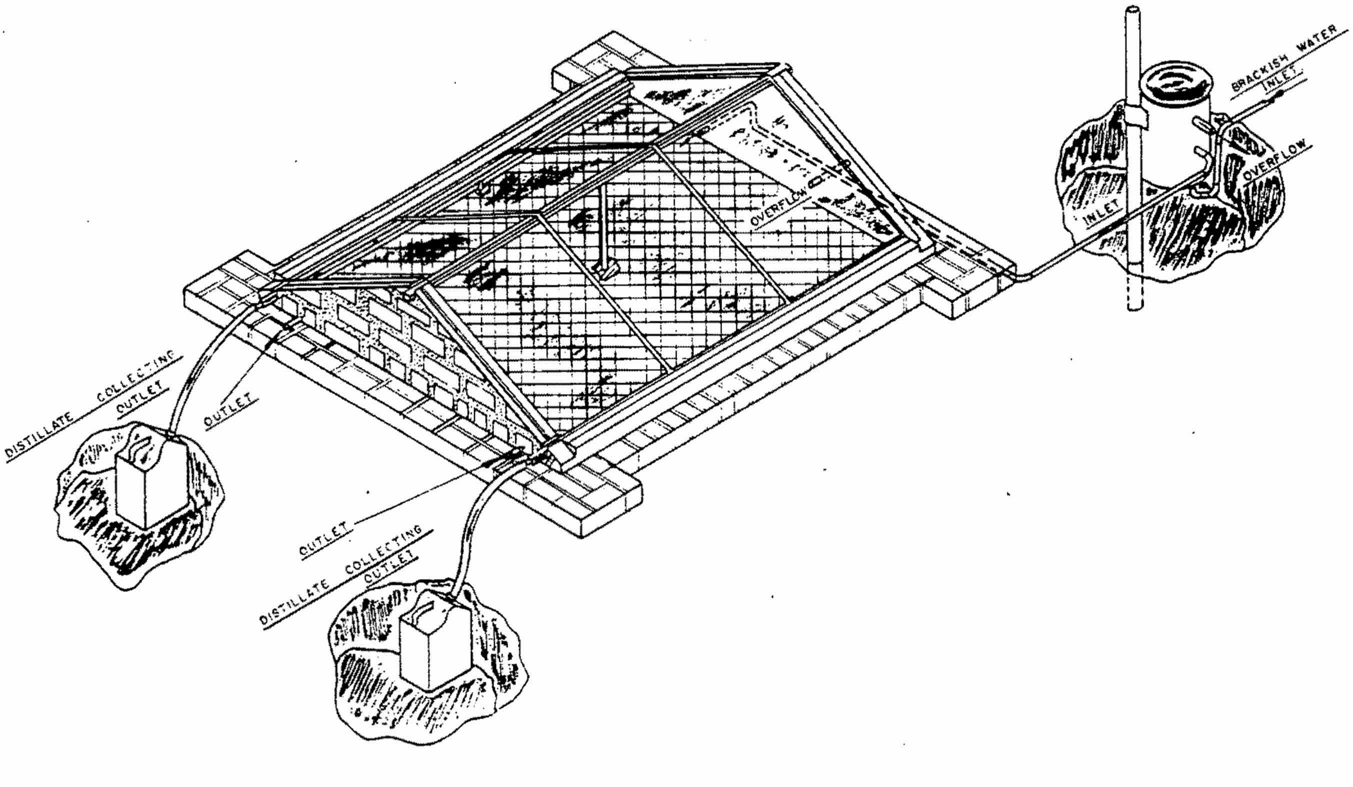


Figure 3.17: Installation of the CSIR 1960s basin still prototype

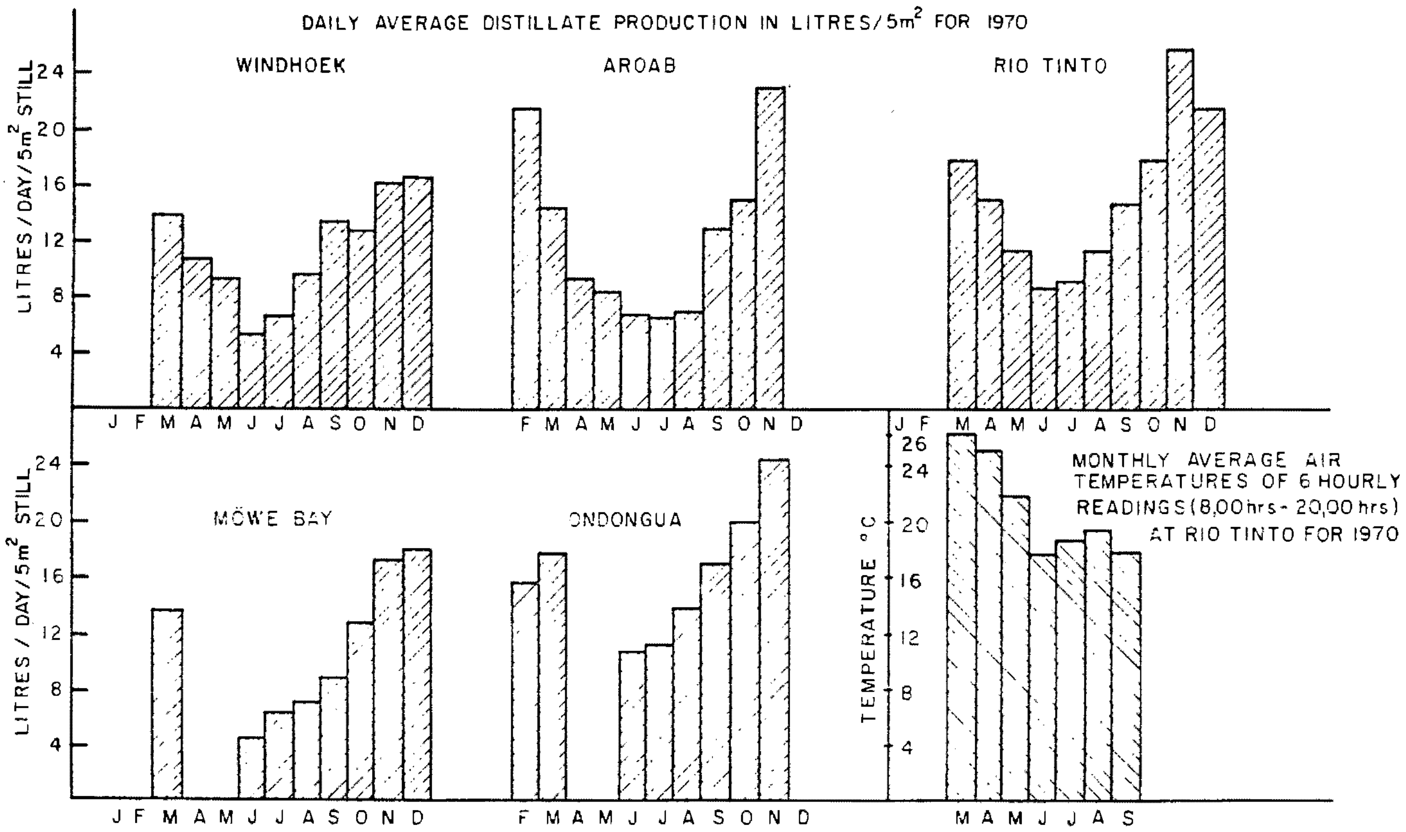


Figure 3.18: Production rates of CSIR 1960s basin still prototype operated at five different localities in SWA.

3.5.2 Rural Industries Innovation Centre (Botswana)

A second solar distillation initiative in Southern Africa took place in Botswana at the Rural Industries Innovation Centre (RIIC) during the mid 1980s (Rural Industries Innovation Centre, 1987). RIIC began research into the problem of treating saline groundwater after a request for help from the Kgaligadi District Development Council in 1981. After testing various basin still prototypes, a Mexican design was selected as offering the best potential (Figure 3.19). This still comprises a black fibreglass base 1,5 m by 1,0 m, with a pitched glass roof. Fibreglass is an interesting choice of material. It is prohibitively expensive - each 1,5 m^2 basin cost over R600 - but it was chosen over masonry because of its suitability for centralised production. Masonry was also found to be unsuitable because of its tendency to crack and fall into disrepair.

At three settlements in the Kalahari the RIIC constructed distillation plants comprising 60 to 80 still units, all feeding their distillate into a common collection tank. The whole area was surfaced to enable what little rain there was to be collected and it was fenced off to prevent damage by animals. The local council payed a member of the community to take responsibility for the operation and maintenance of the plant. Such a plant was found to cost in the order of R100 000 to construct (1991 prices), but maintenance is minimal.

At Zutshwa, one of the places where stills were installed, the salinity of the feed water was 230 000 mg/ℓ, which is seven times saltier than seawater! Such salinities are, apparently, not uncommon in inland salt pans. Interestingly the stills were not adversely affected, only requiring more frequent cleaning. It was initially hoped to earn a substantial revenue from the sale of salt from the Zutshwa still, but apparently this has not worked out (the market is resistant to unrefined salt).

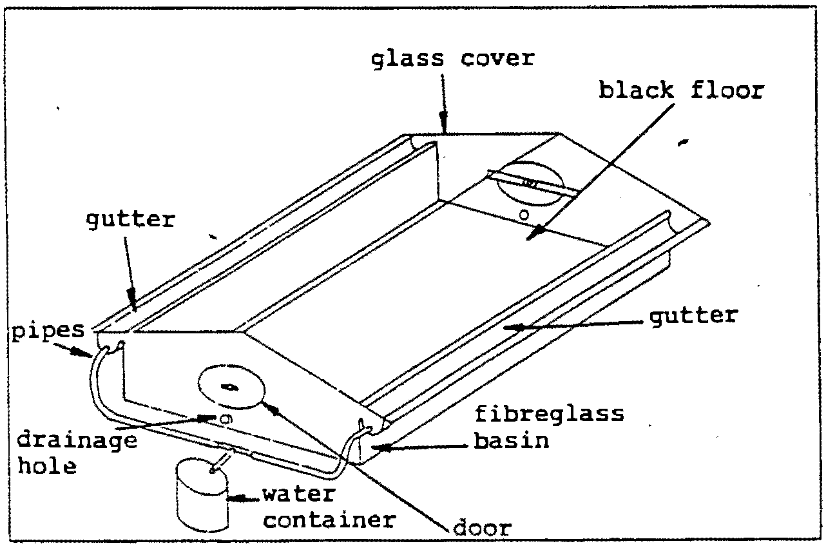


Figure 3.19: The fibreglass basin still adopted by the RIIC

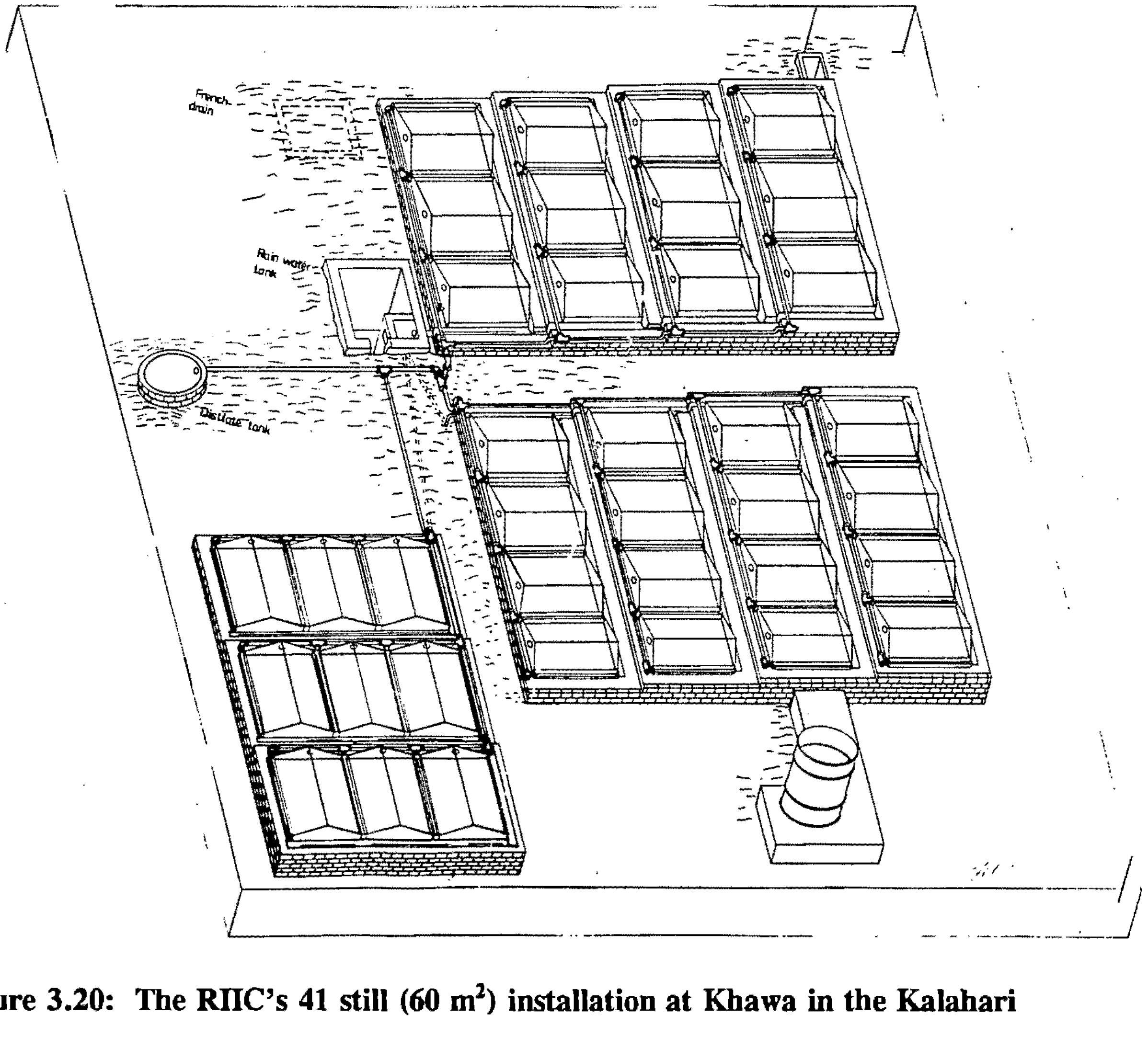


Figure 3.20: The RIIC's 41 still (60 m^2) installation at Khawa in the Kalahari

The RIIC stills production has shown the same pattern as that found for the basin stills in South West Africa in the 1960s (section 3.4.1, Figure 3.18) i.e. a maximum of up to 5 $\ell/m^2/d$ in summer, dropping down to less than two 2 $\ell/m^2/d$ in winter.

3.6 Problems encountered with solar stills

The following problems with solar stills are described in the literature. Remedies are suggested for some of the problems, where applicable.

- Large scale community-based stills generally fall into disrepair through the lack of adequate administration and management. There is little enough maintenance to be done (filling, cleaning of glass weekly, removal of scale buildup at longer intervals) but failure to rectify glass or pipe breakages will seriously affect the workings of the whole plant. In the case of large stills where several hundred metres may be under one glass cover, a glass breakage affects the efficiency of the whole unit. The hydraulics of such large installations are also complicated by the competing needs to drain the distillate, and to keep the water in the basins evenly spread. (Gomkale, 1988 and Natu, 1979)

- Several authors make mention of algal growth in the basin stills as being a long-term inhibiting factor on still productivity. This can be controlled by addition of an algicide such as $CuSO_4$ addition (Ahmed et al 1967).

- Concrete or brick and mortar have often been used in the construction of large scale stills. Where the basins are long (100m is not uncommon in large stills) then it becomes very difficult to prevent the cracking of the still basins due to differential settlement of the still foundation. Such cracking can cause the total failure of a basin due to brine loss. Prevention through reinforcing the base is expensive, and asbestos cement does not fare any better. (Frick and Hirschmann, 1973)

- Where the feed water has a high suspended solids content, the still basins will silt up over time, decreasing their efficiency (Ahmed, 1967). A cure for this would be to hold the feed water in retention dams for a sufficiently long period before allowing it to pass through to the still (conventional coagulation, flocculation, filtration is presumably out of the question in the context of a site where a still is applicable). An alternative to retention might be horizontal roughing filtration (gravel/coarse sand filtration).

- In the 1960s plastic covers were promoted by some authors. It was felt that their higher thermal conductivity (being thin) would allow a greater degree of cooling of the still cover. It was also felt that they were cheaper (Hay, 1973). Nowadays it is generally accepted that plastic covers are impractical for the following reasons (Hirschmann, 1975):

a) plastic covers are in general less wettable than glass, in other words the condensate on a plastic cover is more inclined to form droplets which 1) reflect some of the incoming radiation and 2) tend to drop back into the basin;
b) plastic covers are more prone to wind damage, as they flutter;
c) plastic covers do not last under UV light - even the modern plastics having high UV resistance will not last more than a few years before they will become brittle and crack; and
d) plastic covers cloud with time, reducing their transmissivity;

□ Some stills are designed without easy access for cleaning. Most basin stills have to have panels of their glass cover removed to allow cleaning, so cleaning is often not done. Yet cleaning is necessary, even in continuous flow processes, because of the buildup of scale that occurs on the basin floor, on wicks, and on the water surface. (Natu, 1979)

□ Stills installed in areas that regularly experience extreme weather conditions (wind, hail) are prone to damage (Gomkale, 1988). This can be allowed for to an extent by increasing the thickness of the glass (but thicker than 5mm will lead to significant fall off in efficiency, especially on cloudy days), by anchoring the stills, and by installing hail screens if hail is a problem.

□ Stills need to be protected from animals, and often from children. Gomkale (1988) even cites peacocks as a source of damage to a large community still in India.

CHAPTER 4

DESCRIPTION OF EXPERIMENTAL WORK ON SOLAR DISTILLATION

4.1 Early efforts - separating the heating and evaporation/condensation functions

One of the first solar distillation units tested experimentally separated the heating and the evaporating/condensing functions into two separate compartments. The thinking behind this idea ran as follows:

- ☐ The rate of evaporation is proportional to the temperature difference between the water surface and the condensation surface, which in the case of a conventional still is the inside of the transparent glass cover. In conventional stills this temperature difference is typically 5 to 10 °C.
- ☐ If one could therefore route the heated feed water to a point where it was released to condense on a much cooler surface, the rate of evaporation would increase.

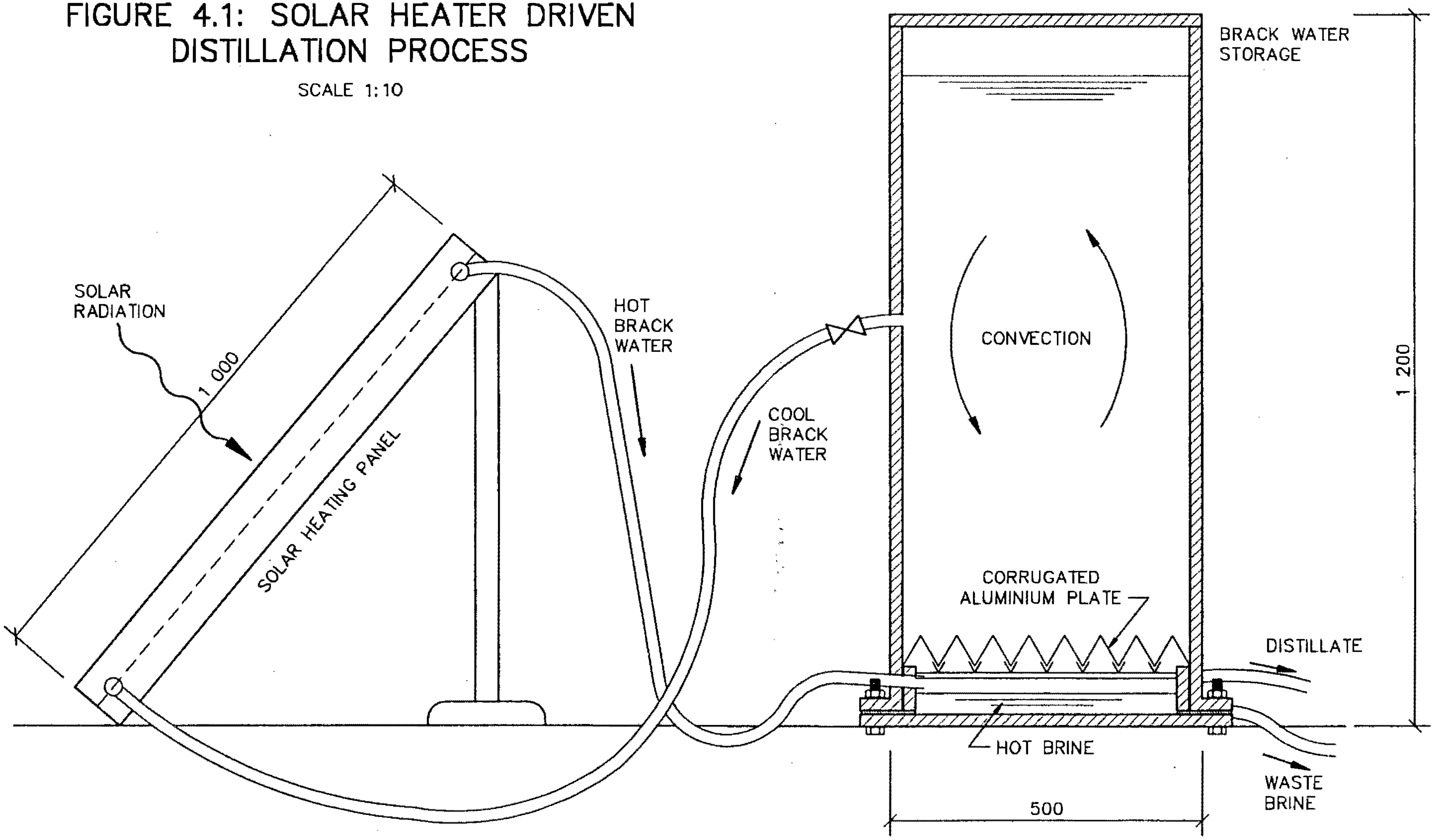
To test this idea the apparatus shown in Figure 4.1 was constructed. The brack water was stored in an insulated tank which was provided with a false floor about 5 cm above its base. The cool brack water (± 20 °C) was routed to a conventional solar heating panel, where it would be heated to about 60 °C (temperature depending on flow rate and sunshine intensity). The hot water was then routed to the lower compartment of the feed storage tank, that formed beneath the false floor mentioned above. This lower compartment comprised a pool of hot water above which was fixed a corrugated aluminium roof. This roof was the false floor of the upper cool storage section. The proposed principle of operation was that water vapour would rise from the hot water to the cooler corrugated roof, where it would condense and run off into a system of distillate collection channels. The roof temperature would remain relatively cool, as all heat transferred to it would be quickly conducted away by and dissipated within the large body of cool brack water stored above it.

Flow through the system was to be ensured by the head difference between the water in the upper brack water storage compartment to that in the evaporation chamber, and by the thermo-siphon effect of the solar panel itself (the heated water in the panel rises, creating a thermal suction or siphon in its wake, which brings in fresh cool water).

The system worked hydraulically after one or two hitches in the distillation collection had been rectified, but its performance as a distillation apparatus was poor. Looking back with the benefit of hindsight it is possible to understand why this idea was not fated to succeed. It was shown mathematically in the previous chapter that the evaporative heat transfer in a distillation process is in fact far more sensitive to operating temperature, T_w, than to the brine/cover temperature difference, T_w-T_g. This result was illustrated in Figure 3.11, which depicted the energy transfer fractions in a solar still as a function of T_w. This fact was not well understood at the time of constructing this apparatus.

FIGURE 4.1: SOLAR HEATER DRIVEN DISTILLATION PROCESS

SCALE 1:10



D.A. Still

How much distillate could be produced by such a system? Solar heaters typically operate with efficiencies of 30 to 50%, depending on the temperature of the feed and the flow rate (Chinnery, 1971). Assume a 40% efficiency for this panel, which we will say has a 1 m2 area. Assume an average day's radiation, 20 000 kJ/m2. At 40% efficiency 8 000 kJ will be utilized to heat the brack water. Water has a thermal capacity of 4,2 kJ/ °C, in other words 8 000 kJ could be used to heat 100 litres of water by 19 °C, say from 20 °C to 39 °C. Assume a perfectly insulated connection between the solar panel and the evaporation/condensation chamber, the heat input to the evaporation/condensation chamber will then be 8 000 kJ. Referring to Figure 3.11, which although developed for the conventional still will nevertheless hold roughly true for this situation, it can be seen that with a water/cover temperature difference of 19 °C and a water temperature of 39 °C, the evaporative heat transfer fraction will be 50% of the total transferred through evaporation, convection and radiation from the water surface. Assuming zero heat losses from the brine, 4000 kJ of heat will be transferred through evaporation, which has a mass equivalent of 1,6 kg of water. In reality the figure will be more like 1 kg because some heat will be lost between the solar heater and the evaporation chamber, and some in the waste brine stream, and because convection in this confined space cannot be expected to be as high as that for the conventional solar still, for which Figure 3.11 has been developed. A conventional solar still, receiving 20 000 kJ/m2 of radiation, would produce 3,5 litres of water, at far lower cost!

This exercise demonstrated the truth of the conventional wisdom that a little knowledge is a dangerous thing. In fact it will never pay to couple a solar heater to a solar still purely to increase the efficiency of the still, because solar heaters cost more to build per m^2 than do solar stills, without being able to operate at higher efficiencies.[a]

4.2 Subsequent work - comparison of basin and wick stills; optimisation of wick stills

The remainder, and bulk, of the experimental work done in this reearch proceeded on three fronts:

- ☐ A basin still obtained from the Rural Industries Innovation Centre (RIIC) in Botswana was monitored because this is the classic still design and it gives one a good basis for comparison.
- ☐ Work was done on the multiple effect inclined wick still, with a view to optimising the design.
- ☐ Work was done on the single effect inclined wick still, and the design was optimized.

Figure 4.2 shows work in progress on the three still types: the single effect inclined wick stills are to the left, the basin still is in the middle, and the multiple effect inclined wick still is to the right.

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[a] Taking advantage of available waste heat (cooling water from an engine perhaps) would be a different matter, again providing this energy could be collected at a cost not higher than justified by the increase in productivity of the still. Another aspect, demonstrated in Chapter 6, is that it is advantageous to construct the header feed tank to the still in a way that it absorbs solar energy, preheating the water.

Global radiation was measured half-hourly with a Kipp and Zonen solarimeter, and the daily radiation totals were checked against those obtained by the Weather Bureau at their Pretoria Forum station, 10 km west of the CSIR. Figure 4.3 shows the solarimeter with its coupled integrator, which is standing on top of a Honeywell 24 channel recorder (used for temperature measurements).

Figure 4.2: **General layout of experimental work on solar stills: single-effect inclined wick still to left; basin still in the centre; and multiple-effect inclined wick still to right.**

Figure 4.3: **Kipp and Zonen Solarimeter and integrator; Honeywell 24 channel recorder for temperature measurement**

4.3 Basin Still

The basin still obtained from the RIIC was monitored intermittently between April 1988 and April 1991. Distillate production was measured at least daily, but at times more often. For a month in 1989 the distillate production was measured continuously with the help of a strain gauge and a chart recorder. Glass and water temperatures were recorded morning and noon for a few months using thermocouple wires and the 24 channel Honeywell recorder. The midday inside glass temperature is generally about five degrees cooler than the water in the basin, and about five degrees warmer than the outside glass temperature. During the night temperatures revert to the ambient temperature. Typical basin water temperatures during the heat of the day are 60 to 70 °C. The most important data collected on the basin still (distillate production and global radiation) is included in Appendix B.

4.4 Multiple effect inclined wick still

The multiple effect inclined wick still is attractive on paper but difficult to implement. Figure 4.4 below shows the multiple effect inclined wick still on the test rig at the CSIR. The feed water is required to flow down the underside of the cell cover, with the distillate on the cell floor.

It requires some ingenuity to get the feed water to flow in and out of the still without mixing with the distillate. Figure 4.5 illustrates the top, side and bottom edge details of the multiple effect still worked on in this research. The top edge detail shows three different methods tried for getting the water to flow into the still without dripping down to the cell floor. In the first method tried, method (a), water was inroduced to a channel on the outside of the frame. This channel was perforated in a way to permit the passage of water through to the wick. Unfortanately the rubber seal required at that joint (not shown in the diagram) caused the gap between the perforations and the wick to be large enough to allow a significant fraction of the feed to dribble down to the cell floor instead of being drawn into the wick. Method (b), which routed the feed into a 5 mm perforated plastic tube fixed to the still roof, proved more successful, but a large amount of salt was still found to be coming through in the distillate stream at the bottom. One of the principal problems with this type of still is that it is a closed box: trouble shooting is difficult when you cannot see what is actually happening. The final feed method, method (c), had the wick extending outside the still frame into a trough where it could suck up the feed water. Though inelegant, this method proved successful.

Another problem area is the fixing in place of the wick, which must cling to the roof of the still cell. Initially the wick was stretched and clamped in place on the sides. This worked at times but when dry the cloth tended to billow, with the result that brine would drip onto the condensate surface. The wick was then glued along the edges and in the middle, but without the stretching and clamping. This proved even less successful. The method that has now been found to work satisfactorily is to attach the cloth to the aluminium plate using an aerosol adhesive spray, although whether this will stand up to months of use in the hot sun remains to be seen.

A remaining problem is the collection and removal of distillate and brine from the bottom of the still. The outlets fitted to the still on manufacture were of a compression kind that required a tube of internal diameter of about 3 mm, with the result that the still constantly develops airlocks. It is now believed that this may all along have been the principle cause of the brine/distillate crossflow contamination. Some data from tests on this still conducted in June and August 1990 are included in Appendix C.

The difficulty experienced with getting this still to work reliably prompted some serious doubt about its applicability in a rural context. When working it may be more efficient in terms of distillate produced per square metre of still area, but it is not simple and reliable. It is also not going to be more cost competitive than a single effect solar still: from the literature it appears that a multiple effect still functioning well will double the output of a single stage inclined wick still, but it was found to be more than twice as expensive to build, so there is no advantage in this considerable increase in complexity.[a]

Figure 4.4: Multiple effect inclined wick still on the test rig at the CSIR

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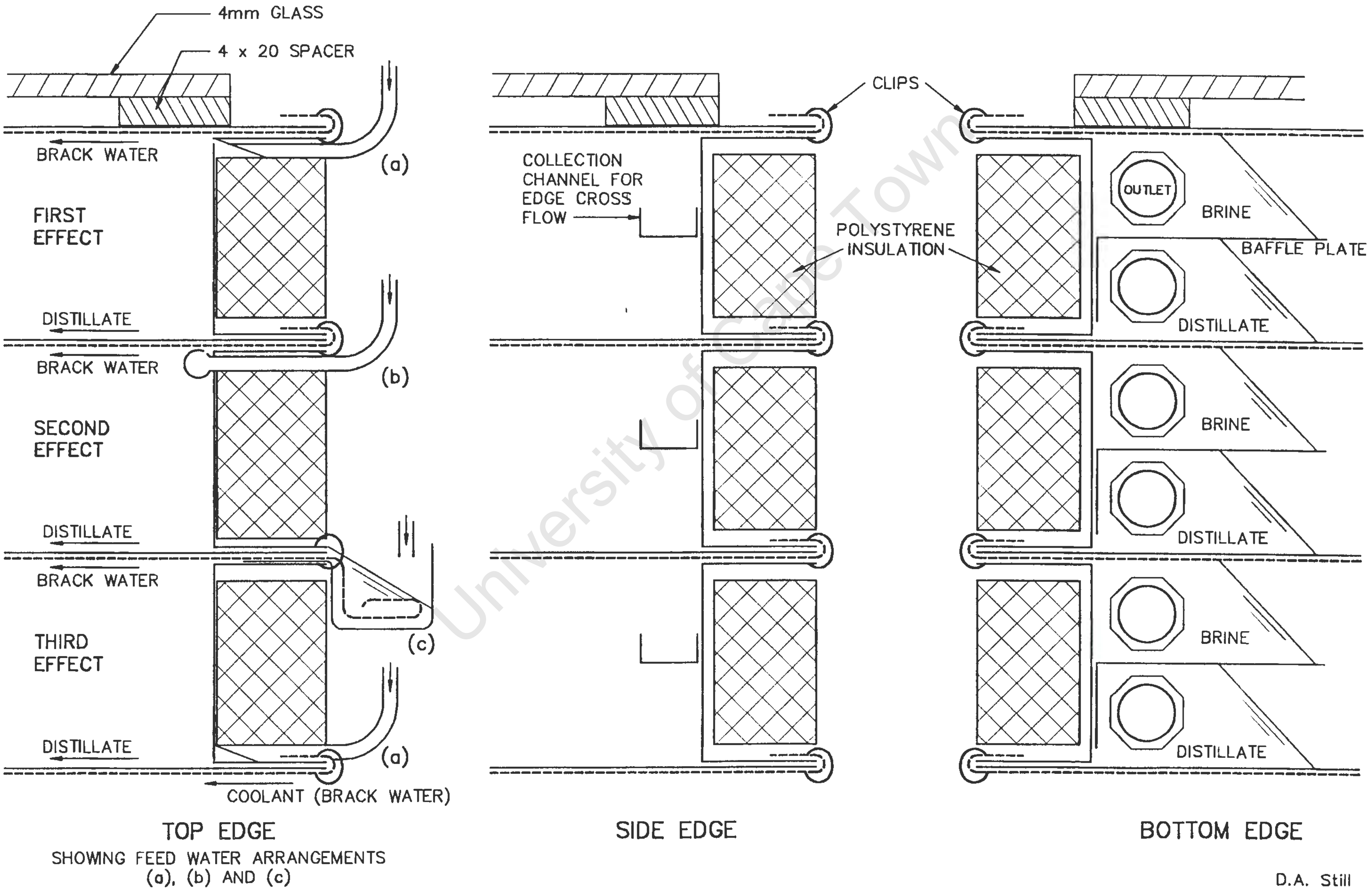
[a] The decision to build this still was influenced largely by the paper of Ouahes and Le Goff (1987), who claimed it as a "hardy, high yield solar distiller". They claim production figures of 15 ℓ/m^2/d, which is at least three times that which could be achieved by a basin still. Closer inspection of the paper reveals a very sparse data set, and no evidence that the still's production was ever measured over a full 24 hours. It is quite possible that the still's midday production has been extrapolated over a ten or twelve hour period to give the quoted 15 ℓ/d. Subsequent reading of the papers by Yeh (1987, 1988, 1990) indicate that production for this type of still is actually in the range 6 to 8ℓ/d - i.e. about double that for basin stills. Dunkle (1961) is also interesting on this subject: *The ultimate utility of the multiple effect diffusion still depends on the development of an economical unit capable of long periods of trouble-free operation. Many problems remain to be solved, particularly with regard to the maintenance of proper flow conditions over the plates. Problems of corrosion, sedimentation, scaling and salt deposition require further study.* This experience has at least taught this researcher to treat others' research with more scepticism, particularly when claims of unusually high performance are being made. In the main, it seems that people do not so much read from others' research as quote from it.

FIGURE 4.5: MULTIPLE EFFECT INCLINED WICK STILL – EDGE DETAILS

SCALE 1:1



4.5 Inclined Wick Still

The single effect inclined wick still (Figure 4.6) proved much more successful. After initial success with the first two inclined wick stills a further two were built to enable various parameters of the design to be tested. These four stills are shown with their feed tanks in Figure 4.7.

The following measurements were made for the inclined wick stills on a daily basis: global radiation, distillate production, ambient temperature range, feed water flux and salinity. Certain parameters were varied for comparative purposes. These included the wick type, the feed water flux and the feed water salinity. The primary results of these tests appear in Appendix D, and the results are analysed in Chapter 5, *Results and Discussion.*

Other aspects that were tackled were the rate of fade of the dye in the wick, discussed in Chapter 5, and the problem of reduction in wettability of a glass surface exposed to the atmosphere, discussed in Chapter 7, *Implementation.*

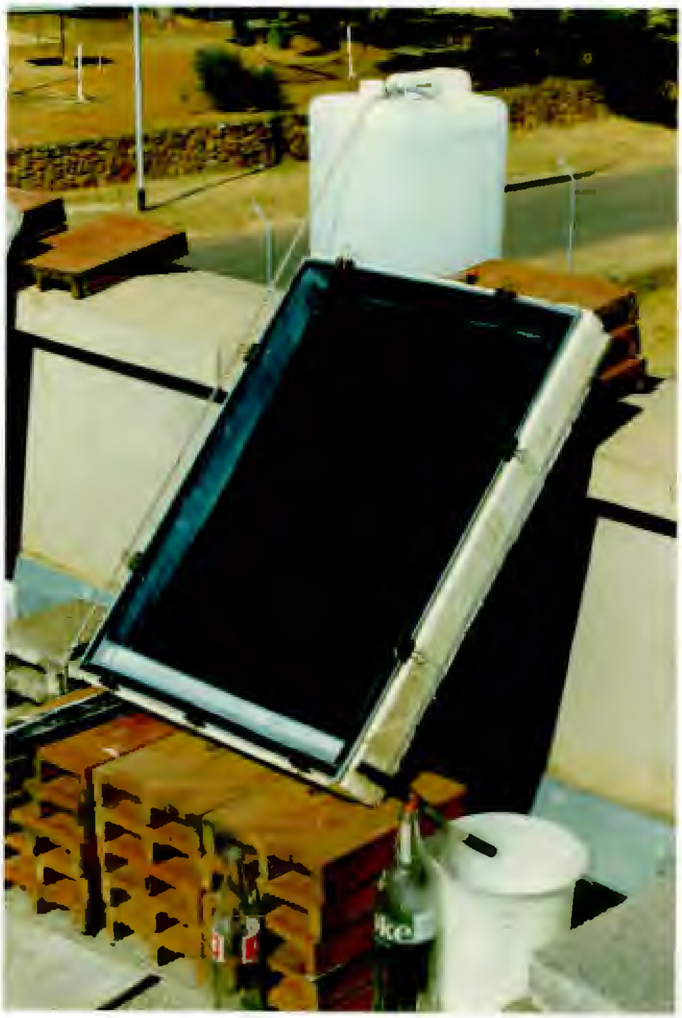


Figure 4.6: Single effect inclined wick still

Figure 4.7: The four inclined wick stills being tested in parallel for comparison of design parameters

CHAPTER 5

RESULTS AND DISCUSSION

5.1 Productivity and efficiency of the basin still

Figure 5.1 shows the productivity of the basin still over the calendar year. The radiation data that goes with this production appears in Figure 5.2. As can be seen the two plots bear a strong resemblance to each other. The correlation between production and radiation for the basin still is given in Figure 5.3. Above 10 MJ/m^2/d the relationship between output and radiation can be approximated by the equation:

$$M_d = 0{,}2.\ Q_{rad} - 1$$

where: M_d = mass in kilogrammes (or volume in litres) of distillate

Q_{rad} = 24 hour global radiation (MJ/m^2)

The efficiency of the still through the calendar year is shown in Figure 5.4. It can be seen that the efficiency lies in a band between 30 and 40 %, with the average being closer to the latter in the summer and the former in the winter.

The low output that occurs on some summer days is generally due to rain and overcast conditions. Provided that provision is made for rain collection this need not be a problem. However on overcast but dry winter days production can drop to as little as 0,5 litres/m^2.

Efficiencies are generally slightly lower and more scattered at lower sun intensities (Figure 5.5). This is because there is a higher fraction of diffuse radiation on some of the days where the global radiation measurement is low. Diffuse radiation is not able to penetrate the glass cover as effectively as direct radiation.

Figure 5.1: Annual variation of basin still productivity as measured at CSIR, Pretoria, April 1988 to April 1991

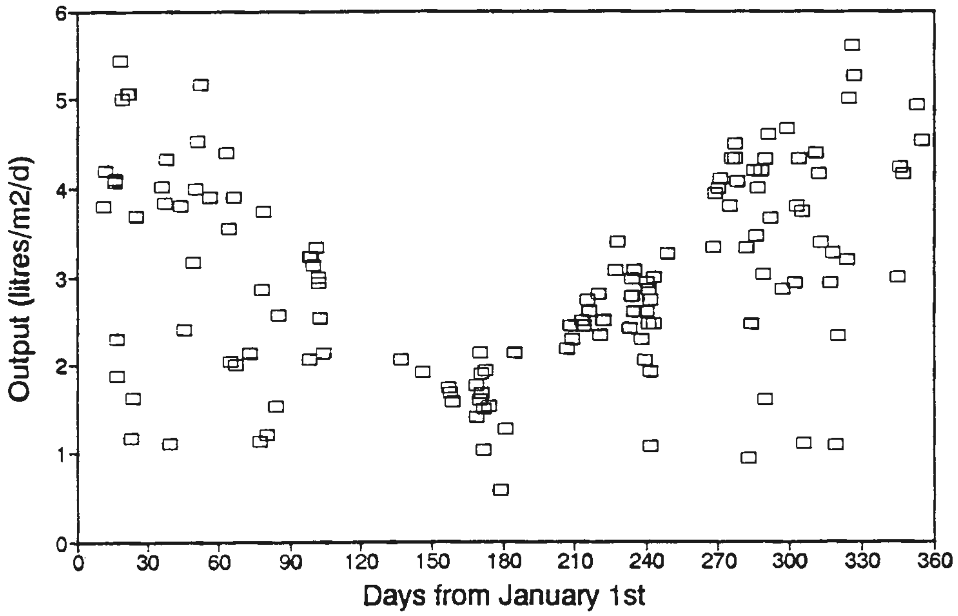


Figure 5.2: Global radiation data measured concurrently with basin productivity data shown in Figure 5.1

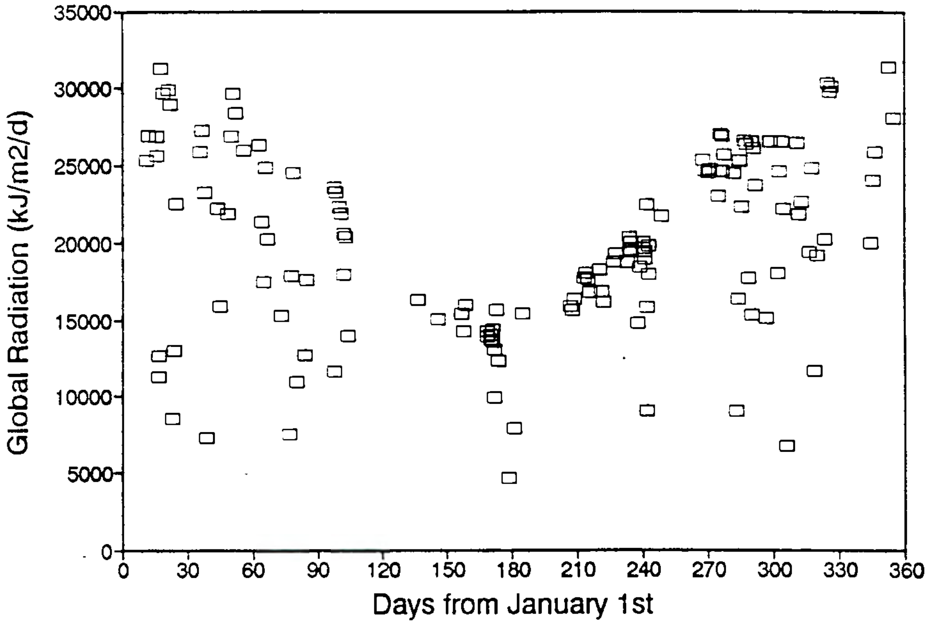


Figure 5.3: Correlation between global radiation and productivity of basin still as measured at CSIR, Pretoria, April 1988 to April 1991.

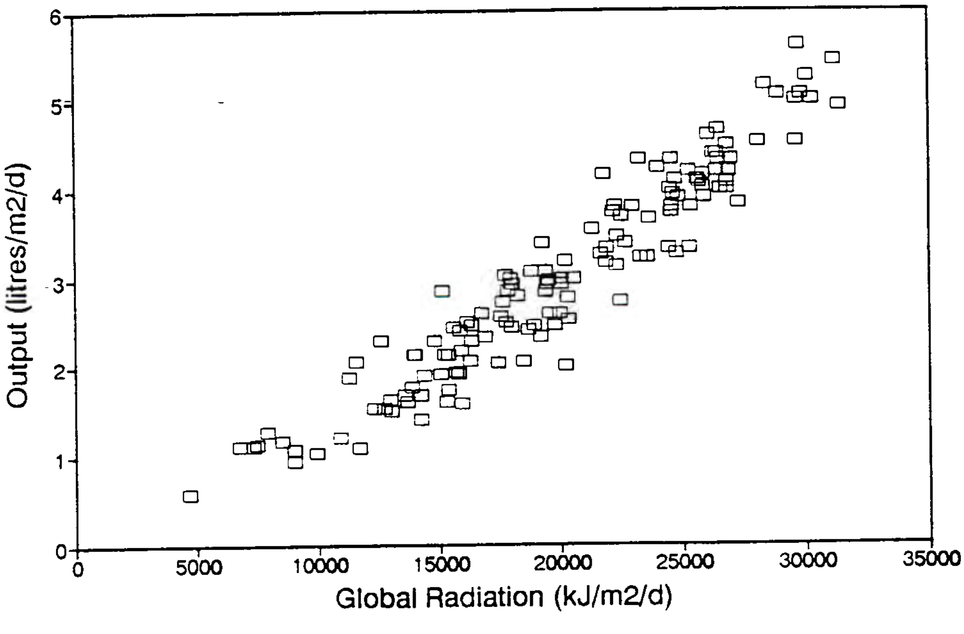


Figure 5.4: Annual variation in efficiency of the basin still observed at CSIR, 1988 to 1991. During the cooler months efficiencies are reduced.

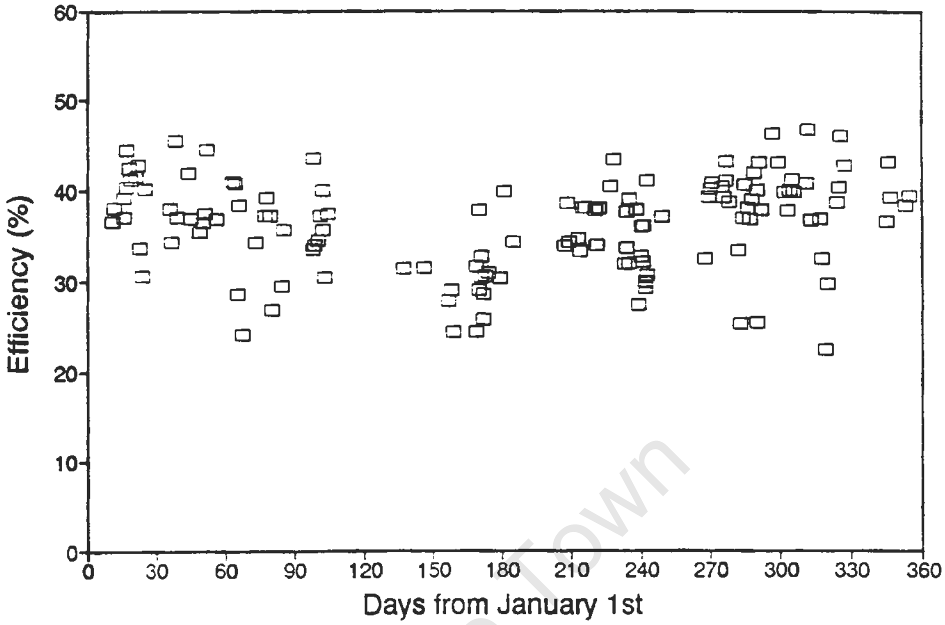
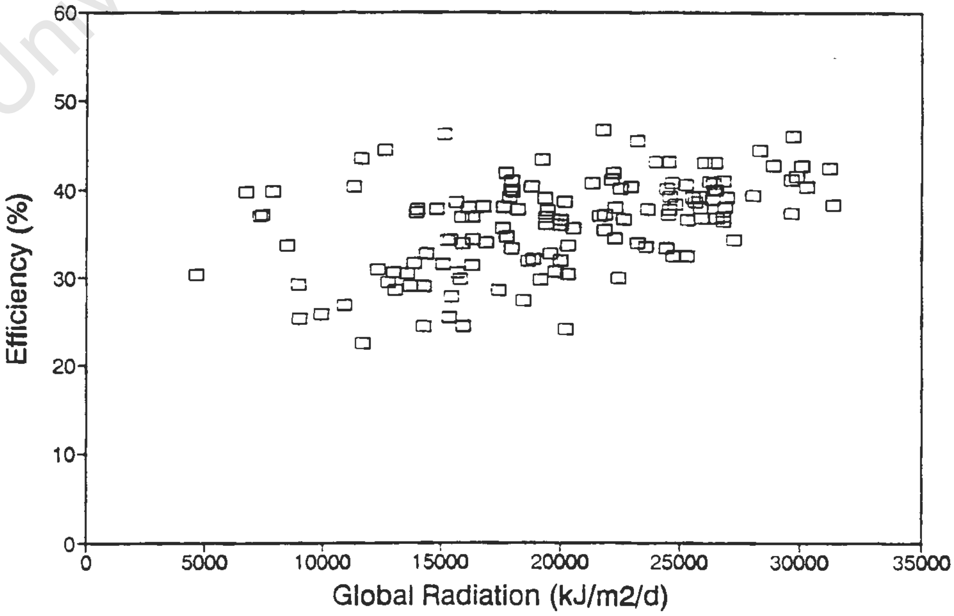


Figure 5.5: Basin still efficiency plotted against global radiation.



5.2 Effect of basin water depth on the basin still

Some authors hold that it is optimum to maintain a shallow depth of water in the still's basin. In order to examine whether this effect could be detected over the likely operating range of the prototype being tested at the CSIR, each of three different water depths were maintained for a period of about two weeks each during September/October 1989. The depths tested were 10 mm, 20 mm and 30 mm, corresponding to volumes in the still of 15, 30 and 45 litres. The average efficiencies measured for the three depths were:

Depth (mm)	**Average efficiency** (%)
10	40,7
20	37,0
30	40,3

The plots of the efficiencies over the respective test periods appear in Figure 5.6 below. All that can be concluded from these tests is that the efficiency of the basin type solar still is not significantly affected by changes in its water depth over the likely operating range of 10 to 30 mm. It is possible that larger variations of depth might produce more marked changes in efficiency.

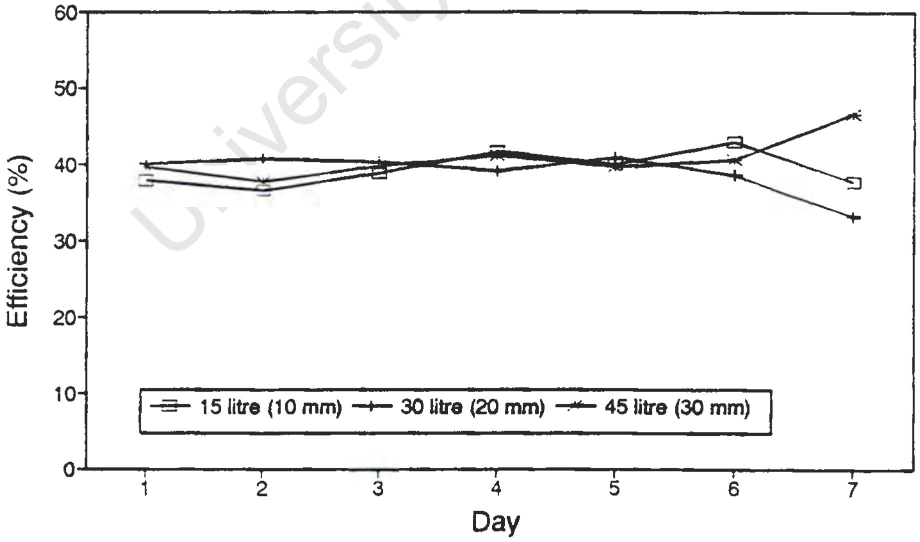


Figure 5.6: Effect on efficiency of depth of water in a basin-type solar still

5.3 Productivity and efficiency of the inclined wick stills

Figure 5.7 shows the productivity of the inclined wick still prototypes tested at the CSIR in Pretoria over a calendar year. The radiation data that goes with this production appears in Figure 5.8. During the period of testing the radiation was particularly variable, which makes these plots harder to interpret than Figures 5.1 and 5.2, which showed the same data for the basin stills. However there is once again a strong correlation between productivity and radiation, and this is illustrated in Figure 5.9.

Figure 5.7: Annual variation of inclined wick still productivity as measured at CSIR, Pretoria, August 1990 to July 1991

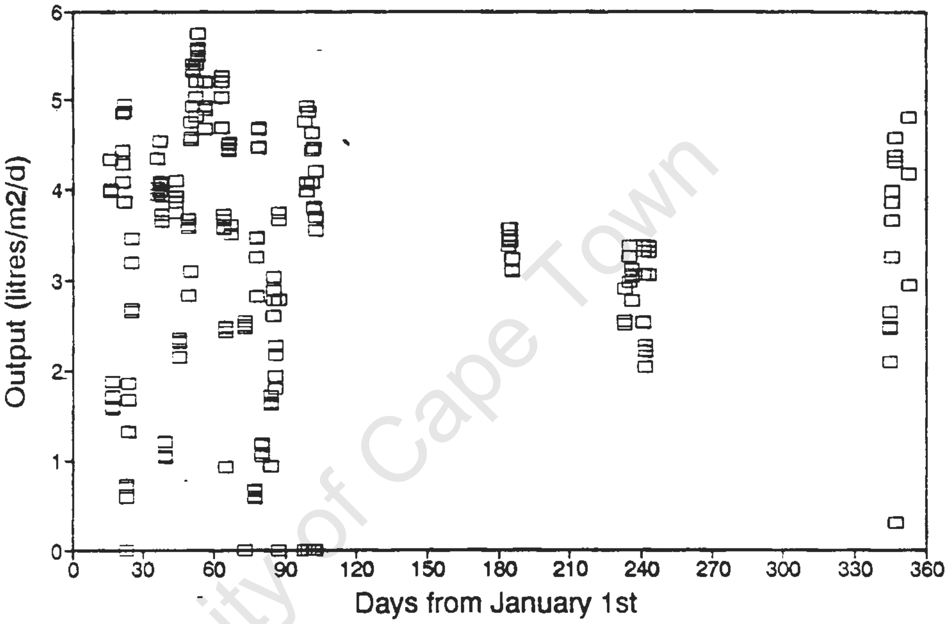
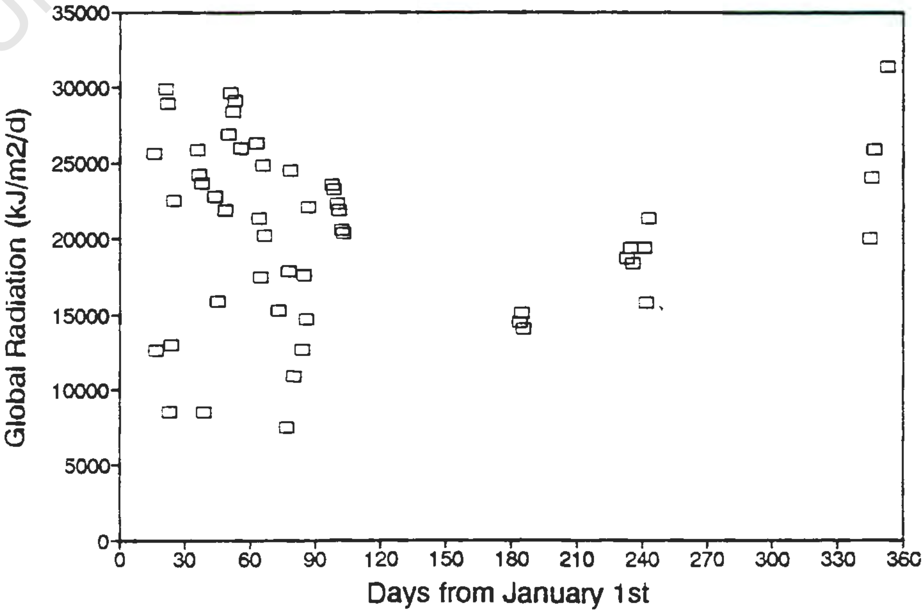


Figure 5.8: Global radiation data measured concurrently with inclined wick productivity data shown in Figure 5.7



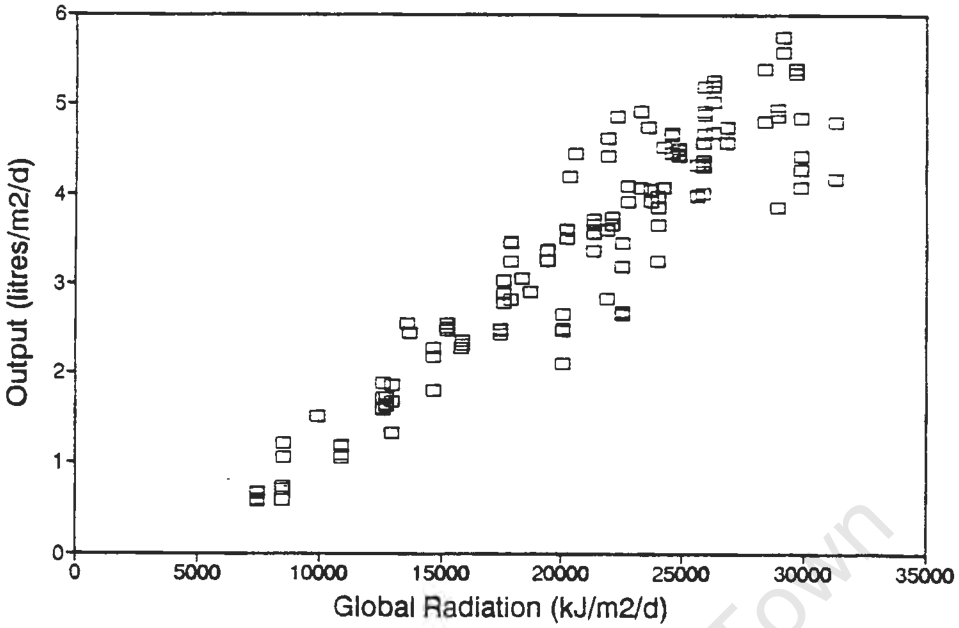


Figure 5.9: **Correlation between global radiation and productivity of inclined wick still as measured at CSIR, Pretoria, August 1990 to July 1991.**

A line fitted through the data in Figure 5.9 has the equation:

$$M_d = 0{,}21.Q_{rad} - 1$$

where: M_d = mass in kilogrammes (or volume in litres) of distillate
Q_{rad} = 24 hour global radiation (MJ/m^2)

This line is similar to that obtained for the basin still (Figure 5.3), being only slightly steeper (slope 0,21 versus 0,20). It is however when plotting the variation of the inclined wick still's efficiency through the year (Figure 5.10) that one observes a marked difference to the pattern observed for the basin-type still. Whereas the basin still shows a drop-off in efficiency in the cooler winter months, the inclined wick still comes into its own in the winter, showing efficiencies of over 50%. The higher efficiency is achieved through the more favourable orientation of the absorber plane during the winter months when he sun is at an angle of almost 50° from the vertical (the efficiency definition is based on the radiation incident on a horizontal surface).

Figure 5.10: Annual variation in efficiency of inclined wick stills observed at CSIR, August 1990 to July 1991

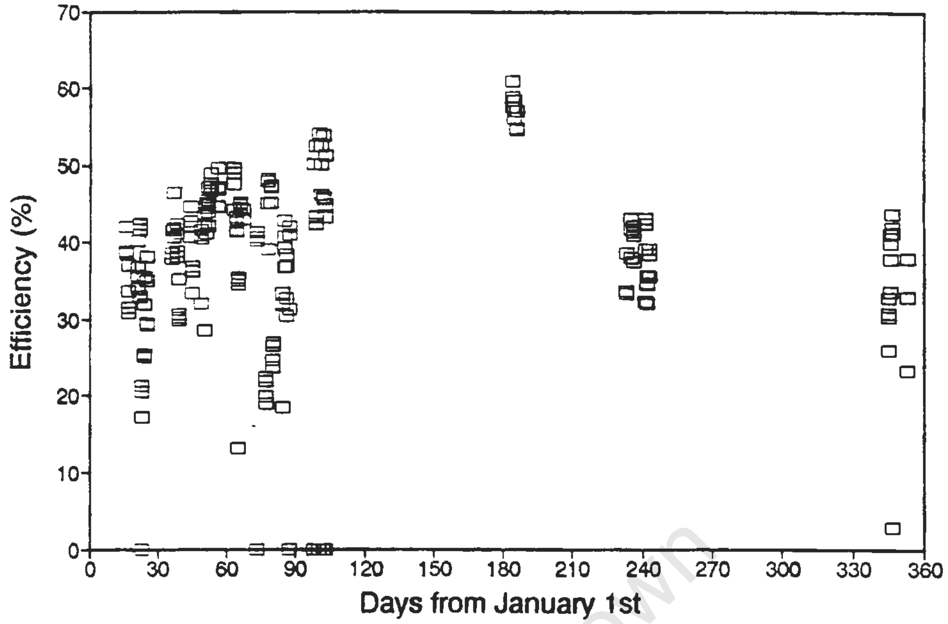
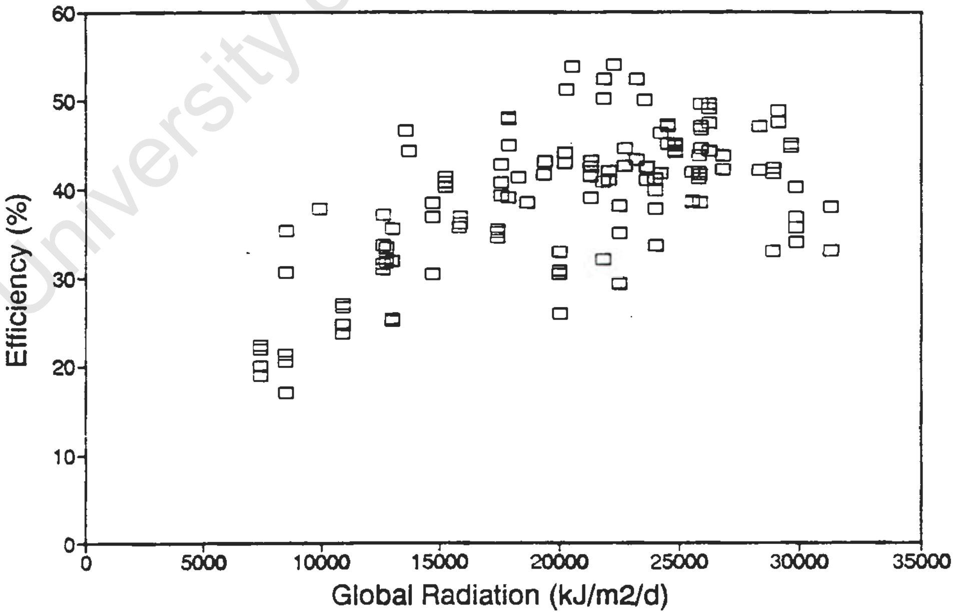


Figure 5.11: Inclined wick still efficiency plotted against global radiation



5.4 Parametric analysis of inclined wick still design

In order to better understand the operation and design of an inclined wick still four parameters were selected for closer examination: the flow rate, or flux, of the feed water; the salt concentration in the influent; the distance between the glass cover and the still wick (the still depth, not the same as water depth in a basin still); and the type of material used for the wick.

5.4.1 Effect of feed water flux on wick still

Figure 5.12 below shows the observed relationship between feed water flux and still efficiency. The data indicate that there is an optimum flux of about 1,5 ℓ/m^2/hr. When the flux drops below 1,0 ℓ/m^2/hr the still starts to dry out and there is a drop-off in efficiency. When the flux gets too high (above 3,0 ℓ/m^2/hr) the effect of the loss of heat from the system through the waste brine becomes marked. In practice it is difficult to regulate such low flows, and thus it is encouraging that there is a wide zone (1,0 - 3,0 ℓ/m^2/hr) of flux that can be tolerated without serious penalty. It should also be noted that this plot groups together data from days of varying solar intensity. On the cooler days the optimum flux would be at the lower end of the range, while on the warmer days it will move up. Again in practice the still will operate at a fixed flux regardless of weather, so this sort of general combined plot gives one the best idea of a suitable long-term setting.

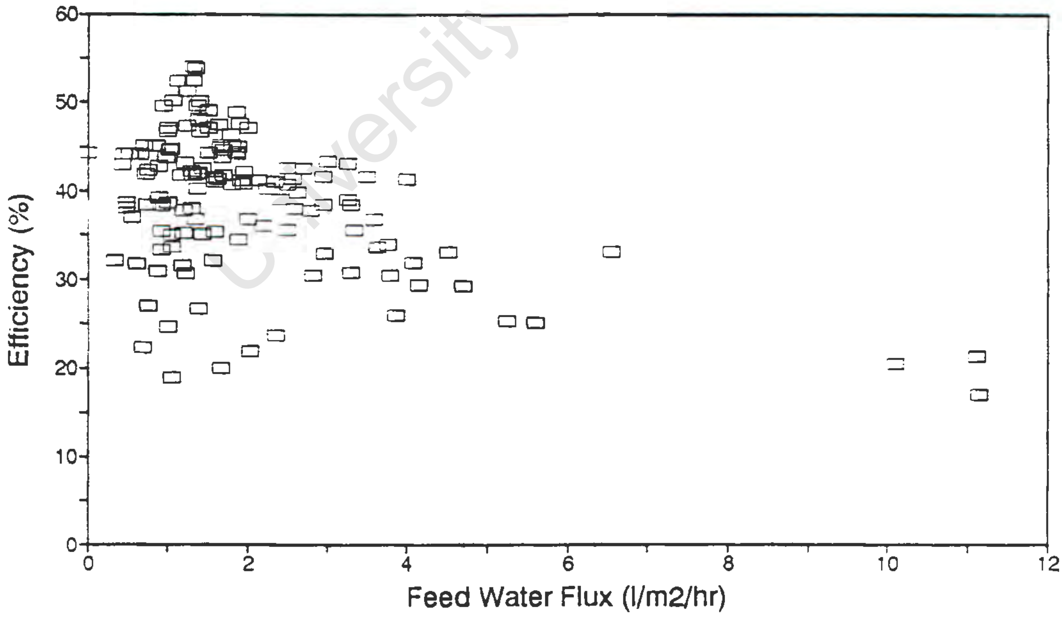


Figure 5.12: The effect of feed water flux on inclined wick still efficiency

5.4.2 Effect of feed water salinity on the wick still

An important practical consideration for any desalination process is its sensitivity to the salinity of the influent. In the case of membrane processes such as Reverse Osmosis the process becomes significantly more costly as the salinity of the feed water increases. Figure 5.13 shows that increasing feed water salinity from 100 to over 100 000 μS/cm (from tap water salinity to double sea-water salinity) has no effect on the efficiency of an inclined wick still. While there is a certain amount of scatter in the data owing to the variability in the weather over the period that these tests were made, it can be seen that the mean efficiency is insensitive to increasing salinity.

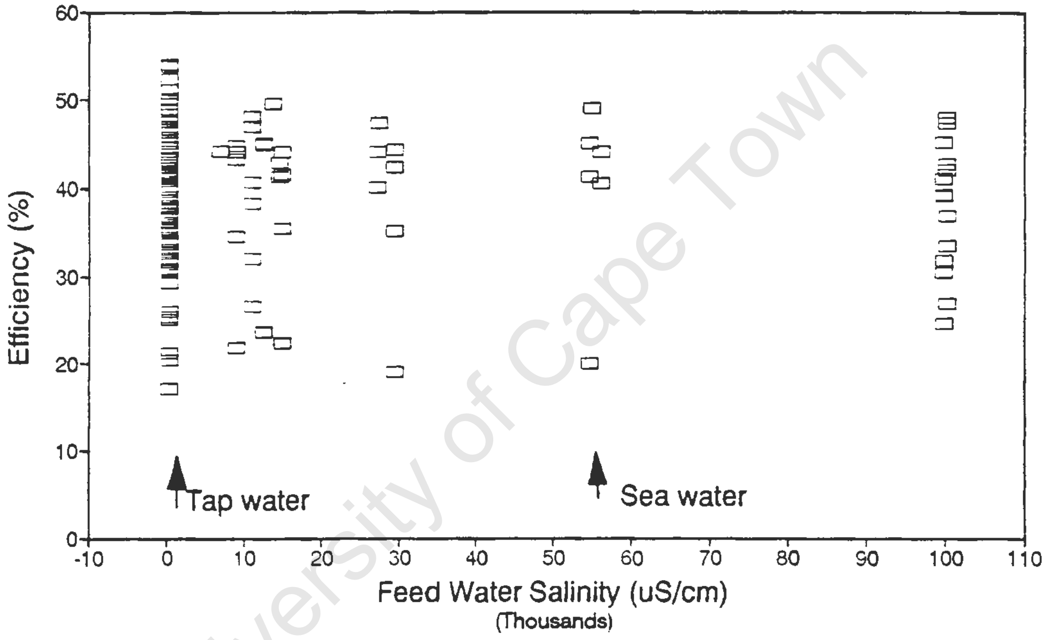


Figure 5.13: Effect on inclined wick still efficiency of increasing feed water salinity.

5.4.3 Effect of basin depth on the wick still

In designing an inclined wick still it is important to know whether there is any significance in the depth of basin which is specified. Obviously there will be material savings if a shallower basin is used, so this is the economically desirable direction in which to go. In August 1990 four basin depths were simultaneously monitored, and the comparison of their average efficiencies over the test period is given in Figures 5.14. The depths chosen were 40 mm, 70 mm, 100 mm and 150 mm. As can be seen the average efficiencies varied little, but there is evidence that 70 mm is optimum. The deeper still is disadvantaged in that its collector surface is partly shaded during the early morning and late afternoon, and this could explain the 4% lower average efficiencies observed for the 150 mm still as opposed to the 70 mm still. At very shallow depths one will begin to restrict the freedom of the convective vapour currents that transport the vapour from wick to glass, and this effect may be responsible for the slight drop off in efficiency observed from 70 mm depth to 40 mm depth (1%). Quite apart from thermodynamic considerations, it is impractical to build the inclined wick still much shallower than 70 mm because of the need to accommodate the collection channel and drainage pipes at the still bottom.

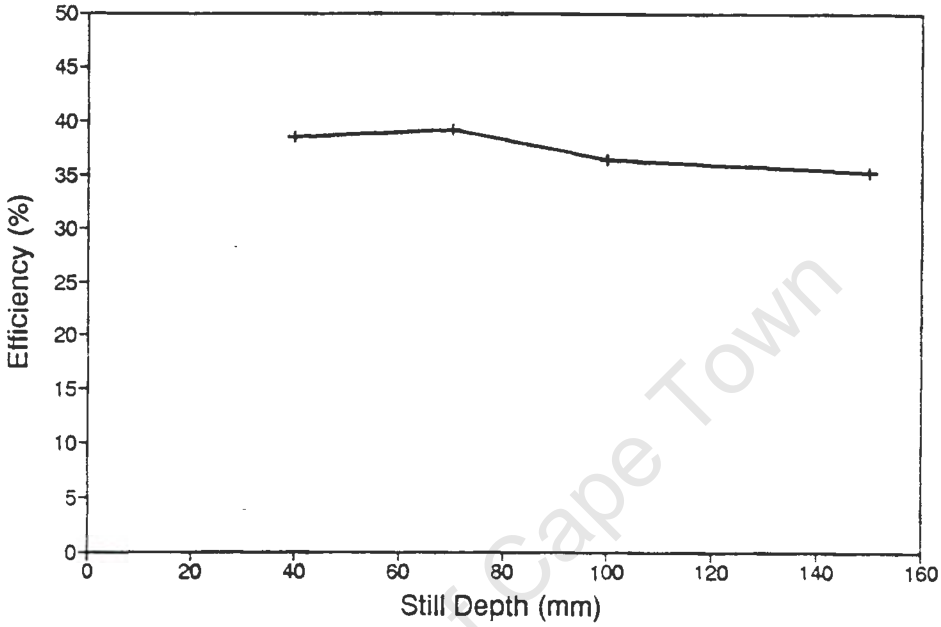


Figure 5.14: Average efficiencies of wick stills of varying depth

5.4.4 Effect of wick fabric type and colour on the wick still

Tests were done to check whether it mattered particularly what kind of fabric is used for the wick in the still. The first test that a fabric must pass is a basic absorbency test. An absorbent fabric will show a definite capillarity: it will be able to draw water up into itself against gravity. To be successful in an inclined wick still it should be able to pull water up at least 5 centimetres against gravity within a few minutes. In contrast a non-absorbent fabric will show a low capillarity, taking hours to pull water up only one or two centimetres. A fabric that was found to be unsuitable was a densely woven synthetic sold as gabardine. Crimplene, cotton t-shirt and cotton/polyester t-shirt fabric display good absorbency and capillarity.

New black cotton, faded black cotton, new black crimplene, and faded black crimplene were monitored side-by-side to determine if there was any measurable difference in the efficiency of inclined wick stills attribu to these differences in fabric type. Figure 5.15 shows the efficiency plots for the four stills over the period of the test, with a key detailing which fabric was in which still at each stage. As can be seen from the key, the fabrics were rotated halfway through the test to ensure that differences between stills would be averaged out. The resulting plots (Figure 5.15) indicate that the stills are relatively insensitive to the difference between a fully natural and a fully synthetic fabric. In fact the average efficiency for the cotton fabric through the test was 40,9 %, while that for the synthetic was 39,6 %, with standard deviations of 4,9 and 5,1 % respectively. The average efficiency for the faded fabrics was 40,4 %, and that for the new was 40,1 %, with standard deviations of 5,0 and 4,9 % respectively.

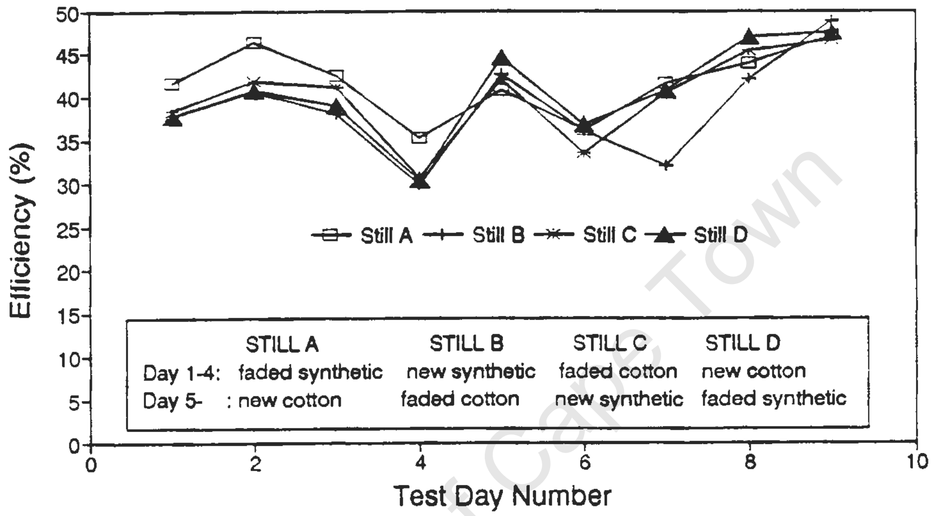


Figure 5.15: Comparison of efficiency of natural and synthetic, new and faded fabrics in inclined wick stills.

While intuitively an unfaded natural fabric might seem the best to use in an inclined wick still, these experiments show that the still is in fact fairly insensitive to the blackness or synthetic mix of the fabric used. Provided it is absorbent and retains at least a dark grey colour when wet, it will perform adequately.

Comparative tests were also performed on cotton t-shirting and crimplene to monitor the rate at which the dye fades when the fabric is exposed to the sun. After 65 days the fabrics had both faded appreciably, but to about the same degree. Unfortunately the cotton fabric disappeared before the next observation was made, which was after 152 days. The remaining crimplene fabric had continued to fade and had reached a point where re-dyeing would be advisable. In all cases only the upper side of the fabric fades, so that before re-dyeing is necessary the fabric can simply be inverted.

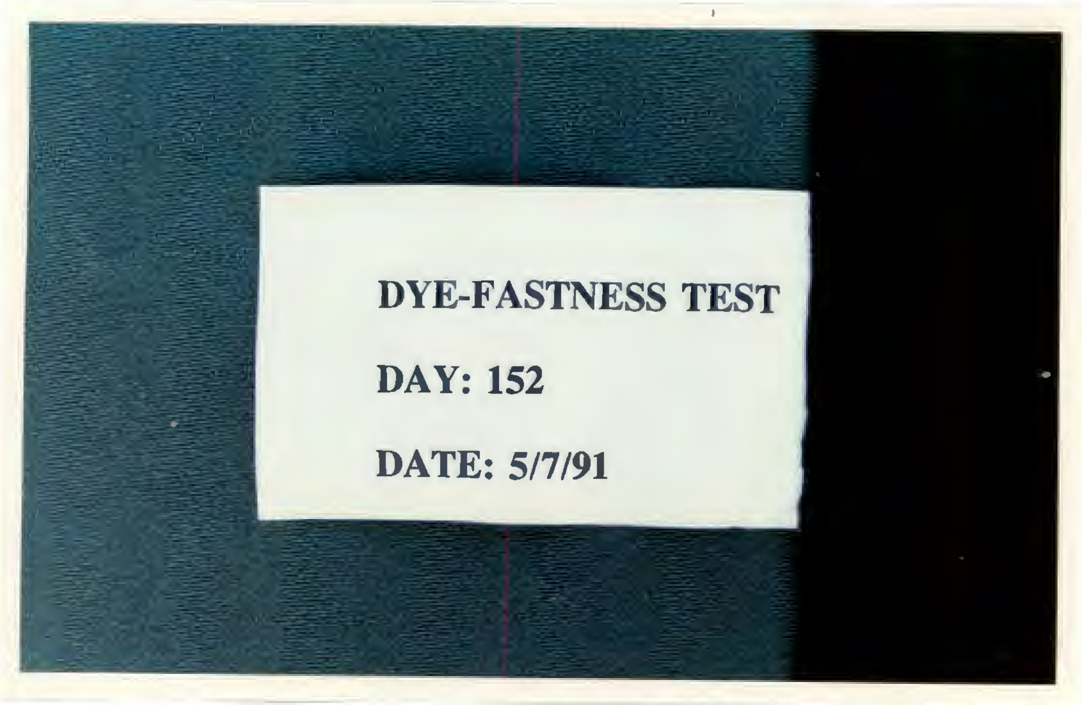


Figure 5.16: **Degree of dye-fading observed after five months (152 days)**

Based on these tests, the following wick maintenance schedule can be proposed: after six months use the wick should be rinsed and inverted; after one year's use it should be re-dyed. With time the wick can be expected to rot, but the fabric is under no stress so it should last for several years. A synthetic or synthetic/natural blend fabric should last longer in the sun than a fully natural fibre. As an initial rough estimate, for costing purposes, a wick life of three years is suggested.

5.5 Comparison of the wick still and basin still

Figure 5.17 shows that there is no significant difference in the response of wick and basin stills to solar radiation during the months when the sun is close to vertical in the midday sky. During the winter months, however, when at Southern African latitudes the sun is between 40 and 60° from the vertical, it becomes highly advantageous to be able to have a collector surface which is tilted towards the sun. The basin still is horizontally orientated and averages only 1,7 ℓ/m^2/day production in the winter. The inclined wick still produces double that.

Although it is perhaps acceptable to have some fall off in water production during the winter months, when drinking water consumption will be lower, the basin still's winter production is inconveniently low. The inclined wick still shows a more stable production through the year. If a unit has to be sized to guarantee a certain minimum production throughout the year, then the inclined wick still would allow a more economic design at Southern African latitudes.

In equatorial regions, where the suns position in the sky is not so affected by the seasons, there would be little advantage to be gained from using an inclined still. *It is interesting to note, however, that all the world's dry, arid regions are situated on or outside the tropics. The implication is that most places in the world where desalination of brack water or seawater would be desirable are situated at latitudes where the inclined still has a major advantage.*

Wherever a still is erected, it needs to be out of the way of animals and children who may inadvertently damage the glass. Roofs are well suited for this end. On flat roofs a basin still can be easily installed, while an inclined wick still will require some kind of support frame to achieve the desired inclination towards the sun. In contrast, on pitched roofs an inclined still can be easily installed, but it would be quite impractical to install a basin still. As the majority of houses in South Africa have pitched roofs, inclined wick stills would generally prove easier to install.

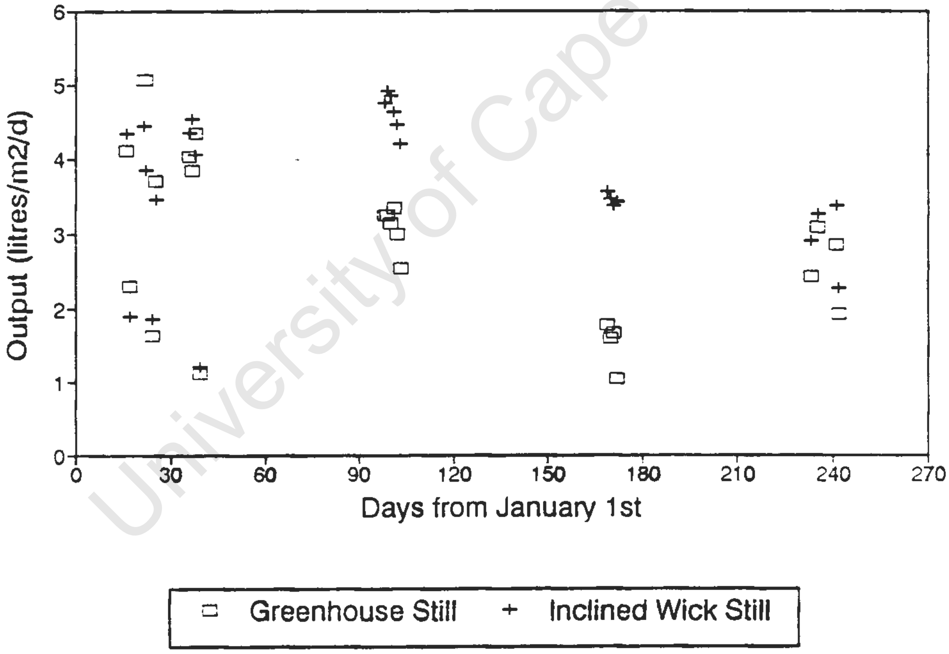


Figure 5.17: Comparison of summer and winter production of basin and wick stills.

CHAPTER 6

FIELD TESTS

Field tests have been conducted at two locations: the farm of Mr Dawid Pieterse in the Matlabas valley of the Northwestern Transvaal; and in the village of Paulshoek, which is on the Leliefontein reserve in Namaqualand.

6.1 Matlabas Valley: Pieterse's farm

6.1.1 Field test unit description

The basic unit constructed for both the Matlabas test and the Namaqualand test was an inclined wick still of approximately two square metres area. The stills differed, however, in the design of the header tank for storing the feed water. In the case of the still installed on the farm of Mr Pieterse, the header tank was made integral to the still, being formed essentially by a compartment above the wick area. This still is shown in Figure 6.1, with the glass cut away (accidentally!) which gives a better impression of the design. The total still area is 2,0 m^2 (outside measurement), with the wick area 1,6 m^2 and the header tank 0,3 m^2. The header tank has a capacity of 24 litres, which is a day's capacity at 1,5 litres per square metre of wick through a ten hour day. This means that the tank need only be filled once daily to give the still enough water to operate. Having a glass cover the header tank not only stores the feed water, but it also pre-heats it. Thus although the wick area is only 1,6 m^2, the still utilizes the solar energy incident over its full 2 m^2 area. The estimated retail cost of this still is R440, tax included.

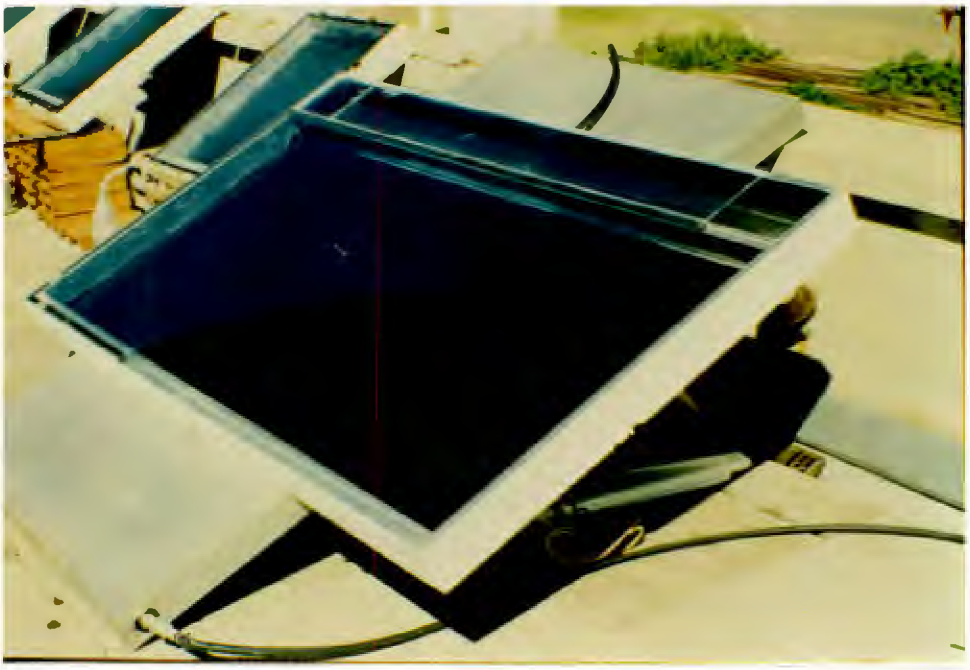


Figure 6.1: Inclined wick still of 2 m^2 area with integral header tank used for field test on the farm of Mr Dawid Pieterse, Matlabas Valley.

Flow from the header tank to the wick is controlled by two orifices sized to permit the optimum feed rate. These orifices are of 0,5 mm diameter, and may need to be unblocked from time to time. The glass cover is attached by a system of aluminium clips which allow it to be relatively simply removed and refitted.

The still was erected on the roof of an outbuilding, and there was sufficient water pressure to allow for the still to be filled from a nearby tap. The slope of the roof was 20° and its orientation was East-North-East. Figure 6.2 below shows the general arrangement.

Figure 6.2: Field test in progress on the Pieterse farm, Matlabas Valley.

6.1.2 Quality of feed water

Owing to the recent good rains in the Northwestern Transvaal, the Pieterse's borehole is currently delivering water of quality better than typically experienced by them. An analysis done on a sample taken from their borehole (Table 6.1) shows that this water is within acceptable limits for domestic consumption, although the total salinity of 1500 mg/ℓ[a] indicates a water that would be unpleasant to the taste and which would be poor for washing.

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[a] Salinities quoted in this chapter were measured in the field with a temperature compensating WTW conductivity meter. The readings in μS/cm were converted to mg/ℓ TDS using Walton's figure, which is reproduced in Appendix G.

Table 6.2: Field test results for the Pieterse farm, Matlabas

Date	Feed water (litres)	Distillate (litres)
28/4/91	20,0	8,0
29/4	20,0	7,5
30/4	20,0	8,5
1/5	21,0	8,0
2/5	19,0	8,0
3/5	20,5	7,5
4/5	20,5	8,5
	Average distillate	8,0

6.1.4 Design weaknesses and lessons learned

Two pieces of glass comprised the glass cover of the wick area of the still. Each piece measured 900 x 915 mm x 3 mm. These pieces were supported on only three sides, with the joint between the two pieces of glass being unsupported. This arrangement apparently gave unsatisfactory support to the glass because, whether due to wind or thermal stresses, the glass was found to crack. Although two spare pieces of glass were left on the farm they soon also cracked and this test terminated. Building on this experience the stills installed in Namaqualand were provided with extra support for the glass and to date no problems have been experienced with the glass covers there.

6.2 Paulshoek, Namaqualand

The village of Paulshoek is situated on the Leliefontein Reserve of Namaqualand, and has a population of approximately 500 people. The village does not appear on any but the most detailed maps, but it is 20 km south east of Leliefontein, which can be found east of Kamieskroon. While Leliefontein itself lies on the watershed of the Kamiesberg and enjoys an annual rainfall of over 300 mm, Paulshoek is on a semi-desert plateau and has only 100 mm. The water in the village is very brackish, as it is in most of Namaqualand and the Karroo to the east. At present those villagers who can afford it pay water vendors in their community R10 per 200 litre drum transported from the nearest sweet water source. This is R50/m^3 compared with the R1/m^3 typically paid by city dwellers in South Africa for their domestic water! The Kamiesberg Ontwikkelings Vereniging is presently investigating what can be done to improve the quality of the Paulshoek water supply, and it was through this initiative that the CSIR came to be invited to set up some pilot stills at the village.

6.2.1 Field test unit description

Two inclined wick stills were fabricated, each of similar design. The header tank was in this case provided by a rack of black low density polyethylene (LDPE) piping of 50 mm internal diameter. The rack had an internal volume of 22,3 litres, or a day's supply at the recommended feed rate. To allow batch filling the rack was fitted with an air bleed valve at its upper end. The wick area was 1,8 m^2. Flow control was by means of ½ " brass valve. The expected retail cost of this still is R500, tax included.

One of the stills was installed on the roof of the village school (Figure 6.3), the other at the house of the chairman of the water committee, Mr Karl Joseph (Figure 6.4).

Figure 6.3:
Inclined wick still, with rack style header/heater tank, installed on the Paulshoek school's roof

The still at the school was fixed on the roof which was pitched at 20° and orientated East-North-East. It was installed in a way that it could be filled by connecting the feed pipe to a tap in the schoolyard, or by pumping with a small handpump from a water container. This latter measure was made necessary because of the unreliability of the supply at the tap.

Figure 6.4: Inclined wick still mounted on wooden frame at Mr Joseph's house, Paulshoek.

The still at Mr Joseph's house was mounted on a wooden frame, which can be adjusted to two settings: 50° for the winter months, and 25° for the summer. The point of mounting it on a frame and not on a roof was to allow it to be more easily viewed by the community.

6.2.2 Quality of feed water

A sample of the water taken at Paulshoek from the village water supply reservoir was found to have a conductivity of 334 mS/m, which equates to a Total Dissolved Solids content of approximately 2230 mg/ℓ. This is over the maximum health specification of 2000 mg/ℓ. In addition the flouride and chloride contents of the water are above health limits. The analysis of the water is given in Table 6.3 below. Apparently the quality is at times poorer than this. For interest samples were also taken at Garies and Kamieskroon, the two towns on the N7 route to the west. At Garies the municipal water supply had a TDS of 3150 mg/ℓ, and at Kamieskroon the figure was 2900 mg/ℓ. The flouride levels are 1,9 and 2,0 mg/ℓ respectively. The Namaqualand town of Bitterfontein to the south has groundwater salinities of over 4000 mg/ℓ, but it now benefits from a state-subsidised Reverse Osmosis desalination plant.

Table 6.3: Chemical analysis of water being used for domestic consumption in Paulshoek, Namaqualand

Description	Recommended limit (SABS 241-1984) (mg/ℓ)	Maximum allowable limit (mg/ℓ)	Observed (mg/ℓ)
Sodium (Na)	100	400	195
Nitrate and Nitrite (as N)	6	10	1,4
Sulphate (SO_4^-)	200	600	162
Chloride (Cl)	250	600	776
Flouride (F)	1,0	1,5	2,0
Total Dissolved Salts (TDS)	500	2000	2230

6.2.3 Field test results

While the still at Mr Joseph's house is functioning well and is being cared for and monitored on a daily basis, the still at the school is to date only intermittently used. According to the Water Committee the school still functions about as well as the still at Mr Joseph's house, but to date records have not been kept so it is impossible to verify this. The problem is partly due to the unreliability of the water supply to the school, but the real explanation probably lies in the lack of any individual responsibility for the still (the problem is being followed up with the water committee and the school head, and will hopefully be resolved after the resumption of school on July 15). Mr Joseph on the other hand benefits personally from his still and takes good care of it. He says he is very happy with it and as a result of it he no longer has to transport water from the sweet water well 5 km distant.

A violent storm which struck the Western Cape on 26/6/91 turned the wooden frame, on which the still was mounted, onto its side. One of the glass panes had to be replaced and the frame was staked at all four corners to prevent a recurrence. There were no readings between 26/6 and 2/7.

The results from the still at Mr Joseph's house are plotted in Figure 6.5 below. The data appear in Appendix E.

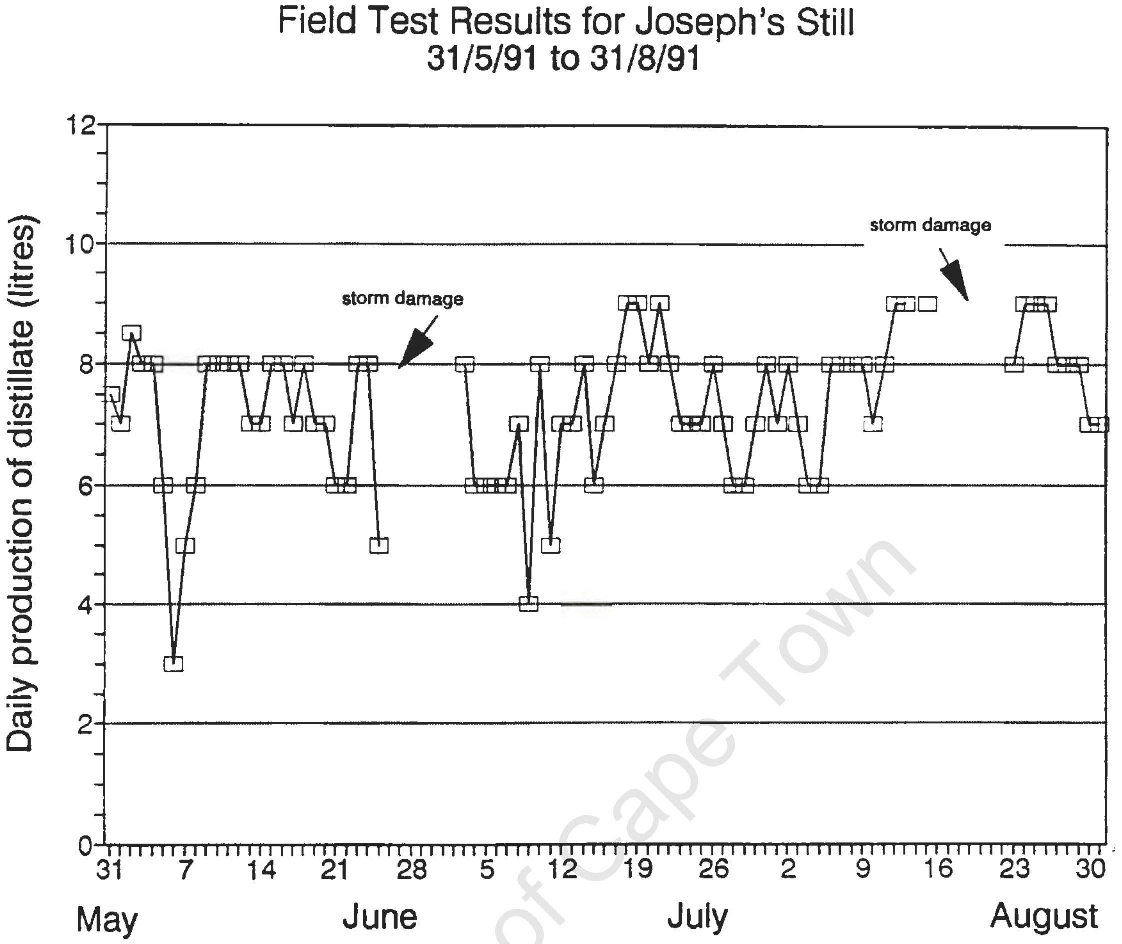


Figure 6.5: **Field test results for the Mr Joseph's still, Paulshoek**

The average distillate produced was 7,3 ℓ/d. The wick area is 1,83 m^2, but the still panel's full area is 1,95 m^2. On this basis the still's production is 3,74 ℓ/m^{2}/d. One has somehow to take account of the LDPE pipe heater/header assembly, which has a projected area of 0,7 m^2. Using then the total projected area of 2,65 m^2 the still's production is 2,75 ℓ/m^2/d. The average daily solar radiation on a horizontal surface for this area at this time of year is 12 600 kJ/m^2 (20 000 kJ/m^2 on a surface inclined 50° to the horizontal). Using the standard equation the still's efficiency is 53 %. The cost per litre of distillate is 3,8 cents, allowing for amortization over an expected 10 year life, and for maintenance (see section 7.3). In assessing these results it is interesting to note that they span almost exactly the winter months June to August.

6.2.4 Design weaknesses and lessons learned

Flow into the still was through a single inlet, situated at the top of the still to one side of the mid-panel glass support. From this inlet the feed was required to spread evenly throughout the full area of the wick. To ensure that it reached the far corners it was necessary to open the inlet valve to allow a flow rate greater than optimum. It also meant that the still was particularly sensitive to differences in level between its left and right sides. Both of these problems would have been avoided if the panel area had been restricted to $1 m^2$.

The heater/header rack was not a good idea for the following reasons: it effectively doubled the area required for installing the still; it was not cheap, costing a total of R60 in pipes and fittings; and it required too much attention to level the pipes in a way that would prevent airlocks from forming.

6.3 Conclusions from field tests

6.3.1 Panel design

The design used for the Matlabas test is more cost effective than that used in the Namaqualand tests. It is also more compact and easier to install. More thought will need to be given to the arrangement for allowing water to pass from the header tank through to the wick area. The present arrangement, a fine orifice (0,5 mm) seems likely to be prone to blockage. Relatively simple changes to the inlet could however allow for the orifice to be scoured hydraulically during filling, and this could lengthen the intervals between maintenance on the orifice.

6.3.2 Panel size

It was for reasons of labour economy that the field test prototypes were made to the full scale expected to be sui for a household solar still unit ($2 m^2$). With the benefit of hindsight, however, it would be better to make the standard still panel $1 m^2$ in area. Users can then buy as many panels as are required to meet their daily needs. A $1 m^2$ panel is the more convenient, practical size in terms of transport, erection, feed water distribution through the wick, and glass support.

CHAPTER 7

IMPLEMENTATION

7.1 Optimum design

The best year round production is given by the inclined wick type stills. The multiple-effect inclined wick stills are not reliable enough for use in practice, and though they display high efficiencies when they work they are no more cost effective than the ordinary single-effect inclined wick still.

The recommended design is thus a single-effect inclined wick still of the type installed on the Pieterse farm during the first field test (see Section 6.1). This design would be modified to allow for hydraulic scouring of the throughflow orifice, and the panel area would be restricted to 1 m^2. It should be noted that this size is nominal: the actual size is determined by the standard size of glass sheet as made by glass manufacturers. By sizing the still to take the standard glass sheet uncut there is a significant saving in the price of the still. The actual outside dimension of the still is 1125 mm x 915 mm.

Figures 7.2, 7.3 and 7.4 show the proposed final prototype. The thinking behind the proposed "scale-free" inlet arrangement is detailed in section 7.5.3. Other minor details to note are:

☐ The sizing of the wick baffle at 30 mm is not arbitrary. The 20 mm baffle used in the Paulshoek still was a little low for effective damming of feed water when the still is inclined to 50°. At flatter angles, say 20 to 30° as on most pitched roofs, the dimension would not be so critical.

☐ The sizing of the outlets at 15 mm is also intended. These outlets, particularly the distillate outlet, operate under very low heads because of the dimensions of the apparatus. Use of smaller diameter tubes can cause air-locks and distillate overflows.

7.2 Expected life of still

The wearing materials in the still are:

☐ *The wick.* As mentioned in Section 6.4.4 the wick would need to be re-dyed annually, and should be inverted midway between these services. The wick life is estimated at three years.

☐ *The basin.* The basin has in all tests to date been made from aluminium sheeting. A corrosion audit conducted after seven months of testing found the metal to be in good condition, showing very little sign of pitting. Any pits that did perforate the still over time could be repaired fairly simply, as the basin is not under pressure. Mild steel, galvanised or coated with some other treatment would cost the same as aluminium sheet (0,9 mm thick), and may not last as long. Copper is prohibitively expensive. HDPE plastic might work, but the moulding would be very costly at the volumes expected for this market, and the plastic itself is not cheap. The soft aluminium alloy that is commercially available is recommended, and its design life can be estimated at 10 years.

- ☐ *The glass:* The glass will not wear, but accidents during maintenance and storm damage can not be discounted. Assume a pane will last four years.
- ☐ *The rubber seals:* Assume replacement every two years.

The expected still life can thus be set at 10 years, with some replacement of wearing parts along the way.

7.3 Cost of distilled water from this design

The materials in this design would cost R110 at retail prices. Allowing R60 for a man-day to do the fabrication, R30 for marketing, R50 for profit and R30 for tax the final retail price would be R280 for a 1 m^2 panel. The user will then still have to provide the pipe work to link the inlet and the outlets to the feed and the collection tanks. The latter will also have to be purchased. Half inch garden hosepipe retails for R25 for a 30 metre roll, and this should be sufficient for the average installation. Jerry cans for collecting distillate and brine retail for R20 for 20 litre cans. So the average household will probably have the following outlay:

Stills, 2 panels	R560
Hosepipe and fittings	R35
Collection jerry (assume only distillate collected)	R20
TOTAL:	R615

For this R615 they will obtain an average of say 8 litres of distillate per day, possibly more. In summer the figure could get as high as 11 litres, and in winter it may drop to 7 litres. At 8 litres per day they will obtain 2920 litres per year, say 2,9 m^3. Depending on their feed water quality this may allow them to produce between 3,0 and 6,0 m^3 of drinking water per year (assume quality 800 mg/ℓ TDS), with the lower limit set for sea water feed (35 000 mg/ℓ TDS) and the upper for feed at 1600 mg/ℓ TDS.

Amortizing R615 over 10 years at a 5% real interest rate, the annual payment would be R615 x 0,1295, or R79-64, say R80. This amount would have to escalate at the rate of inflation to allow pay off after 10 years.

The annual maintenance costs would be R5 for glass, R1 for seal replacement, and R3 for wick replacement, making a total of R9, say R10. This amount would also escalate at the rate of inflation.

The total annual cost for water obtained from the still would be R90, giving a range of R15 to R30/m^3 for the blended drinking water product, depending on feed water quality.

Compared with the R26/m^3 water that the 100 m^3/day state-subsidised Bitterfontein/Nuwerus Reverse Osmosis desalination plant is producing, this looks quite favourable. For fairness of comparison, however, it should be mentioned that Solar Distillation at that kind of scale would require paid maintenance staff, which would push the cost up somewhat.

Economies can be achieved by providing the still cover with baffles to collect rainwater on rainy days. For example, at an annual rainfall of 200 mm (typical for high salinity areas) the still would yield an extra 200 litres of water in the year. A more logical solution for the homeowner is, however, to concentrate on rainwater harvesting from the full area of his roof, which would yield more significant amounts of water.

7.4 Types of installation

How would the still technology be implemented? There would be two basic types of installation: the household unit, probably fitted on a roof and supplied by available water pressure (Figure 7.5); and the small community plant, probably comprising a number of stills arranged in parallel on the ground with a single feed tank, and a single collection tank. Figure 7.6 shows the largest size installation that *could* still be economical and practical, under favourable circumstances - 49 panels for an average production of 200 ℓ/d of distillate (estimated cost with tanks, soakaway and fencing - R20 000). The latter is more economical in the collection and distribution systems, but has extra costs such as the fencing off of the area to protect it from animals. From a maintenance point of view the household installation is preferable, but in poorer communities such as Paulshoek the lack of water pressure and the lack of sturdy pitched roofs makes an alternative approach necessary.

A manufacturer should concentrate on producing the standard still panel, which could then be incorporated into any desired configuration. The panels could be provided with a small operation and maintenance guide, along with installation instructions. With the guide a chart could be provided giving the users an idea of what production they could expect to get from their stills depending on geographical location and the season. For larger installations a design service could be provided.

7.5 Maintenance concerns

7.5.1 The problem of the reduction of wettability of glass that is exposed to the atmosphere

If a sheet of glass is exposed to the atmosphere for a length of time a film forms on its surface, reducing its wettability. If, for example, the glass cover of a still is inverted after several months use, the condensate no longer runs smoothly down to the condensate collection channel, but forms droplets which fall back onto the wick. The droplets also reflect part of the incoming light. This problem is illustrated in Figure 7.1.

The problem should if possible be avoided by marking the outside surface of a still cover before removing it, and ensuring that it is replaced in the same orientation. Where the problem of reduced wettability due to film formation does present itself, however, it can be solved by the addition of a solution of dilute ammonia to the feed water. The volatile ammonia vaporizes with the water vapour, and dissolves the film on the inside glass surface. In the case of inclined wick stills, for example, the addition of 2 ml of 30% ammonia solution per litre of feed water returned the glass to its as-new condition within 48 hours. The distillate should not be drunk for two days after the addition of ammonia to the feed.

Commercial products that are marketed to improve the ability of car windscreens to remain clear in rain are particularly unhelpful, as their effect is precisely to decrease the wettability of a glass surface.

Figure 7.1: The problem of reduced wettability of a glass cover that has been refitted upside down.

7.5.2 Corrosion - points to note

Discussions were held with Mr Bryan Callaghan, a CSIR corrosion specialist on secondment to the S.A. Naval Dockyard Materials Laboratory at Simonstown. The following points arose from the discussion:

- If the still is fitted to a corrugated iron roof, care should be taken to minimize the contact between the still panel and the roof. The still should not be fitted flush onto the roof, but use should be made of rubber washers to space it a few mm off the roof. The points on the roof at which contact is to be made should be soundly painted before the still is installed. [This precaution is to protect the roof - the patches at which contact is made will tend to collect moisture and will be more prone to rust than the rest of the roof.]
- Crevices created by rivets should be sealed over with silicone rubber or polysulphide.
- If the feed water is expected to be high in copper then it would be preferable to make the still basin from mild steel, suitably primed and coated with two coats of cold tar epoxy. The presence of copper ions in solution promotes corrosion of aluminium.
- Care should be taken to seal the joints of the polystyrene cladding in such a way that rain water will not be able to find its way to the space between the cladding and the aluminium basin. If water should become trapped in this space accelerated corrosion would occur.

A corrosion audit conducted by Ron Cromarty, a corrosion and paint specialist with the CSIR, on the experimental inclined wick stills after six months of use indicated very little corrosion. The use of the softer (and purer) of the commercially available aluminium alloys for construction of the basin will promote corrosion resistance. The most likely corrosion problem with aluminium is pitting. Fortunately the unit is not pressurised so a small leak is not expected to affect its functioning. If corrosion does develop over longer periods of use, the basin bottom (where the corrosion will most likely occur) can be sanded and painted with a suitable sealing compound (e.g. cold tar epoxy, with self-etching zinc-chromate primer underneath)

7.5.3 Removal of scale

Temperatures of up to 75°C are reached in the still during the heat of the day. This is above the 70°C at which the alkaline scales $Mg(OH)_2$ and $CaCO_3$ begin to precipitate out of solution. With time there will be a build-up of scale on the wick, and this should be rinsed out when the wick is inverted or redyed (six-monthly maintenance recommended). The only point at which scale deposition may present a serious obstacle to the functioning of the still is the fine (0,6mm) orifice which permits flow from the header/heater chamber to the evaporation chamber. To avoid scale build-up at this point two features have been incorporated in the design (Figure 7.3):

- ☐ the feed water pipe has been brought forward to a point just a few mm short of the orifice. During filling of the header tank there will be a high degree of turbulence at the orifice as the incoming water jets against the partition wall between the evaporation chamber and the header chamber. If the still is from time to time filled in the heat of the day this incoming stream will be significantly cooler than the area around the orifice, and some thermal shocking can be expected to occur.

- ☐ a feed water baffle has been specified 10 mm downstream of the orifice. This baffle will ensure that, even at an incline of up to 50°, the orifice itself is always below the water surface. Since scale tends to precipitate mainly at the surface the orifice should escape the worst of the scale deposition.

If scale is seen to be forming around the orifice, the addition of several hundred mg/ℓ of acid to the feed water as a shock dose (not recommended on a continuous basis owing to corrosion effects) would remove some of the scale. Again the proximity of the inlet nozzle to the orifice is designed to maximize the benefit from such acid dosing.

Failing these measures, the glass cover can be unclipped and the scale can be removed by hand with a knife and a pin. Ideally this measure should not be required more often than the routine six monthly care of the wick.

This "scale-free" inlet arrangement has yet to be proven on scaling waters in the field. If it fails to achieve its purpose an external connection between the two still chambers will have to be used. This would be fitted with a valve that could be adjusted whenever scale effects should jeopardize the continuity of flow to the evaporation chamber. This arrangement would be both more expensive, thermally less efficient and less elegant, so it is hoped that it will not be necessary.

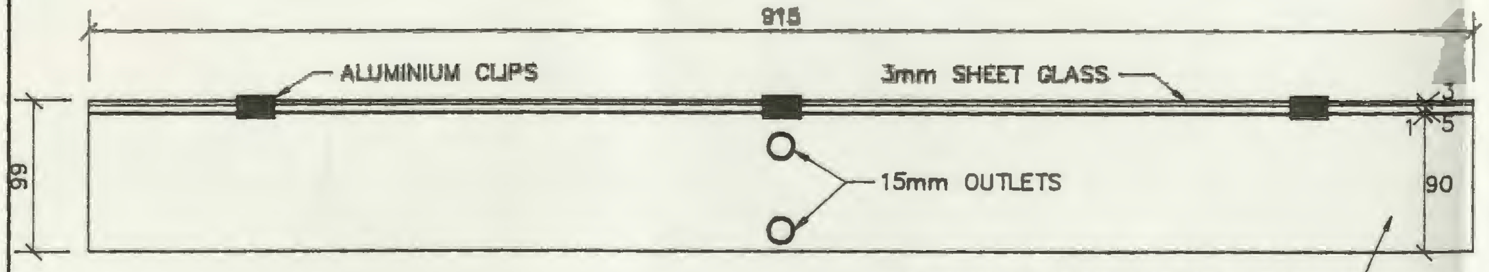
FIGURE 7.2: INCLINED WICK SOLAR STILL

(PLAN AND ELEVATION)

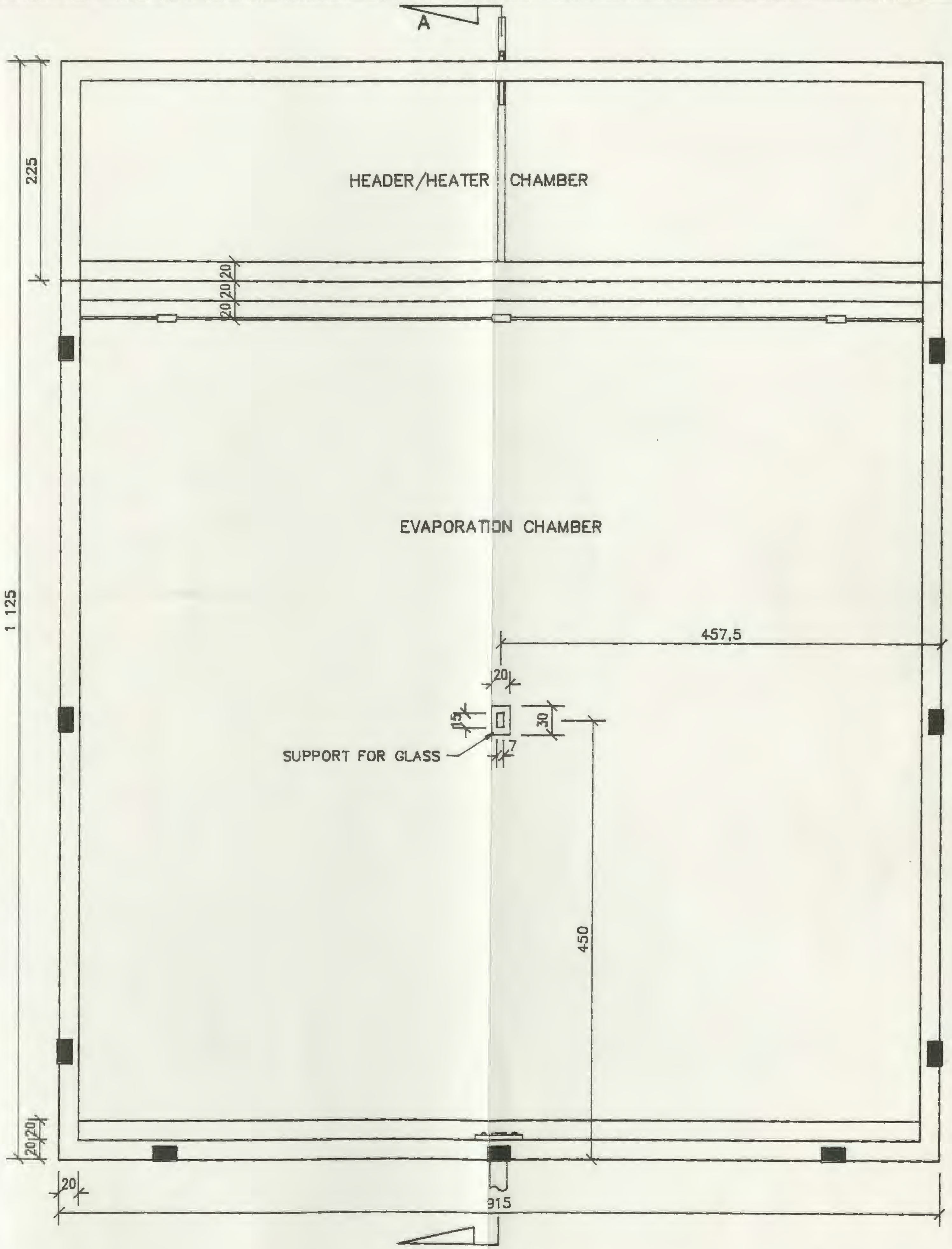
SCALE 1:5

NOTES:

1) ALUMINIUM BASIN TO BE MADE FROM 1,0mm SOFT ALLOY SHEET.
2) JOINTS TO BE FOLDED, RIVETTED AND SEALED WITH SILICONE SEALANT (TYPE CLEAR, FOR NON-POROUS SURFACES). NO ALUMINIUM WELDING IS NEEDED.
3) CLAD ALUMINIUM IN 20mm THICK POLYSTYRENE SHEETING, DENSITY CLASS 24dv, WITH PROTECTIVE BITUMINOUS COATING.
4) PAINT HEADER/HEATER CHAMBER BLACK. (APPLY BLACK PVA OVER SELF-ETCHING ZINC CHROMATE PRIMER).
5) FOR INLETS AND OUTLETS USE COMMERCIALLY AVAILABLE PVC FITTINGS.
6) ALUMINIUM CLIPS FOR SECURING GLASS TO BE CUT FROM COMMERCIALLY AVAILABLE 20 x 10 CHANNEL SECTION.
7) SEAL ALL RIVETS FROM THE INSIDE WITH SILICONE AFTER FASTENING.
8) ALL DIMENSIONS ARE IN mm.



ELEVATION



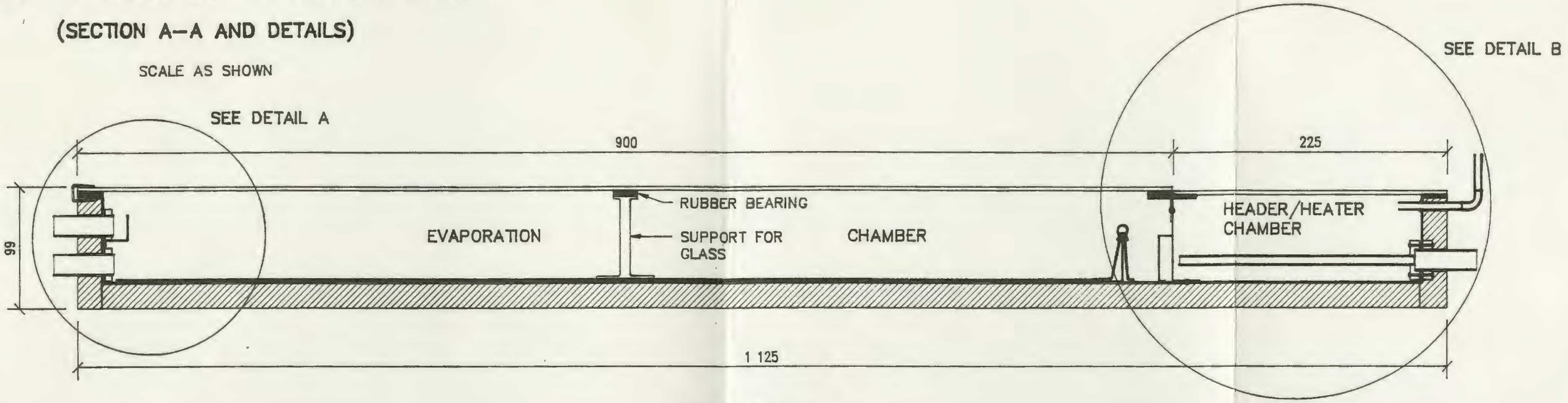
PLAN

D.A. Still

FIGURE 7.3: INCLINED WICK SOLAR STILL

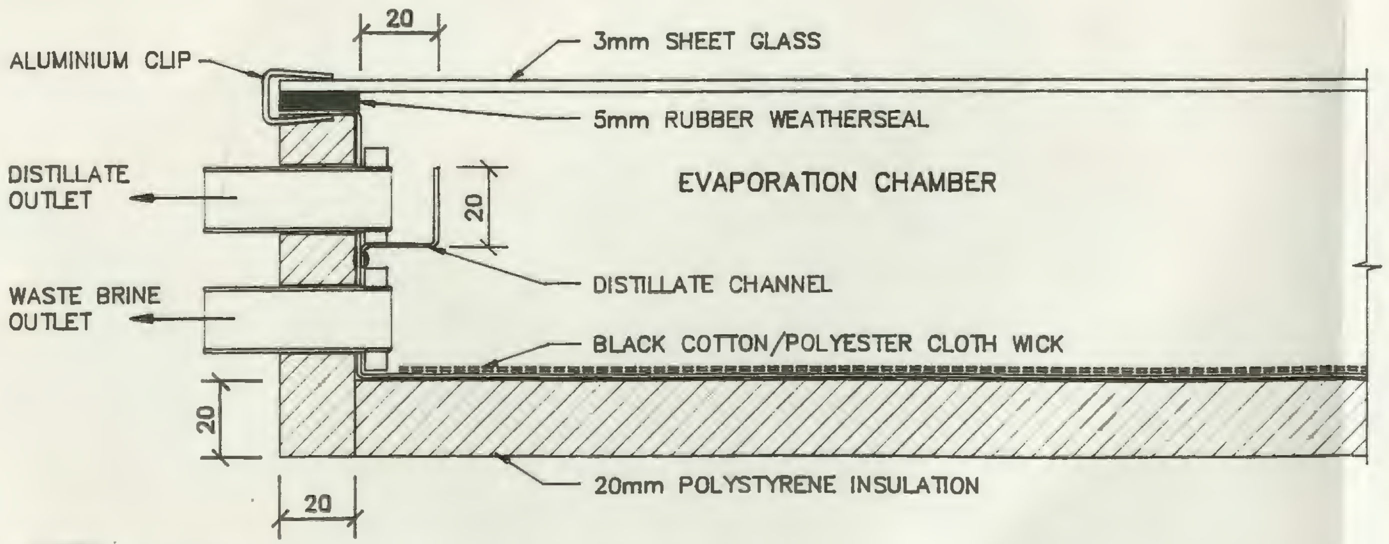
(SECTION A–A AND DETAILS)

SCALE AS SHOWN



SECTION A–A

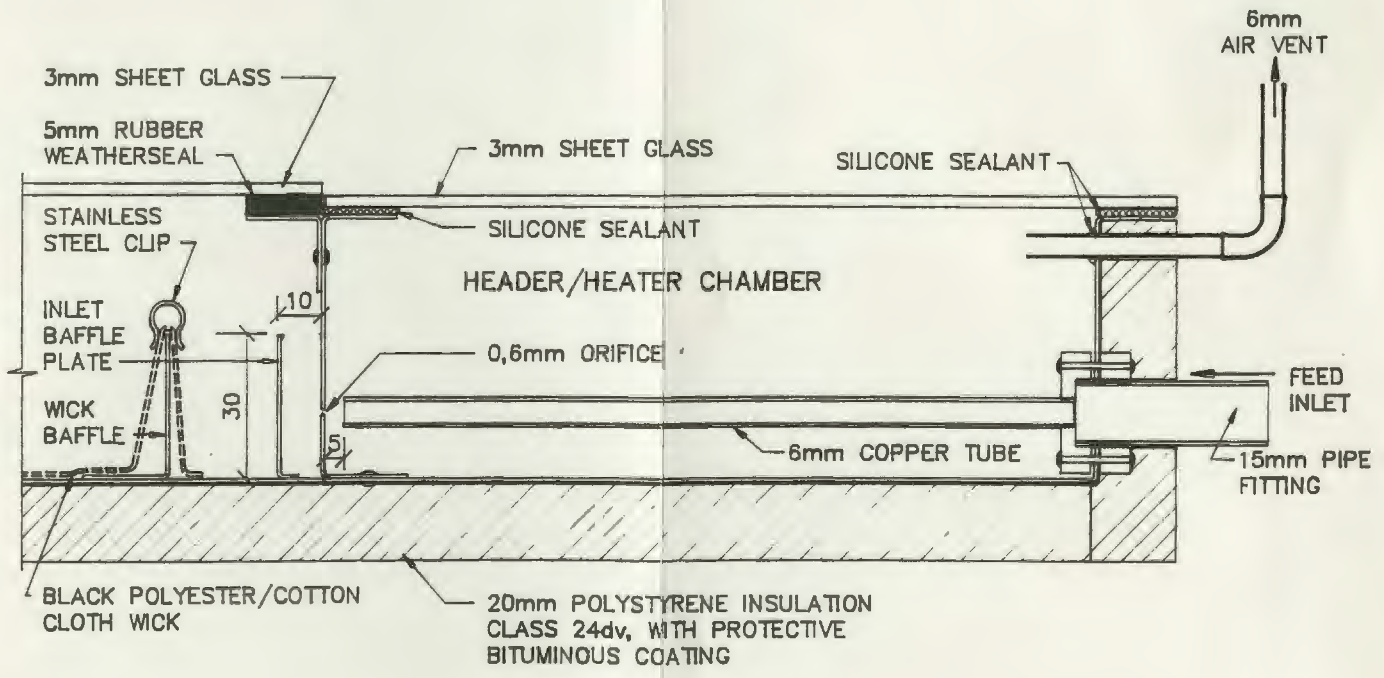
SCALE 1=4



NOTES:
FOR OUTLETS USE STANDARD 15mm PVC PIPE FITTINGS

DETAIL A

SCALE 1=2



DETAIL B

SCALE 1=2

D.A. Still

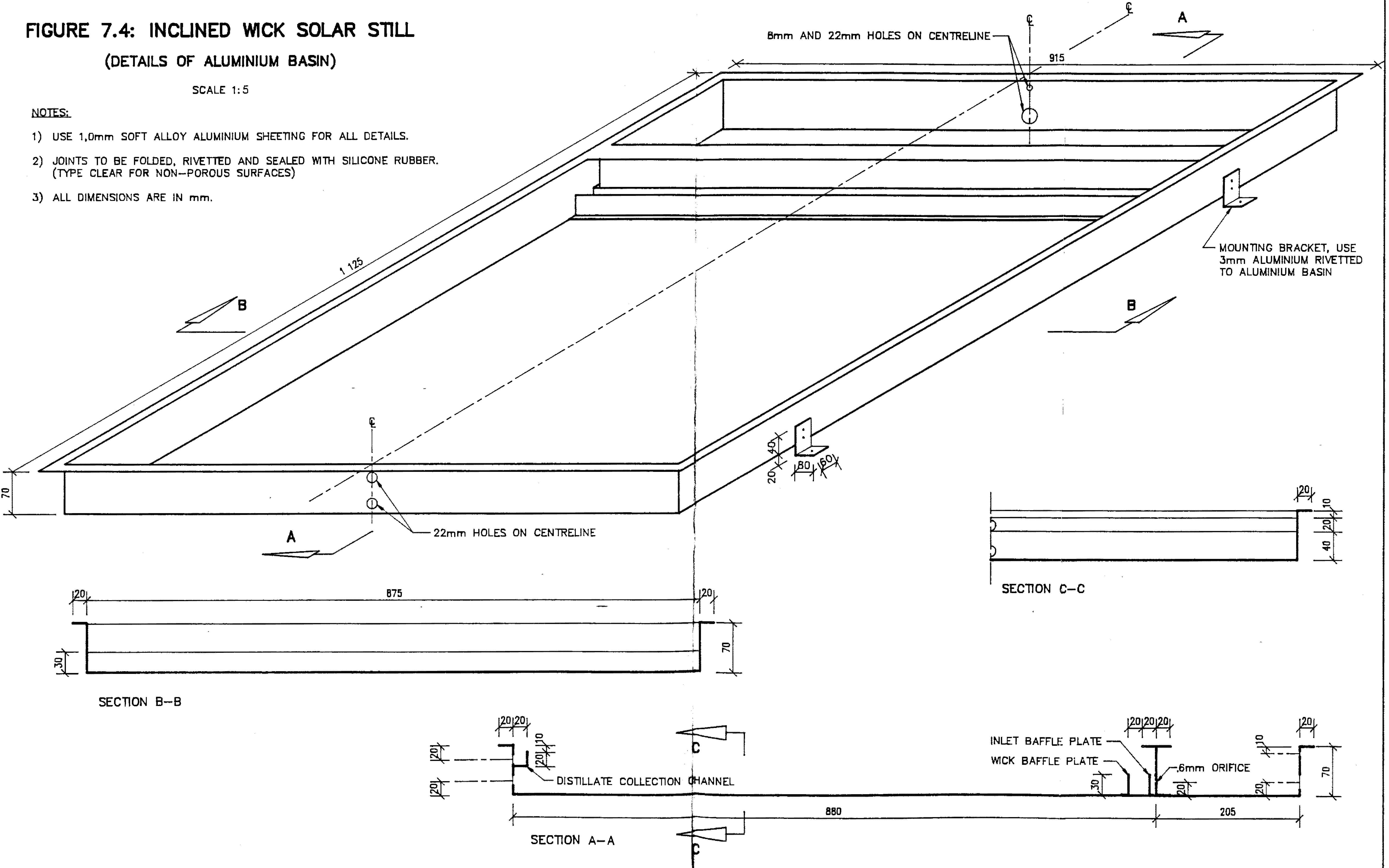
FIGURE 7.4: INCLINED WICK SOLAR STILL

(DETAILS OF ALUMINIUM BASIN)

SCALE 1:5

NOTES:

1) USE 1,0mm SOFT ALLOY ALUMINIUM SHEETING FOR ALL DETAILS.
2) JOINTS TO BE FOLDED, RIVETTED AND SEALED WITH SILICONE RUBBER. (TYPE CLEAR FOR NON-POROUS SURFACES)
3) ALL DIMENSIONS ARE IN mm.



D.A. Still

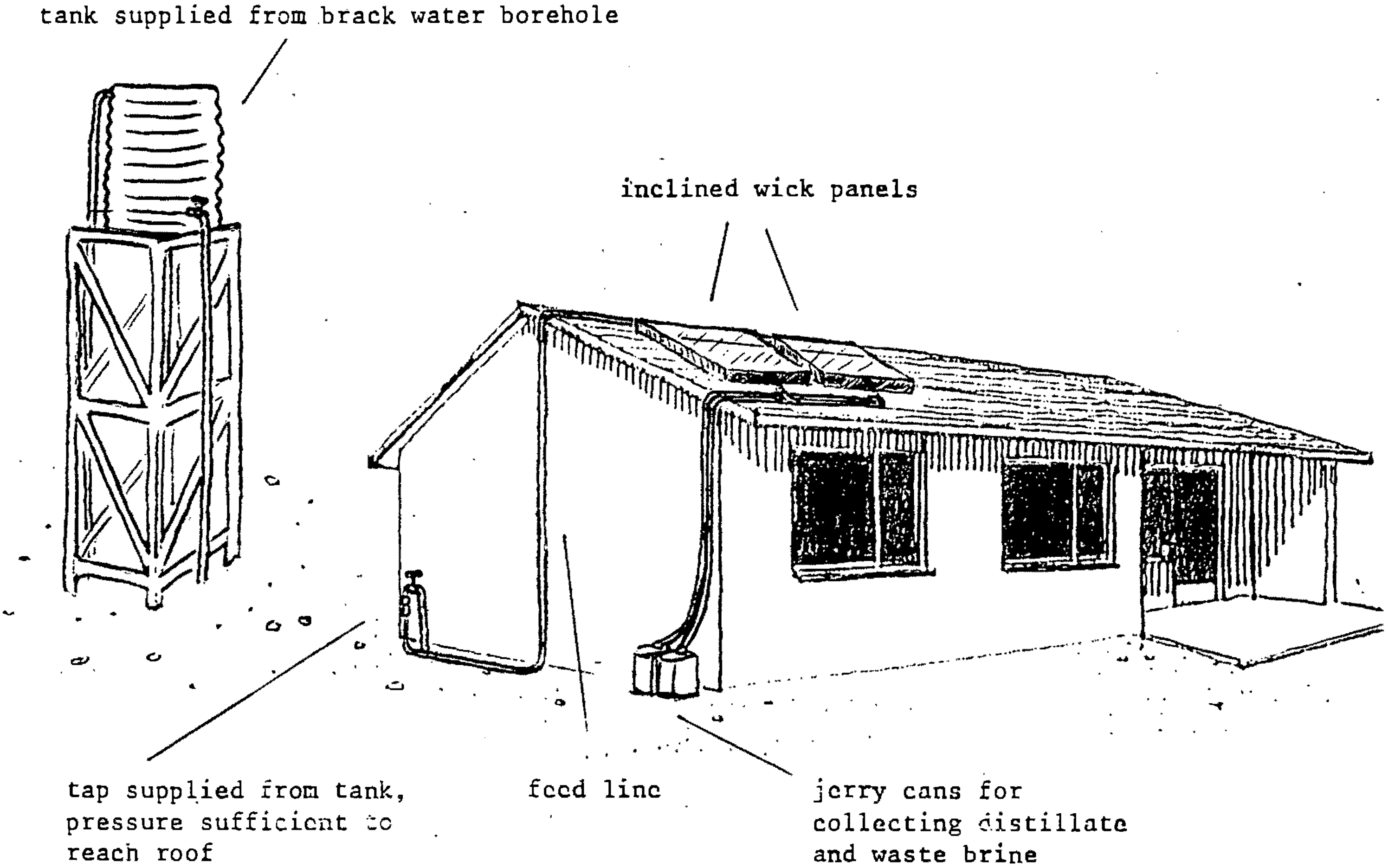


Figure 7.5: Inclined wick still - proposed household installation

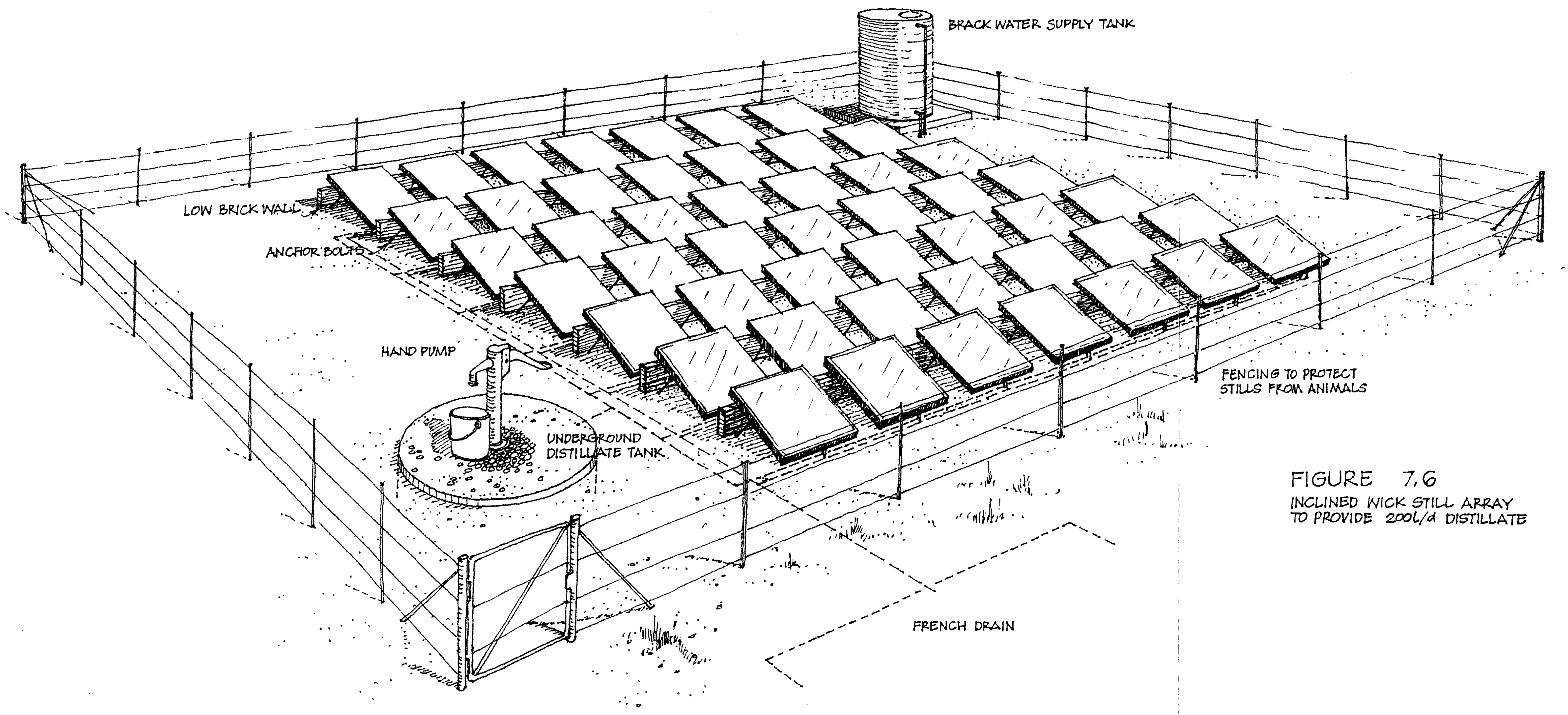


FIGURE 7.6
INCLINED WICK STILL ARRAY
TO PROVIDE 200l/d DISTILLATE

CHAPTER 8

CONCLUSIONS AND RECOMMENDATIONS

The following **conclusions** can be drawn from the study :

- Solar distillation is the only desalination technology that offers the possibility of affordable desalination at a household scale (from 20 ℓ/d for drinking water only to 100 ℓ/d for drinking and washing).
- Both inclined wick stills and basin stills are simple and reliable.
- The multi-effect inclined wick still is not rugged and reliable in operation, and is not more cost-effective than the simpler single effect inclined wick still.
- The inclined wick still is the optimum design because its yield is not so much reduced during the winter months. Its winter yield averages over 3,0 $\ell/m^2/d$, and its summer yield exceeds 5 $\ell/m^2/d$ on clear days.
- The inclined wick still is optimally 50 to 80 mm in depth, 1 m^2 in area, should have a black or nearly black cotton or polyester wick, should be fed at a rate of between 1 and 2 $\ell/m^2/hr$, and is not sensitive to the salinity of the feed water.
- The recommended standard 1 m^2 inclined wick still panel should be able to be retailed for under R300. Two of these would be necessary to provide the average household with its drinking water throughout the year. Amortizing the cost of a household installation over the expected still life of 10 years, and allowing for maintenance costs, the distillate produced would have a cost of R30/m^3; which would give a drinking water cost of R15/m^3 if one to one blending is applied. According to the market survey this should be affordable to a large share of those dependent on brackish groundwater.

The following **recommendation** is made:

- A final prototype inclined wick should be made, taking account of lessons learned from the field tests to date, and this prototype should be tested in the field for at least a year.

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APPENDIX A

Extracts from and Summary of Market Survey for Small Scale Desalination Equipment

APPENDIX A: EXTRACTS FROM AND SUMMARY OF MARKET SURVEY FOR SMALL SCALE DESALINATION EQUIPMENT

A.1 Introduction

Included in this Appendix are the following extracts from the CSIR report *Market survey for small scale desalination equipment* by D.A. Still et al, 1989:

- ☐ short survey of farmers of the Matlabas River Valley, North Western Transvaal;
- ☐ survey of black rural villagers in the Potgietersrus area, May 1989;
- ☐ population figures for small municipalities in high salinity areas;
- ☐ sample questionnaire sent to hospitals around Southern Africa;
- ☐ source water quality analyses of Boesmansriviermond and Port Alfred, both of which rely on brack water sources for some of their needs.

The market survey divided the market into the following logical sectors: farmers, municipalities, hospitals and clinics, technikons, technical colleges and schools, SATS (railway sidings), black rural and peri-urban dwellers, and the military. The only sectors that promised a market for small desalination units were farmers and black rural communities. Hospitals do use small amounts of distilled water every day but this is a very small part of their running costs and does not concern them. Schools generally use electric distillation apparatus supplied by the Education Departments. Again, the high cost of this equipment is not a problem to the schools. The SATS could definitely use small scale desalination at a few of their more remote sidings, but the number is negligible. The military would go for higher capacity processes such as Reverse Osmosis for established bases.

The only market segments that promised significant demand were farmers and black rural communities. These demands are, however, projected to be significant enough to make the local development of this technology worthwhile (combined total 3000 to 22500 units).

A.2 Survey of farmers in the Kiesel District, Matlabas Valley

A.2.1 Introduction

Farmers in Namaqualand, the Eastern Cape, Northern Cape and Northern Transvaal, as well as northern Namibia, experience problems with saline water sources in general. Farmers use many different methods to address the problem of producing drinking water for their own use, including de-ionizers, electrical water distillers, chemicals etc. However, most of these soon break down under the conditions on the farms. This has lead to the general opinion among farmers that desalination is too costly and too much trouble, and they therefore are resigned to live with their brackish water. Others pipe or collect water from alternative fresh sources, often at great cost.

A short survey was done on farmers in the area lying between the Matlabas and Limpopo rivers in the Kiesel district. The survey was done to test the farmers' feelings on the need for desalination, the possible application of small solar distillation units (20 l/day) and their reaction to a possible price (R 500 - R 1 000).

Farms in this area generally have an ample supply of water, but in many cases the water is not fit for consumption by humans or animals.

A.2.2 Details of sample of farmers surveyed

No.	RESPONDENT	SITUATION
1	K. Venter Matjiesfontein PK Kiesel (832)	Brackish water in boreholes. Drinking water pumped and transported from river.
2	J.J. Fourie Canterbury PK Kiesel (923)	When river not flowing -> problems. Gets water from river (5 - 6 km). Boreholes high Fl and $NO3^-$.
3	S.W.H. Smit Zanddrift PK Kiesel (663)	Water very hard. Drinking water transported from river (1 - 2 km).
4	Johan Stander Canterbury PK Kiesel (950)	No problems with drinking water.
5	M.J. Roux Worchester PK Kiesel (737)	Strong borehole with good drinking water near house.
6	J. Gouws Ventershoop PK Kiesel (815)	Boreholes turn brackish after rains. Two boreholes in use.
7	A.M. McAlpine Hendriksdal PK Kiesel (815)	No problems with drinking water. Ample water on farm.
8	Willie Pieterse P/S X626 Thabazimbi (015379 739/617)	Borehole water undrinkable. Fetches water from other borehole (10km) in watercart.
9	Piet Lee Wentzel PK Kiesel (818)	Borehole water slightly brackish. Worsens when river not flowing.

A.2.3 Response to small scale desalination

No.	RESPONSES
1	Not necessary at moment because of recent rains. In times of drought will probably be good idea, but cost is worrying. Still feels project to be viable.
2	Will definitely use desalination if available at reasonable price. Willing to help with evaluations.
3	Will respond positively to solar distiller.
4	Desalination not necessary for farm. Knows of a lot of people he feels will use technology.
5	No problems experienced with drinking water. Will therefore not need solar distiller.
6	No problems with drinking water.
7	No need for desalination.
8	At first very positive about solar desalination. Says that price is out of proportion with effectivity. If more effective (i.e. > >20 l/day) becomes attractive.
9	Feels water is not too bad. On question of whether he feels the need for desalination, the farmer felt it would not pay to employ the technology.

A.2.4 Analysis of farm survey

The general feeling was that this may be a bad time (May 1989 - floods had occurred in March) to conduct the survey, as a lot of rain fell in recent times. In times of drought (of which the last one was not long ago) the water tends to become much more brackish, and this compounds the problems already experienced. The responses must thus be seen in this light. Nevertheless the response is not discouraging. Taking respondents 1, 2 and 3 as positive, the vote in favour from this small sample is 3 out of 9 or 33%.

An assessment of the number of farmers living in the remote arid regions of the country is 13 000 (based on the 1983 Agricultural Census). Assuming that the 33% positive response obtained for Matlabas is above average, one may conservatively estimate that as many as 2000 farmers (15%) nationwide may be interested in a small scale desalination device. If the Matlabas response is more representative, the need in this sector could amount to as many as 5000 units. The most optimistic scenario is that at least 5000 farmers inside South Africa, and more outside, will buy an average of 50 litres of desalination capacity each. Taking the standard unit as having a 20 litre capacity, this would amount to 12 500 units in demand.

A.3 Survey of Black Rural Villagers in the Potgietersrus Area, May 1989

by Miss B. Mogane

A.3.1 Introduction

A pilot study to assess the need for small scale desalination was undertaken in two tribal wards of Shongwane and Vienna, west of Potgietersrus, in May 1989. Fortunately, in Shongwane, the researcher was able to discuss the saline problem with six of the tribal authority council members who expressed concern regarding the extent of the problem. The latter tribal authority emphasized the need for a solution and would support any organization which may offer assistance in this regard.

In addition to this discussion, a total of 31 households were randomly selected for interviews in Shongwane and Vienna villages, which together have approximately 600 households.

A.3.2 Details of the survey

Response to the five questions asked was as follows:

Do you have problems with the salinity of your drinking water?

All but one respondent, including the Shongwane Tribal Authority Council, mentioned that salinity is a problem. Unfortunately, the one respondent who negated the idea was drunk, therefore, could not give an objective view of the situation. Saline water is indeed a problem, especially in Vienna. Samples taken by us had a TDS content of over 3 000 mg salt per litre. Apparently, salty water causes the following problems:

- ☐ severe diarrhoea, especially to visitors and newcomers in the village;
- ☐ changes the taste of food, especially tea, to an extent that no milk can be used in coffee or tea;
- ☐ in order to quench the thirst, especially in summer, people have to drink more water;
- ☐ after bathing, the skin turns grey, moreover no bath soap but powdered soap could be used because with the former, little lather is produced. When washing clothes, more soap is needed;
- ☐ some people experience high blood pressure due to the heavy salt content in water, moreover, more sugar is used in tea.

How much desalted water do you need per day for drinking?

The study established that most households interviewed comprised of 5 to 10 members. Therefore, their need for desalted water for drinking purposes ranged between 10 and 25 litres per day. However, respondents mentioned that they also need desalted water for bathing and washing clothes, seeing that they use a lot of detergents for these activities.

If there were an apparatus for household desalination, would you be interested in buying it?

All respondents answered positively to this question. However, two respondents mentioned that due to poverty and unemployment, they may only afford the unit on an instalment basis. Therefore, arrangements should be made for credit facilities in this regard. Most respondents seem desperate, and have no hope for solutions to the problem. They also mentioned that the stills be made available at local cooperatives and stores. However, respondents emphasized that a demonstration is necessary to witness the effectiveness of stills.

How much will you be prepared to pay for a desalination still?

Example: R300 for 6 litres/day

R500 for 10 litres/day

All but two respondents mentioned that the choice will be based on affordability and benefits to be achieved. Two respondents would opt for the R500 still.

Are there organizations working on improvement of water supply in your area?

Except for the Department of Agriculture, there are no organizations involved in the improvement of water supply in the area.

A.3.3 Conclusion

The need for desalination for small scale water supply cannot be overemphasized. People in rural areas desperately seek solutions to this problem because boreholes are their only sources of water. The Potgietersrus region is but an example of areas with saline problems. In most parts of Bophuthatswana, especially in Moretele, Ganyesa and the Kudumane regions, saline water is severe. A study undertaken by the Division of Water Technology in Heuningsvlei, Bophuthatswana, also revealed an urgent need for desalination. People are prepared to spend money in order to desalinate their water because they have to walk long distances in order to obtain an acceptable quality of water for drinking. In Maubane and Makapanstad salinity is a problem which needs to be addressed at the earliest convenience. On the basis of this pilot study, a conclusion is made that an effective method of removing salt from water will be well received by concerned communities in Southern Africa.

The size of this sector is probably in the order of 50 000 households (or 350 000 people). With the shortage of capital typical of this sector, it is very risky to project how it might *really* respond to a product whose costs are almost all up front. Given some sort of state backing (e.g loan finance) for community installations, there would definitely be a market. A probable range (of 20ℓ standard units) would be 1 000 to 10 000.

A.4 Population figures for small municipalities in high salinity areas

These figures are only really of relevance to the small to intermediate desalination technologies, such as Reverse Osmosis and Electrodialysis. In addition to these more formal small towns, however, there are countless other small settlements in the homelands and reserves which do not have formal recognition. The village of Paulshoek on the Leliefontein Reserve, where one of the field tests for the stills was done, is a typical example. With a population of 500, no electricity, and no town administration to speak of, it is the kind of place where community stills might have application.

Municipality	Population
Aberdeen	4005
Albertinia	1712
Amalia	360
Arlington	181
Bathurst	411
Bedford	2286
Bethulie	941
Bitterfontein	726
Boesmansriviermond	19295
Bonnievale	3649
Brandvlei	751
Britstown	6016
Calitzdorp	3845
Cathcart	359
Cookhouse	891
Darling	3603
De Rust	1145
Eendekuil	616
Excelsior	2633
Fouriesburg	219
Frasersburg	1013
Garies	1160
Groblershoop	430
Hanover	762
Herbertsdale	327
Hoopstad	1021
Hopefield	3163
Hopetown	4338
Jacobsdal	1046
Jagersfontein	3161
Jansenville	1655
Kakamas	1958

Town contd.	**Population contd.**
Karasburg	4038
Kareedouw	1302
Klipplaat	1261
Koffiefontein	1349
Koringsberg	281
Lambert's Bay	1824
Lindley	804
Loxton	4309
Makwassie	561
Marydale	1744
Niekerkshoop	98
Niewoudtville	1044
Onseepkans	790
Ottoshoop	141
Pacaltsdorp	4111
Pearston	1936
Petrusburg	894
Philippolis	923
Piketberg	421
Porterville	3585
Prince Albert	3525
Prince Albert Hamlet	1680
Reivilo	307
Riebeeck Kasteel	1703
Riebeeck-Oos	472
Rieviersonderend	1885
Springfontein	872
Stella	405
Steytlerville	2400
Stilbaai	1958
Strydenburg	1400
Swartruggens	1011
Tarkastad	1015
Tulbach	2912
Vanrhynsdorp	1016
Vanwyksvlei	1065
Vosburg	897
Warrenton	3699
Williston	1632
Willowmore	3855
Total	**138812**

A.5 Sample questionnaire sent to hospitals around South Africa

DIVISION OF WATER TECHNOLOGY, CSIR
APPROPRIATE TECHNOLOGY PROGRAMME

Assessment of the Need for Desalination of Water on a Small Scale

NAME OF HOSPITAL/CLINIC: W.F. KNOBEL HOSPITAL

POSTAL ADDRESS: PRIVATE BAG X65

LONSDALE 0710 Telephone: LONSDALE 2

PART 1

1.1 Do you use distilled water in your hospital/clinic? [✓ Yes] No

If *YES:*

- For what is it used? FOR IN CUBATORS
- At what rate (litres/day) is it used? 5 Litres 1 d
- From where is it obtained? SESHEGO LEBROTARY
- What does it cost in cents/litre? NOTHING

1.2 What do you think would be a reasonable amount to pay to have your own still at the hospital/clinic producing your own distilled water? (tick one)

- 2 to 4 cents/litre ☒
- 4 to 6 cents/litre ☐
- 6 to 8 cents/litre ☐

PART 2

2.1 **Do you have a problem with the salinity of your drinking water?** Yes | No

If *YES:* X

- Where does this saline water come from?

  FROM BORE HOLE

- Have you ever had the water quality tested? Yes X No

  If *YES* , append the results of the quality tests to this sheet, detailing concentration of various minerals.

  If *NO* , what indicates to you that the quality of your drinking water is unacceptable?

  WATER TASTE SALTY

  BOILER WATER SHOWS LIME IN IT

- What volume of drinking water do you estimate is used daily (litres)? 50 000

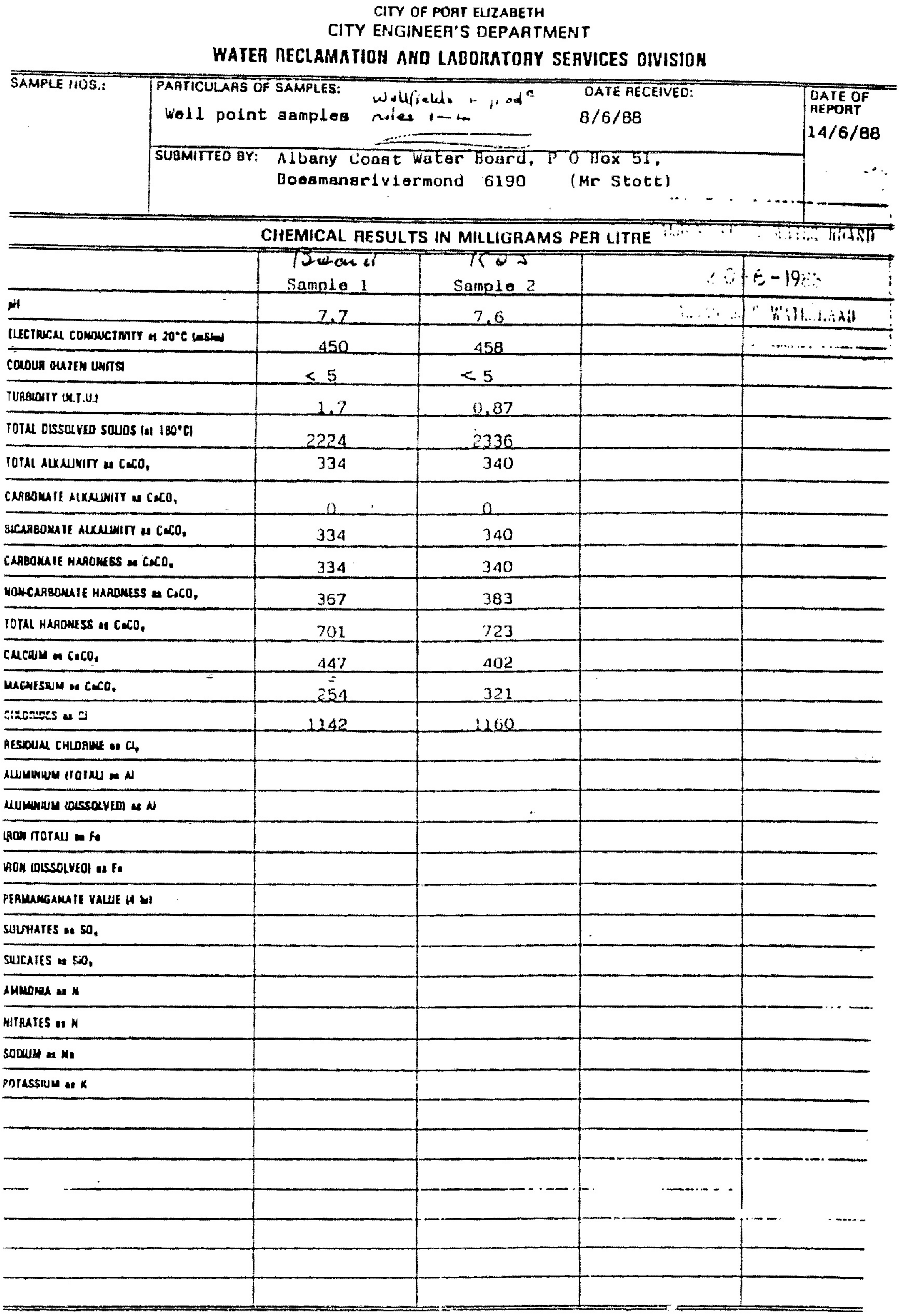
- What do you think would be a reasonable amount to pay to own your own desalination plant at the hospital/clinic for desalinating your drinking water? (tick one)
  - 1 to 2 cents/litre ☐
  - 2 to 3 cents/litre ☐
  - 3 to 4 cents/litre ☒
  - 4 to 5 cents/litre ☐

Use the enclosed reply paid envelope to return your survey to:

Division of Water Technology, CSIR
PO Box 395, Pretoria, 0001

Thank you for your co-operation!

A.6 Typical source water quality analyses of two municipalities reliant on brack water: Boesmansriviermond and Port Alfred



CITY OF PORT ELIZABETH
CITY ENGINEER'S DEPARTMENT
WATER RECLAMATION AND LABORATORY SERVICES DIVISION

SAMPLE NOS.:	PARTICULARS OF SAMPLES: Well point samples wellfields + pond [illegible]	DATE RECEIVED: 8/6/88	DATE OF REPORT 14/6/88
	SUBMITTED BY: Albany Coast Water Board, P O Box 51, Boesmansriviermond 6190 (Mr Stott)		

CHEMICAL RESULTS IN MILLIGRAMS PER LITRE

	Bmond Sample 1	[illegible] Sample 2		
pH	7,7	7,6		
ELECTRICAL CONDUCTIVITY at 20°C (mS/m)	450	458		
COLOUR (HAZEN UNITS)	< 5	< 5		
TURBIDITY (N.T.U.)	1,7	0,87		
TOTAL DISSOLVED SOLIDS (at 180°C)	2224	2336		
TOTAL ALKALINITY as $CaCO_3$	334	340		
CARBONATE ALKALINITY as $CaCO_3$	0	0		
BICARBONATE ALKALINITY as $CaCO_3$	334	340		
CARBONATE HARDNESS as $CaCO_3$	334	340		
NON-CARBONATE HARDNESS as $CaCO_3$	367	383		
TOTAL HARDNESS as $CaCO_3$	701	723		
CALCIUM as $CaCO_3$	447	402		
MAGNESIUM as $CaCO_3$	254	321		
CHLORIDES as Cl	1142	1160		
RESIDUAL CHLORINE as Cl_2				
ALUMINIUM (TOTAL) as Al				
ALUMINIUM (DISSOLVED) as Al				
IRON (TOTAL) as Fe				
IRON (DISSOLVED) as Fe				
PERMANGANATE VALUE (4 hr)				
SULPHATES as SO_4				
SILICATES as SiO_2				
AMMONIA as N				
NITRATES as N				
SODIUM as Na				
POTASSIUM as K				

PEM 328 (7/85)

W/1/5

PORT ALFRED MUNICIPALITY

WATER SALINITY TESTS 1985

SAMPLE NUMBER	LOCATION DESCRIPTION	SALINITY IN MG/LITRE (ppm)											
		JAN	FEB	MARCH	APRIL	MAY	JUNE	JULY	AUG	SEPT	OCT	NOV	DEC
1.	KOWIE RIVER POOL	2875	2789	2961	2875	2990	2961	2995					
2.	BATHURST STREAM-SOURCE BATHURST STREAM-OUTFALL	2443 4456	2501 4450	2616 4600	2588 4600	2675 4600	2585 4600	2702 5031					
3.	MANSFIELD DAM	1782	1783	1984	2300	2358	2214	2128					
4.	TRENT FARM STREAM INTO MANSFIELD	-	-	-	-	-	-	-					
5.	DUNE WATER SUPPLY WELL 1 WELL 2 WELL 3 WELL 4	 2530 2012 1581 1869	 2271 2013 1580 1811	 2530 2013 1610 1754	 1725 1380 1150 1438	 1265 1610 1144 1265	 2530 1150 1035 2415	 4715 1840 977 4830					
6.	MAINS TAP WATER	2070	2070	-	1466	1495	-	1898					
7.	MEDOLINO POND ERF 278	-	-	-	-	-	-	-					
8.	RUFANES RIVER FARM DAM (MIKE LEGG)	2530	1840	-	2645	2013	-	2415					
9.	LUSHINGTON STREAM												
10.	BLOUKRANS RIVER												
11.	RAINWATER												
12.	SEAWATER												
13. 5	DUNES: WELL No. 5	-	-	-	-	2300	1179	4888					
14.													
15.													

APPENDIX B

Primary Data from Monitoring of Basin Still at CSIR, Pretoria
(April 1988 - April 1991)

BASIN STILL RESULTS

Date	Global Radiation (kJ/m2)	Distillate (litres)	(l/m2)	Enthalpy of vapourisation (kJ/kg)	Efficiency (%)
8-Apr-88	11587	3.10	2.07	2442	43.6
12-Apr-88	17941	4.40	2.93	2442	39.9
14-Apr-88	13940	3.20	2.13	2442	37.4
17-May-88	16308	3.10	2.07	2477	31.4
26-May-88	15064	2.87	1.91	2477	31.5
6-Jun-88	15413	2.60	1.73	2477	27.9
7-Jun-88	14257	2.50	1.67	2477	29.0
8-Jun-88	15950	2.36	1.57	2477	24.4
18-Jun-88	14234	2.10	1.40	2477	24.4
19-Jun-88	14007	3.20	2.13	2477	37.7
20-Jun-88	14390	2.85	1.90	2477	32.7
21-Jun-88	13033	2.25	1.50	2477	28.5
22-Jun-88	15692	2.90	1.93	2477	30.5
23-Jun-88	12296	2.30	1.53	2477	30.9
28-Jun-88	4682	0.86	0.57	2477	30.3
30-Jun-88	7876	1.90	1.27	2477	39.8
04-Jul-88	15384	3.20	2.13	2477	34.3
26-Jul-88	15904	3.26	2.17	2477	33.8
27-Jul-88	15619	3.65	2.43	2477	38.6
28-Jul-88	16330	3.42	2.28	2458	34.3
1-Aug-88	17756	3.75	2.50	2458	34.6
2-Aug-88	17988	3.65	2.43	2458	33.3
3-Aug-88	17635	4.10	2.73	2458	38.1
4-Aug-88	16776	3.90	2.60	2458	38.1
8-Aug-88	18223	4.20	2.80	2458	37.8
9-Aug-88	16877	3.50	2.33	2458	34.0
10-Aug-88	16167	3.75	2.50	2458	38.0
15-Aug-88	18797	4.62	3.08	2458	40.3
16-Aug-88	19249	5.10	3.40	2458	43.4
22-Aug-88	19499	4.48	2.99	2458	37.6
23-Aug-88	20006	3.90	2.60	2458	31.9
30-Aug-88	8973	1.60	1.07	2458	29.2
31-Aug-88	17960	4.50	3.00	2458	41.1
6-Sep-88	21660	4.90	3.27	2458	37.1
4-Oct-88	24540	6.50	4.33	2442	43.1
17-Oct-88	15325	2.40	1.60	2442	25.5
21-Dec-88	28090	6.80	4.53	2442	39.4
11-Jan-89	25352	5.70	3.80	2442	36.6
12-Jan-89	26904	6.30	4.20	2442	38.1
16-Jan-89	26826	6.10	4.07	2442	37.0
17-Jan-89	11297	2.80	1.87	2442	40.4
18-Jan-89	31217	8.15	5.43	2442	42.5
19-Jan-89	29635	7.50	5.00	2442	41.2
26-Aug-89	14795	3.42	2.28	2458	37.9
27-Aug-89	18443	3.08	2.05	2458	27.4
28-Aug-89	19570	3.90	2.60	2458	32.7
29-Aug-89	18907	3.70	2.47	2458	32.1
30-Aug-89	22430	4.10	2.73	2458	30.0
31-Aug-89	19789	3.70	2.47	2458	30.6
25-Sep-89	25307	5.00	3.33	2458	32.4
26-Sep-89	24608	5.90	3.93	2458	39.3
27-Sep-89	24485	6.00	4.00	2458	40.2
28-Sep-89	24715	6.16	4.11	2458	40.8
2-Oct-89	22974	5.70	3.80	2442	40.4
3-Oct-89	26990	6.50	4.33	2442	39.2
4-Oct-89	26807	6.75	4.50	2442	41.0
5-Oct-89	25674	6.10	4.07	2442	38.7
9-Oct-89	24424	5.00	3.33	2442	33.3
10-Oct-89	8982	1.40	0.93	2442	25.4

11-Oct-89	16339	3.70	2.47	2442	36.9
12-Oct-89	25246	6.30	4.20	2442	40.6
13-Oct-89	22305	5.20	3.47	2442	38.0
14-Oct-89	26548	6.00	4.00	2442	36.8
15-Oct-89	26379	6.30	4.20	2442	38.9
16-Oct-89	17716	4.55	3.03	2442	41.8
17-Oct-89	26467	6.50	4.33	2442	40.0
18-Oct-89	26064	6.90	4.60	2442	43.1
19-Oct-89	23656	5.50	3.67	2442	37.9
24-Oct-89	15133	4.30	2.87	2442	46.3
26-Oct-89	26457	7.00	4.67	2442	43.1
29-Oct-89	18013	4.40	2.93	2442	39.8
30-Oct-89	24555	5.70	3.80	2442	37.8
31-Oct-89	26500	6.50	4.33	2442	39.9
1-Nov-89	22133	5.60	3.73	2442	41.2
2-Nov-89	6750	1.65	1.10	2442	39.8
7-Nov-89	26414	6.60	4.40	2442	40.7
8-Nov-89	21787	6.25	4.17	2442	46.7
9-Nov-89	22658	5.10	3.40	2442	36.6
13-Nov-89	19415	4.4	2.93	2442	36.9
14-Nov-89	24748	4.92	3.28	2442	32.4
15-Nov-89	11697	1.62	1.08	2442	22.5
16-Nov-89	19189	3.50	2.33	2442	29.7
20-Nov-89	20192	4.80	3.20	2442	38.7
21-Nov-89	30311	7.50	5.00	2442	40.3
22-Nov-89	29723	8.40	5.60	2442	46.0
23-Nov-89	30082	7.90	5.27	2442	42.8
18-Jun-90	13859	2.65	1.77	2478	31.6
19-Jun-90	13686	2.40	1.60	2478	29.0
20-Jun-90	13559	2.50	1.67	2478	30.5
21-Jun-90	9920	1.55	1.03	2478	25.8
21-Aug-90	18683	3.63	2.42	2458	31.8
22-Aug-90	20303	4.17	2.78	2458	33.7
23-Aug-90	19382	4.62	3.08	2458	39.1
28-Aug-90	20018	4.40	2.93	2458	36.0
29-Aug-90	19399	4.27	2.85	2458	36.1
30-Aug-90	15811	2.88	1.92	2458	29.8
11-Dec-90	20024	4.50	3.00	2442	36.6
12-Dec-90	23984	6.36	4.24	2442	43.2
13-Dec-90	25844	6.24	4.16	2442	39.3
19-Dec-90	31394	7.40	4.93	2442	38.4
16-Jan-91	25577	6.15	4.10	2442	39.1
17-Jan-91	12614	3.45	2.30	2442	44.5
21-Jan-91	29840	7.60	5.07	2442	41.5
22-Jan-91	28917	7.60	5.07	2442	42.8
23-Jan-91	8484	1.75	1.17	2442	33.6
24-Jan-91	12980	2.43	1.62	2442	30.5
25-Jan-91	22510	5.54	3.69	2442	40.1
5-Feb-91	25860	6.03	4.02	2442	38.0
6-Feb-91	27280	5.75	3.83	2442	34.3
7-Feb-91	23220	6.50	4.33	2442	45.6
8-Feb-91	7290	1.66	1.11	2442	37.1
13-Feb-91	22220	5.71	3.81	2442	41.8
14-Feb-91	15865	3.60	2.40	2442	36.9
18-Feb-91	21852	4.75	3.17	2442	35.4
19-Feb-91	26814	6.00	4.00	2442	36.4
20-Feb-91	29625	6.80	4.53	2442	37.4
21-Feb-91	28352	7.75	5.17	2442	44.5
25-Feb-91	25908	5.85	3.90	2442	36.8
4-Mar-91	26272	6.60	4.40	2442	40.9
5-Mar-91	21301	5.33	3.55	2442	40.7
6-Mar-91	17432	3.05	2.03	2442	28.5
7-Mar-91	24845	5.85	3.90	2442	38.3
8-Mar-91	20212	3.00	2.00	2442	24.2
14-Mar-91	15241	3.20	2.13	2442	34.2
18-Mar-91	7441	1.70	1.13	2442	37.2

19-Mar-91	17873	4.30	2.87	2442	39.2
20-Mar-91	24522	5.60	3.73	2442	37.2
21-Mar-91	10909	1.80	1.20	2442	26.9
25-Mar-91	12708	2.30	1.53	2442	29.5
26-Mar-91	17576	3.85	2.57	2442	35.7
8-Apr-91	23555	4.85	3.23	2442	33.5
9-Apr-91	23242	4.85	3.23	2442	34.0
10-Apr-91	22262	4.70	3.13	2442	34.4
11-Apr-91	21891	5.00	3.33	2442	37.2
12-Apr-91	20541	4.50	3.00	2442	35.7
13-Apr-91	20334	3.80	2.53	2442	30.4

APPENDIX C

Primary Data from Monitoring of Multi-effect Inclined Wick Still at CSIR, Pretoria (June 1990, August 1990)

SINGLE CELL DIFICAP DISTILLATION TESTING: 18/6/90 to 21/6/90 Feed salinity 300 uS/cm

Note: The name "DIFICAP" used in this appendix is an abbreviation of "capillary film distiller" and derives from the paper by Ouahes and Le Goff (1987). It is in fact no different to multiple effect inclined wick stills described elsewhere in the literature.

DATE: 18/6/90

	Elapsed Time	Distillate (ml/m2)	Conductivity (uS/cm)	Calculated crossflow (ml)	Corrected Distillate	Cumulative Distillate	Brine out (ml/m2)	Coolant (ml/m2)
Start 8:00	0	0				0	0	0
	205	630	80	168	462	462		
	318	0	80	0	0	462	2800	2125
	405	1220	80	325	895	1357	1500	240
	525	370	3	4	366	1723	1200	550
	1440	4900	230	3757	1143	2866	>5000	2800

Global Radiation (kJ/m2): 13859 Efficiency (%): 51 31

DATE: 19/6/90

	Elapsed Time	Distillate (ml/m2)	Conductivity (uS/cm)	Calculated crossflow (ml)	Corrected Distillate	Cumulative Distillate	Brine out (ml/m2)	Coolant (ml/m2)
Start 8:15	0	0				0	0	0
	130	530	150	265	265	265	>5000	90
	445	1500	8	40	1460	1725	2400	0
	1440	1000	260	867	133	1858	4600	0

Global Radiation (kJ/m2): 13686 Efficiency (%): 34

DATE: 20/6/90

	Elapsed Time	Distillate (ml/m2)	Conductivity (uS/cm)	Calculated crossflow (ml)	Corrected Distillate	Cumulative Distillate	Brine out (ml/m2)	Coolant (ml/m2)
Start 8:15	0	0				0	0	0
	110	30	1	0	30	30	6750	0
	227	580	0	0	580	610	4500	0
	465	860	3	9	851	1461	4100	0
	1440	130	5	2	128	1589	>5000	0

Global Radiation (kJ/m2): 13559 Efficiency (%): 29

DATE: 21/6/90

	Elapsed Time	Distillate (ml/m2)	Conductivity (uS/cm)	Calculated crossflow (ml)	Corrected Distillate	Cumulative Distillate	Brine out (ml/m2)	Coolant (ml/m2)
Start 8:05	0	0				0	0	0
	150	54	5	1	53	53	3500	0
	265	370	5	6	364	417	1820	0
	385	610	4	8	602	1019	1800	0
	489	320	4	4	316	1335	1810	0
	1440	50	3	1	50	1384	>5000	0

Global Radiation (kJ/m2): 9920 Efficiency (%): 35

SINGLE CELL DIFICAP DISTILLATION TESTING: 21/8/90 to 24/8/90

Feed salinity 300 uS/cm

DATE: 21/8/90

	Elapsed Time	Distillate (ml/m2)	Conductivity (uS/cm)	Calculated crossflow (ml)	Corrected Distillate	Cumulative Distillate	Brine out (ml/m2)	Coolant (ml/m2)
Start 8:30	0	0				0	0	0
	120	425	47	66	359	359	700	650
	240	890	52	153	737	1096	1100	290
	330	500	50	83	417	1513	760	120
	450	460	88	135	325	1838	1100	315
	1440	800	240	640	160	1998	overflow	overflow

Global Radiation (kJ/m2): 18683 Efficiency (%): 26

DATE: 22/8/90

	Elapsed Time	Distillate (ml/m2)	Conductivity (uS/cm)	Calculated crossflow (ml)	Corrected Distillate	Cumulative Distillate	Brine out (ml/m2)	Coolant (ml/m2)
Start 8:30	0	0				0	0	0
	120	630	72	151	479	479	3300	900
	240	690	64	146	544	1023	750	400
	330	1000	100	333	667	1689	500	180
	450	180	210	126	54	1743	115	610
	1440	1400	250	1167	233	1977	4000	5000

Global Radiation (kJ/m2): 20303 Efficiency (%): 24

DATE: 23/8/90

	Elapsed Time	Distillate (ml/m2)	Conductivity (uS/cm)	Calculated crossflow (ml)	Corrected Distillate	Cumulative Distillate	Brine out (ml/m2)	Coolant (ml/m2)
Start 8:30	0	0				0	0	0
	130	750	72	180	570	570	1250	550
	240	835	64	177	658	1228	100	75
	330	490	100	163	327	1555	130	110
	450	580	210	406	174	1729	210	650
	1440	1000	250	833	167	1896	7500	5000

Global Radiation (kJ/m2): 19382 Efficiency (%): 24

DATE: 24/8/90

	Elapsed Time	Distillate (ml/m2)	Conductivity (uS/cm)	Calculated crossflow (ml)	Corrected Distillate	Cumulative Distillate	Brine out (ml/m2)	Coolant (ml/m2)
Start 8:30	0	0				0	0	0
	0	0		0	0	0	0	0
	240	1400	63	294	1106	1106	3250	1300
	330	410	120	164	246	1352	100	40
	450	20	60	4	16	1368	0	0
						1368		

Global Radiation (kJ/m2): 18342 Efficiency (%): 18

DOUBLE CELL DIFICAP DISTILLATION TESTING: 28/8/90 to 31/8/90

Feed salinity 300 uS/cm

DATE: 28/8/90

Cell 1	Elapsed Time	Distillate (ml/m2)	Conductivity (uS/cm)	Calculated crossflow (ml)	Corrected Distillate	Cumulative Distillate	Brine out (ml/m2)
Start 11:0	0	0				0	0
	115	860	45	129	731	731	3200
	210	520	47	81	439	1170	1800
	300	380	114	144	236	1405	5500
	1275	340	240	272	68	1473	>5000

Global Radiation (kJ/m2): 13000 Efficiency (%): 28

Cell 2	Elapsed Time	Distillate (ml/m2)	Conductivity (uS/cm)	Calculated crossflow (ml)	Corrected Distillate	Cumulative Distillate	Brine out (ml/m2)	Coolant (ml/m2)
	0	0				0	0	0
	115	650	183	397	254	254	10000	6000
	210	450	116	174	276	530	700	2500
	300	2750	300	2750	0	530	2500	3700
	1275	3200	300	3200	0	530	>5000	3500

Global Radiation (kJ/m2): 13000 Efficiency (%): 10

DATE: 29/8/90

Cell 1	Elapsed Time	Distillate (ml/m2)	Conductivity (uS/cm)	Calculated crossflow (ml)	Corrected Distillate	Cumulative Distillate	Brine out (ml/m2)
Start 8:15	0	0				0	0
	130	510	75	128	383	383	7500
	266	860	20	57	803	1185	2510
	354	560	31	58	502	1687	3600
	465	470	64	100	370	2057	7550
	1455	250	131	109	141	2198	>5000

Global Radiation (kJ/m2): 19399 Efficiency (%): 28

Cell 2	Elapsed Time	Distillate (ml/m2)	Conductivity (uS/cm)	Calculated crossflow (ml)	Corrected Distillate	Cumulative Distillate	Brine out (ml/m2)	Coolant (ml/m2)
	0	0				0	0	0
	130	420	222	311	109	109	1200	2600
	266	510	49	83	427	536	100	1250
	354	410	34	46	364	899	1300	390
	465	190	164	104	86	986	650	4600
	1455	1600	235	1253	347	1332	3500	>5000

Global Radiation (kJ/m2): 19399 Efficiency (%): 13

DATE: 30/8/90

Cell 1	Elapsed Time	Distillate (ml/m2)	Conductivity (uS/cm)	Calculated crossflow (ml)	Corrected Distillate	Cumulative Distillate	Brine out (ml/m2)
Start 8:30	0	0				0	0
	159	190	105	67	124	124	600
	250	215	37	27	188	312	100
	281	430	35	50	380	692	150
	459	300	64	64	236	928	400
	1440	370	169	208	162	1089	>5000

Global Radiation (kJ/m2): 15811 Efficiency (%): 17

Cell 2	Elapsed Time	Distillate (ml/m2)	Conductivity (uS/cm)	Calculated crossflow (ml)	Corrected Distillate	Cumulative Distillate	Brine out (ml/m2)	Coolant (ml/m2)
	0	0				0	0	0
	159	1050	300	1050	0	0	3000	2600
	250	650	300	650	0	0	700	1250
	281	800	240	640	160	160	800	390
	459	750	250	625	125	285	1250	4600
	1440	2400	243	1944	456	741	>5000	>5000

Global Radiation (kJ/m2): 15811 Efficiency (%): 12

DATE: 31/8/90

Cell 1	Elapsed Time	Distillate (ml/m2)	Conductivity (uS/cm)	Calculated crossflow (ml)	Corrected Distillate	Cumulative Distillate	Brine out (ml/m2)
Start 8:30	0	0				0	0
	144	780	27	60	720	720	50
	240	335	24	23	312	1032	4400
	330	510	32	47	463	1495	2100
	465	650	31	58	592	2088	2400

Global Radiation (kJ/m2): 21318 Efficiency (%): 24

Cell 2	Elapsed Time	Distillate (ml/m2)	Conductivity (uS/cm)	Calculated crossflow (ml)	Corrected Distillate	Cumulative Distillate	Brine out (ml/m2)	Coolant (ml/m2)
	0	0				0	0	0
	144	780	221	493	287	287	80	40
	240	340	70	68	272	559	350	600
	330	1200	232	795	405	964	2400	5000
	465	4200	300	3600	600	1564	650	800

Global Radiation (kJ/m2): 21318 Efficiency (%): 18

APPENDIX D

Primary Data from Monitoring of Inclined Wick Stills at CSIR, Pretoria
(June 1990 - July 1991)

INCLINED WICK STILL DATA: JUNE 1990 to JULY 1991

Date			Radiation	Still Number	Brine Salinity	Brine Flux	Glass Thickness	Still Angle	Still Depth	Cloth Type	Ambient Temp	Still Output	Efficiency (%)	Comment
DD	MM	YY	(kJ/m2)		(uS/cm)	(ml/m2/h)	(mm)	(degrees)	(mm)		(min-max)	(ml/m2)		
18	6	90	13859	F	300	1500	5	20	70	new cottn, dble	6-24	2754	49	
18	6	90	13859	H	300	2100	5	20	150	new cottn, dble	6-24	2243	40	
19	6	90	13686	F	300	1500	5	20	70	new cottn, dble	7-18	2443	44	
19	6	90	13686	H	300	2150	5	20	150	new cottn, dble	7-18	2117	38	
20	6	90	13559	F	300	1400	5	20	70	new cottn, dble	6-20	2551	47	
20	6	90	13559	H	300	1900	5	20	150	new cottn, dble	6-20	2100	38	
21	6	90	9920	F	300	1200	5	20	70	new cottn, dble	8-19	1511	38	
21	6	90	9920	H	300	900	5	20	150	new cottn, dble	8-19	1300	32	
21	8	90	18683	E	300	2400	3	20	40	old cottn, dble	9-19	2900	38	
21	8	90	18683	F	300	3300	3	20	70	old cottn, dble	9-19	2900	38	
21	8	90	18683	G	300	3300	3	20	100	old cottn, dble	9-19	2514	33	
21	8	90	18683	H	300	3250	3	20	150	old cottn, dble	9-19	2543	34	
23	8	90	19382	E	300	3120	3	20	40	old cottn, dble	11-26	3371	43	
23	8	90	19382	F	300	3500	3	20	70	old cottn, dble	11-26	3257	42	
23	8	90	19382	G	300	2800	3	20	100	old cottn, dble	11-26	3257	42	
23	8	90	19382	H	300	2950	3	20	150	old cottn, dble	11-26	2971	38	
24	8	90	18342	E	300	3100	3	20	40	old cottn, dble	12-28	3029	41	
24	8	90	18342	F	300	4000	3	20	70	old cottn, dble	12-28	3057	41	
24	8	90	18342	G	300	2500	3	20	100	old cottn, dble	12-28	3114	42	
24	8	90	18342	H	300	3200	3	20	150	old cottn, dble	12-28	2771	37	
29	8	90	19399	E	300	4000	3	20	40	old cottn, dble	14-30	3314	42	
29	8	90	19399	F	300	3250	3	20	70	old cottn, dble	14-30	3371	43	
29	8	90	19399	G	300	3230	3	20	100	old cottn, dble	14-30	2529	32	
29	8	90	19399	H	300	3760	3	20	150	old cottn, dble	14-30	3057	39	
30	8	90	15811	E	300	3400	3	20	40	old cottn, dble	10-23	2200	34	
30	8	90	15811	F	300	2500	3	20	70	old cottn, dble	10-23	2271	36	
30	8	90	15811	G	300	2700	3	20	100	old cottn, dble	10-23	2214	35	
30	8	90	15811	H	300	3000	3	20	150	old cottn, dble	10-23	2043	32	
31	8	90	21318	E	300	4100	3	20	40	old cottn, dble	10-24	3300	38	
31	8	90	21318	F	300	3250	3	20	70	old cottn, dble	10-24	3357	39	
31	8	90	21318	G	300	3150	3	20	100	old cottn, dble	10-24	3300	38	
31	8	90	21318	H	300	3900	3	20	150	old cottn, dble	10-24	3057	36	
11	12	90	20024	A	300	2816	3	16	70	old cottn, dble	17-31	2457	30	
11	12	90	20024	B	300	3872	3	16	70	old cottn, dble	17-31	2100	26	
11	12	90	20024	C	300	3294	3	16	70	old cottn, dble	17-31	2486	31	
11	12	90	20024	D	300	2968	3	16	70	old cottn, dble	17-31	2657	33	
12	12	90	23984	A	300	1919	3	16	70	old cottn, dble	17-32	3986	41	
12	12	90	23984	B	300	3632	3	16	70	old cottn, dble	17-32	3257	34	

12	12	90	23984	C	300	2789	3	16	70	old cottn, dble	17-32	3657	38	
12	12	90	23984	D	300	2635	3	16	70	old cottn, dble	17-32	3860	40	
13	12	90	25844	A	300	1365	3	16	70	old cottn, dble	18-32	4371	42	
13	12	90	25844	B	300	2000	3	16	70	old cottn, dble	18-32	300	3	C'Thru experiment
13	12	90	25844	C	300	2131	3	16	70	old cottn, dble	18-32	4300	41	
13	12	90	25844	D	300	1687	3	16	70	old cottn, dble	18-32	4571	44	
19	12	90	31280	A	300	1304	3	16	70	old cottn, dble	17-35	4800	38	
19	12	90	31280	B	300	1724	3	16	70	old cottn, dble	17-35	2943	23	C'Thru experiment
19	12	90	31280	C	300	4524	3	16	70	old cottn, dble	17-35	4171	33	
19	12	90	31280	D	300	2582	3	16	70	old cottn, dble	17-35	4800	38	
16	1	91	25577	A	300	746	3	16	70	old cottn, dble	21-35	3971	38	
16	1	91	25577	B	300	484	3	16	70	old cottn, dble	21-35	4000	39	
16	1	91	25577	C	300	1019	3	16	70	old cottn, dble	21-35	4000	39	
16	1	91	25577	D	300	740	3	16	70	old cottn, dble	21-35	4329	42	
17	1	91	12614	A	300	880	3	16	70	old cottn, dble		1571	31	
17	1	91	12614	B	300	1185	3	16	70	old cottn, dble		1600	31	
17	1	91	12614	C	300	1061	3	16	70	old cottn, dble		1714	34	
17	1	91	12614	D	300	555	3	16	70	old cottn, dble		1886	37	
21	1	91	29840	A	300	1370	3	16	70	old cottn, dble	21-35	4843	40	
21	1	91	29840	B	300	3340	3	16	70	old cottn, dble	21-35	4286	36	
21	1	91	29840	C	300	3760	3	16	70	old cottn, dble	21-35	4086	34	
21	1	91	29840	D	300	3594	3	16	70	old cottn, dble	21-35	4429	37	
22	1	91	28917	A	300	1325	3	16	70	old cottn, dble	22-37	4871	42	
22	1	91	28917	B	300	771	3	16	70	old cottn, dble	22-37	4943	42	
22	1	91	28917	C	300	1167	3	16	70	old cottn, dble	22-37	4871	42	
22	1	91	28917	D	300	6541	3	16	70	old cottn, dble	22-37	3857	33	
23	1	91	8484	A	300	11124	3	16	70	old cottn, dble	20-28	729	21	
23	1	91	8484	B	300	11145	3	16	70	old cottn, dble	20-28	586	17	
23	1	91	8484	C	300	10100	3	16	70	old cottn, dble	20-28	700	20	
23	1	91	8484	D	300		3	16	70	old cottn, dble	20-28		0	feed pipe broke
24	1	91	12980	A	300	5252	3	16	70	old cottn, dble	18-26	1329	25	
24	1	91	12980	B	300	4081	3	16	70	old cottn, dble	18-26	1671	32	
24	1	91	12980	C	300	5597	3	16	70	old cottn, dble	18-26	1314	25	
24	1	91	12980	D	300	918	3	16	70	old cottn, dble	18-26	1857	35	
25	1	91	22510	A	300	4159	3	16	70	old cottn, dble	18-29	2671	29	
25	1	91	22510	B	300	1049	3	16	70	old cottn, dble	18-29	3186	35	
25	1	91	22510	C	300	4694	3	16	70	old cottn, dble	18-29	2657	29	
25	1	91	22510	D	300	486	3	16	70	old cottn, dble	18-29	3457	38	
5	2	91	25860	A	300	2408	3	16	70	old crimp	20-32	3943	38	
5	2	91	25860	B	300	2203	3	16	70	new crimp	20-32	3943	38	
5	2	91	25860	C	300	2956	3	16	70	old cottn, dble	20-32	4014	38	
5	2	91	25860	D	300	2943	3	16	70	new cottn, sngle	20-32	4343	42	
6	2	91	24208	A	300	1607	3	16	70	old crimp	21-33	3971	41	
6	2	91	24208	B	300	1571	3	16	70	new crimp	21-33	3986	41	
6	2	91	24208	C	300	1696	3	16	70	old cottn, dble	21-33	4086	42	

6	2	91	24208	D	300	1777	3	16	70	new cottn, sngle	21-33	4529	46
7	2	91	23680	A	300	2300	3	16	70	old crimp	20-35	3643	38
7	2	91	23680	B	300	2063	3	16	70	new crimp	20-35	3714	39
7	2	91	23680	C	300	2341	3	16	70	old cottn, dble	20-35	3929	41
7	2	91	23680	D	300	2705	3	16	70	new cottn, sngle	20-35	4057	42
8	2	91	8528	A	300	1194	3	16	70	old crimp	17-23	1029	30
8	2	91	8528	B	300	1306	3	16	70	new crimp	17-23	1043	30
8	2	91	8528	C	300	1229	3	16	70	old cottn, dble	17-23	1057	31
8	2	91	8528	D	300	1198	3	16	70	new cottn, sngle	17-23	1214	35
13	2	91	22762	A	300	2500	3	16	70	new cottn, sngle		3914	43
13	2	91	22762	B	300	1700	3	16	70	old cottn, dble		4094	45
13	2	91	22762	C	300	2100	3	16	70	new crimp		3857	42
13	2	91	22762	D	300	2500	3	16	70	old crimp		3743	41
14	2	91	15865	A	300	2188	3	16	70	new cottn, sngle		2314	36
14	2	91	15865	B	300	1348	3	16	70	old cottn, dble		2357	37
14	2	91	15865	C	300	1770	3	16	70	new crimp		2143	33
14	2	91	15865	D	300	2212	3	16	70	old crimp		2323	36
18	2	91	21852	A	300	1568	3	16	70	new cottn, sngle	14-22	2829	32
18	2	91	21852	B	300	1940	3	16	70	old cottn, dble	14-22	3600	41
18	2	91	21852	C	300	1571	3	16	70	new crimp	14-22	3571	40
18	2	91	21852	D	300	1487	3	16	70	old crimp	14-22	3671	42
19	2	91	26814	A	300	984	3	16	70	new cottn, sngle	15-29	4743	44
19	2	91	26814	B	300	1300	3	16	70	old cottn, dble	15-29	4571	42
19	2	91	26814	C	300	400	3	16	70	new crimp	15-29	3086	29
19	2	91	26814	D	300	1200	3	16	70	old crimp	15-29	4540	42
20	2	91	29625	A	300	1040	3	16	70	new cottn, sngle		5343	45
20	2	91	29625	B	300	865	3	16	70	old cottn, dble		5386	45
20	2	91	29625	C	300	645	3	16	70	new crimp		5314	44
20	2	91	29625	D	300	1005	3	16	70	old crimp		4914	41
21	2	91	28352	A	300	1964	3	16	70	new cottn, sngle	15-34	4814	42
21	2	91	28352	B	300	1997	3	16	70	old cottn, dble	15-34	5386	47
21	2	91	28352	C	300	1684	3	16	70	new crimp	15-34	5200	45
21	2	91	28352	D	300	1842	3	16	70	old crimp	15-34	5029	44
22	2	91	29105	A	300	1850	3	16	70	new cottn, sngle		5743	49
22	2	91	29105	B	300	1900	3	16	70	old cottn, dble		5586	48
22	2	91	29105	C	300	1700	3	16	70	new crimp		5486	47
22	2	91	29105	D	300	1800	3	16	70	old crimp		5543	47
25	2	91	25908	A	300	997	3	16	70	new cottn, sngle		4886	47
25	2	91	25908	B	300	1028	3	16	70	new cottn, sngle		4666	45
25	2	91	25908	C	300	1015	3	16	70	new cottn, sngle		4920	47
25	2	91	25908	D	300	960	3	16	70	new cottn, sngle		5186	50
4	3	91	26272	A	55000	1509	3	16	70	new cottn, sngle	18-30	5200	49
4	3	91	26272	B	27500	1637	3	16	70	new cottn, sngle	18-30	5029	47
4	3	91	26272	C	13750	1374	3	16	70	new cottn, sngle	18-30	5257	50
4	3	91	26272	D	6875		3	16	70	new cottn, sngle	18-30	4686	44

5	3	91	21301	A	9000	1220	3	16	70	new cottn, sngle	17-32	3714	43	
5	3	91	21301	B	14900	1580	3	16	70	new cottn, sngle	17-32	3571	42	
5	3	91	21301	C	29500	1430	3	16	70	new cottn, sngle	17-32	3651	42	
5	3	91	21301	D	54600	2570	3	16	70	new cottn, sngle	17-32	3557	41	
6	3	91	17432	A	9000	1882	3	16	70	new cottn, sngle	16-27	2429	35	
6	3	91	17432	B	14900	1592	3	16	70	new cottn, sngle	16-27	2486	35	
6	3	91	17432	C	29500	1436	3	16	70	new cottn, sngle	16-27	2469	35	
6	3	91	17432	D	54600	143	3	16	70	new cottn, sngle	16-27	929	13	
7	3	91	24845	A	9000	1650	3	16	70	new cottn, sngle	16-30	4500	45	
7	3	91	24845	B	14900	1850	3	16	70	new cottn, sngle	16-30	4423	44	
7	3	91	24845	C	29500	1850	3	16	70	new cottn, sngle	16-30	4451	44	
7	3	91	24845	D	54600	710	3	16	70	new cottn, sngle	16-30	4520	45	
8	3	91	20212	A	9100	458	3	16	70	new cottn, sngle		3600	44	
8	3	91	20212	B	14700	440	3	16	70	new cottn, sngle		3500	43	
8	3	91	20212	C	27200	527	3	16	70	new cottn, sngle		3600	44	
8	3	91	20212	D	56200	658	3	16	70	new cottn, sngle		3600	44	
14	3	91	15241	A	9100		3	16	70	new cottn, sngle			0	flow problems
14	3	91	15241	B	14700	1626	3	16	70	new cottn, sngle		2543	41	
14	3	91	15241	C	27200	2233	3	16	70	new cottn, sngle		2471	40	
14	3	91	15241	D	56200	2500	3	16	70	new cottn, sngle		2500	41	
18	3	91	7441	A	9000	2037	3	16	70	new cottn, sngle		657	22	
18	3	91	7441	B	14900	696	3	16	70	new cottn, sngle		671	22	
18	3	91	7441	C	29500	1057	3	16	70	new cottn, sngle		571	19	
18	3	91	7441	D	54600	1674	3	16	70	new cottn, sngle		600	20	
19	3	91	17873	A	99900	2403	3	16	70	new cottn, sngle		2820	39	
19	3	91	17873	B	12500	1876	3	16	70	new cottn, sngle		3243	45	
19	3	91	17873	C	11100	1398	3	16	70	new cottn, sngle		3471	48	
19	3	91	17873	D	100400	1397	3	16	70	new cottn, sngle		3457	48	
20	3	91	24522	A	99900	1650	3	22	70	new cottn, sngle	17-30	4471	45	
20	3	91	24522	B	12500	1800	3	22	70	new cottn, sngle	17-30	4463	45	
20	3	91	24522	C	11100	1500	3	22	70	new cottn, sngle	17-30	4657	47	
20	3	91	24522	D	100400	1250	3	22	70	new cottn, sngle	17-30	4686	47	
21	3	91	10909	A	99900	1008	3	22	70	new cottn, sngle	15-25	1086	25	
21	3	91	10909	B	12500	2355	3	22	70	new cottn, sngle	15-25	1043	24	
21	3	91	10909	C	11100	1392	3	22	70	new cottn, sngle	15-25	1171	27	
21	3	91	10909	D	100400	770	3	22	70	new cottn, sngle	15-25	1186	27	
25	3	91	12708	A	99900	625	3	22	70	new cottn, sngle	13-27	1629	32	
25	3	91	12708	B	12500	1851	5	32	70	new cottn, sngle	13-27	943	18	testing fogged glass
25	3	91	12708	C	11100	341	3	32	70	new cottn, sngle	13-27	1643	32	
25	3	91	12708	D	100400	921	3	32	70	new cottn, sngle	13-27	1714	33	
26	3	91	17576	A	99900	900	3	32	70	new cottn, sngle	13-26	2786	39	
26	3	91	17576	B	12500	600	5	32	70	new cottn, sngle	13-26	2606	37	
26	3	91	17576	C	11100	1800	3	32	70	new cottn, sngle	13-26	2886	41	
26	3	91	17576	D	100400	900	3	32	70	new cottn, sngle	13-26	3034	43	
27	3	91	14676	A	99900	3800	3	32	70	new cottn, sngle		1800	30	

27	3	91	14676	B	12500	1600	5	32	70	new cottn, sngle		1943	33	
27	3	91	14676	C	11100	930	3	32	70	new cottn, sngle		2271	38	
27	3	91	14676	D	100400	2000	3	32	70	new cottn, sngle		2180	37	
28	3	91	22076	A	99900	1600	3	32	70	new cottn, sngle		3657	41	
28	3	91	22076	B	12500	1490	5	32	70	new cottn, sngle		2780	31	
28	3	91	22076	C	11100	2920	3	32	70	new cottn, sngle			0	
28	3	91	22076	D	100400	1385	3	32	70	new cottn, sngle		3743	42	
8	4	91	23555	A	300		3	32	70	new cottn, sngle	10-27		0	
8	4	91	23555	B	300		5	32	70	new cottn, sngle	10-27		0	
8	4	91	23555	C	300		4	32	70	new cottn, sngle	10-27		0	
8	4	91	23555	D	300	1400	3	32	70	new cottn, sngle	10-27	4757	50	
9	4	91	23242	A	300	3000	3	32	70	new cottn, sngle	10-27	4063	43	
9	4	91	23242	B	300	1761	5	32	70	new cottn, sngle	10-27	3971	42	
9	4	91	23242	C	300	2413	4	32	70	new cottn, sngle	10-27	4057	43	
9	4	91	23242	D	300	1320	3	32	70	new cottn, sngle	10-27	4914	52	
10	4	91	22262	A	300		3	32	70	new cottn, sngle	12-29		0	
10	4	91	22262	B	300		5	32	70	new cottn, sngle	12-29		0	
10	4	91	22262	C	300		4	32	70	new cottn, sngle	12-29		0	
10	4	91	22262	D	300	1319	3	32	70	new cottn, sngle	12-29	4857	54	
11	4	91	21891	A	300	1071	3	32	70	new cottn, sngle	13-30	4429	50	
11	4	91	21891	B	300	1064	5	32	70	new cottn, sngle	13-30	4071	46	
11	4	91	21891	C	300	1721	4	32	70	new cottn, sngle	13-30	4071	46	
11	4	91	21891	D	300	1134	3	32	70	new cottn, sngle	13-30	4629	52	
12	4	91	20541	A	300	1037	3	32	70	new cottn, sngle	13-29		0	distillate overflow
12	4	91	20541	B	300	1109	5	32	70	new cottn, sngle	13-29	3800	46	
12	4	91	20541	C	300	1920	4	32	70	new cottn, sngle	13-29	3771	45	
12	4	91	20541	D	300	1346	3	32	70	new cottn, sngle	13-29	4457	54	
13	4	91	20334	A	300	929	3	32	70	new cottn, sngle	13-29		0	
13	4	91	20334	B	300	940	5	32	70	new cottn, sngle	13-29	3686	45	
13	4	91	20334	C	300	1683	4	32	70	new cottn, sngle	13-29	3543	43	
13	4	91	20334	D	300	1249	3	32	70	new cottn, sngle	13-29	4200	51	
3	7	91	14497	A	300	3117	3	50	70	new cottn, sngle	7-19	3557	61	
3	7	91	14497	B	300	2078	3	50	70	new cottn, sngle	7-19	3443	59	
3	7	91	14497	C	300	2857	3	50	70	new cottn, sngle	7-19	3371	58	
4	7	91	15113	A	300	1429	3	50	70	new cottn, sngle	7-19	3421	56	
4	7	91	15113	B	300	457	3	50	70	new cottn, sngle	7-19	3564	58	
4	7	91	15113	C	300	1429	3	50	70	new cottn, sngle	7-19	3479	57	
5	7	91	14062	A	300	1071	3	50	70	new cottn, sngle	7-19	3236	57	
5	7	91	14062	B	300	643	3	50	70	new cottn, sngle	7-19	3107	55	
5	7	91	14062	C	300	1214	3	50	70	new cottn, sngle	7-19	3093	54	

MONITORING OF SINGLE EFFECT INCLINED WICK STILLS OF DIFFERENT DEPTHS

DATE: 18/6/90

Note: The still angles for these midwinter tests were about 30 degrees
(For optimum production in winter, 50 degrees would be preferable)

Still Type: Wick 70

Hour	Min	Time Number	Elapsed Time	Output (ml)	Output (ml/m2)	Cmltv. output	Brine (ml)	Cmltv. Brine /m2	Flux (ml/m2/h)
8	0	0.3542	0	0	0	0	0	0	0
11	17	0.4701	167	300	857	857	1200	3429	1540
13	55	0.5799	325	430	1229	2086	1100	6571	1660
15	54	0.6625	444	150	429	2514	620	8343	1109
			1440	84	240	2754	5000	22629	875

Still Type: Wick 150

Hour	Min	Time Number	Elapsed Time	Output (ml)	Output (ml/m2)	Cmltv. output	Brine (ml)	Cmltv. Brine /m2	Flux (ml/m2/h)
8	30	0.3542	0	0	0	0	0	0	0
11	18	0.4708	168	230	657	657	1750	5000	2020
13	50	0.5764	320	360	1029	1686	1780	10086	2414
15	51	0.6604	441	135	386	2071	1150	13371	1821
			1440	60	171	2243	>6000		

Still Type: Basin (for comparison)

Hour	Min	Time Number	Elapsed Time	Output (ml)	Output /m2	Cmltv. output	Temp deg. C
8	30	0.3542	0	0	0	0	
11	18	0.4708	168	220	147	147	21
14	0	0.5833	330	1180	787	933	23
15	59	0.6660	449	600	400	1333	22
			1440	650	433	1767	11

Global Radiation:

Time	(kJ/m2)	Diff.
0.0	0	0
0.5	0	0
1.0	0	0
1.5	0	0
2.0	0	0
2.5	0	0
3.0	0	0
3.5	0	0
4.0	0	0
4.5	0	0
5.0	0	0
5.5	0	0
6.0	2	2
6.5	32	30
7.0	194	162
7.5	611	417
8.0	1046	435
8.5	1145	99
9.0	1831	686
9.5	2867	1036
10.0	3968	1101
10.5	5089	1121
11.0	6246	1157
11.5	7419	1173
12.0	8522	1103
12.5	9559	1037
13.0	10490	931
13.5	11364	874
14.0	12176	812
14.5	12864	688
15.0	13381	517
15.5	13707	326
16.0	13846	139
16.5	13859	13
17.0	13859	0
17.5	13859	0
18.0	13859	0
18.5	13859	0
19.0	13859	0
19.5	13859	0
20.0	13859	0
20.5	13859	0
21.0	13859	0
21.5	13859	0
22.0	13859	0
22.5	13859	0
23.0	13859	0
23.5	13859	0
24.0	13859	0

DATE: 19/6/90

Still Type: Wick 70

Hour	Min	Time Number	Elapsed Time	Output (ml)	Output (ml/m2)	Cmltv. output	Brine (ml)	Cmltv. Brine /m2	Flux (ml/m2/h)
8	30	0.3542	0	0	0	0	0	0	0
10	32	0.4389	122	145	414	414	1220	3486	1918
15	48	0.6583	438	640	1829	2243	1950	9057	1405
			1440	70	200	2443	7600	30771	1312

Still Type: Wick 150

Hour	Min	Time Number	Elapsed Time	Output (ml)	Output (ml/m2)	Cmltv. output	Brine (ml)	Cmltv. Brine /m2	Flux (ml/m2/h)
8	30	0.3542	0	0	0	0	0	0	0
10	30	0.4375	120	136	389	389	1900	5429	2909
15	45	0.6563	435	535	1529	1917	3200	14571	2033
			1440	70	200	2117	10720	45200	1841

Still Type: Basin (for comparison)

Hour	Min	Time Number	Elapsed Time	Output (ml)	Output /m2	Cmltv. output	Temp deg. C
8	30	0.3542	0	0	0	0	11
10	35	0.4410	125	50	33	33	12
15	50	0.6597	440	1750	1167	1200	19
			1440	600	400	1600	8

Global Radiation:

Time	(kJ/m2)	Diff.
0.0	0	0
0.5	0	0
1.0	0	0
1.5	0	0
2.0	0	0
2.5	0	0
3.0	0	0
3.5	0	0
4.0	0	0
4.5	0	0
5.0	0	0
5.5	0	0
6.0	2	2
6.5	39	37
7.0	195	156
7.5	574	379
8.0	992	418
8.5	1145	153
9.0	1797	652
9.5	2772	975
10.0	3830	1058
10.5	4973	1143
11.0	6098	1125
11.5	7226	1128
12.0	8322	1096
12.5	9372	1050
13.0	10340	968
13.5	11248	908
14.0	12048	800
14.5	12712	664
15.0	13205	493
15.5	13530	325
16.0	13670	140
16.5	13686	16
17.0	13686	0
17.5	13686	0
18.0	13686	0
18.5	13686	0
19.0	13686	0
19.5	13686	0
20.0	13686	0
20.5	13686	0
21.0	13686	0
21.5	13686	0
22.0	13686	0
22.5	13686	0
23.0	13686	0
23.5	13686	0
24.0	13686	0

DATE: 20/6/90

Still Type: Wick 70

Hour	Min	Time Number	Elapsed Time	Output (ml)	Output (ml/m2)	Cmltv. output	Brine (ml)	Cmltv. Brine /m2	Flux (ml/m2/h)
8	30	0.3542	0	0	0	0	0	0	0
10	12	0.4250	102	98	280	280	750	2143	1425
12	8	0.5056	218	300	857	1137	700	4143	1478
16	8	0.6722	458	460	1314	2451	1400	8143	1329
			1440	35	100	2551	6500	26714	1141

Still Type: Wick 150

Hour	Min	Time Number	Elapsed Time	Output (ml)	Output (ml/m2)	Cmltv. output	Brine (ml)	Cmltv. Brine /m2	Flux (ml/m2/h)
8	30	0.3542	0	0	0	0	0	0	0
10	10	0.4236	100	60	171	171	1200	3429	2160
12	5	0.5035	215	235	671	843	1300	7143	2288
16	5	0.6701	455	400	1143	1986	2100	13143	1786
			1440	40	114	2100	6550	31857	1147

Still Type: Basin (for comparison)

Hour	Min	Time Number	Elapsed Time	Output (ml)	Output /m2	Cmltv. output	Temp deg. C
8	30	0.3542	0	0	0	0	8
10	15	0.4271	105	35	23	23	10
12	12	0.5083	222	330	220	243	16
16	10	0.6736	460	1635	1090	1333	18
			1440	500	333	1667	10

Global Radiation:

Time	(kJ/m2)	Diff.
0.0	0	0
0.5	0	0
1.0	0	0
1.5	0	0
2.0	0	0
2.5	0	0
3.0	0	0
3.5	0	0
4.0	0	0
4.5	0	0
5.0	0	0
5.5	0	0
6.0	2	2
6.5	36	34
7.0	200	164
7.5	595	395
8.0	1025	430
8.5	1150	125
9.0	1801	651
9.5	2778	977
10.0	3848	1070
10.5	4999	1151
11.0	6152	1450
11.5	7299	1460
12.0	8388	1460
12.5	9412	1468
13.0	10341	1482
13.5	11216	1406
14.0	11985	1325
14.5	12630	1174
15.0	13105	1052
15.5	13413	890
16.0	13546	714
16.5	13559	515
17.0	13559	318
17.5	13559	80
18.0	13559	0
18.5	13559	0
19.0	13559	0
19.5	13559	0
20.0	13559	0
20.5	13559	0
21.0	13559	0
21.5	13559	0
22.0	13559	0
22.5	13559	0
23.0	13559	0
23.5	13559	0
24.0	13559	0

DATE: 21/6/90

Still Type: Wick 70

Hour	Min	Time Number	Elapsed Time	Output (ml)	Output (ml/m2)	Cmltv. output	Brine (ml)	Cmltv. Brine /m2	Flux (ml/m2/h)
8	30	0.3542	0	0	0	0	0	0	0
10	43	0.4465	133	84	240	240	1100	3143	1526
12	26	0.5181	236	110	314	554	610	4886	1198
14	25	0.6007	355	150	429	983	650	6743	1152
16	7	0.6715	457	140	400	1383	600	8457	1244
			1440	45	129	1511	5520	22514	970

Still Type: Wick 150

Hour	Min	Time Number	Elapsed Time	Output (ml)	Output (ml/m2)	Cmltv. output	Brine (ml)	Cmltv. Brine /m2	Flux (ml/m2/h)
8	30	0.3542	0	0	0	0	0	0	0
10	40	0.4444	130	70	200	200	800	2286	1147
12	24	0.5167	234	90	257	457	600	4000	1137
14	23	0.5993	353	125	357	814	520	5486	929
16	8	0.6722	458	130	371	1186	300	6343	702
			1440	40	114	1300	1100	8629	199

Still Type: Basin (for comparison)

Hour	Min	Time Number	Elapsed Time	Output (ml)	Output /m2	Cmltv. output	Temp deg. C
8	30	0.3542	0	0	0	0	10
10	45	0.4479	135	30	20	20	13
12	30	0.5208	240	200	133	153	15
14	27	0.6021	357	380	253	407	18
16	0	0.6667	450	540	360	767	19
			1440	400	267	1033	9

Global Radiation:

Time	(kJ/m2)	Diff.
0.0	0	0
0.5	0	0
1.0	0	0
1.5	0	0
2.0	0	0
2.5	0	0
3.0	0	0
3.5	0	0
4.0	0	0
4.5	0	0
5.0	0	0
5.5	0	0
6.0	2	2
6.5	33	31
7.0	158	125
7.5	452	294
8.0	860	408
8.5	1121	261
9.0	1488	367
9.5	2035	547
10.0	2937	902
10.5	3302	365
11.0	4025	723
11.5	4918	893
12.0	5343	425
12.5	5851	508
13.0	6787	936
13.5	7659	872
14.0	8402	743
14.5	9012	610
15.0	9470	458
15.5	9766	296
16.0	9902	136
16.5	9920	18
17.0	9920	0
17.5	9920	0
18.0	9920	0
18.5	9920	0
19.0	9920	0
19.5	9920	0
20.0	9920	0
20.5	9920	0
21.0	9920	0
21.5	9920	0
22.0	9920	0
22.5	9920	0
23.0	9920	0
23.5	9920	0
24.0	9920	0

DATE: 21/8/90

Note: Still angle +/- 30 degrees for these tests.

Still Type: Wick 40

Hour	Min	Time Number	Elapsed Time	Output (ml)	Output (ml/m2)	Cmltv. output	Brine (ml)	Cmltv. Brine /m2	Flux (ml/m2/h)
8	30	0.3542	0	0	0	0	0	0	0
10	37	0.4424	127	280	800	800	1250	3571	2065
12	30	0.5208	240	260	743	1543	1250	7143	2291
14	0	0.5833	330	185	529	2071	1100	10286	2448
16	0	0.6667	450	210	600	2671	1600	14857	2586
			1440	80	229	2900	4750	28429	836

Still Type: Wick 70

Hour	Min	Time Number	Elapsed Time	Output (ml)	Output (ml/m2)	Cmltv. output	Brine (ml)	Cmltv. Brine /m2	Flux (ml/m2/h)
8	30	0.3542	0	0	0	0	0	0	0
10	39	0.4438	129	215	614	614	1900	5429	2811
12	32	0.5222	242	315	900	1514	1900	10857	3360
14	2	0.5847	332	220	629	2143	1500	15143	3276
16	3	0.6688	453	185	529	2671	2200	21429	3379
			1440	80	229	2900	5300	36571	934

Still Type: Wick 100

Hour	Min	Time Number	Elapsed Time	Output (ml)	Output (ml/m2)	Cmltv. output	Brine (ml)	Cmltv. Brine /m2	Flux (ml/m2/h)
8	30	0.3542	0	0	0	0	0	0	0
10	40	0.4444	130	190	543	543	2000	5714	2888
12	34	0.5236	244	290	829	1371	1980	11371	3414
14	4	0.5861	334	190	543	1914	1450	15514	3124
16	4	0.6694	454	140	400	2314	2300	22086	3486
			1440	70	200	2514	5000	36371	881

Still Type: Wick 150

Hour	Min	Time Number	Elapsed Time	Output (ml)	Output (ml/m2)	Cmltv. output	Brine (ml)	Cmltv. Brine /m2	Flux (ml/m2/h)
8	30	0.3542	0	0	0	0	0	0	0
10	42	0.4458	132	175	500	500	2100	6000	2955
12	36	0.5250	246	290	829	1329	1900	11429	3293
14	6	0.5875	336	195	557	1886	1500	15714	3229
16	6	0.6708	456	160	457	2343	2100	21714	3229
			1440	70	200	2543	6750	41000	1188

Still Type: Basin (for comparison)

Hour	Min	Time Number	Elapsed Time	Output (ml)	Output /m2	Cmltv. output	Temp deg. C
8	30	0.3542	0	0	0	0	9
10	34	0.4403	124	150	100	100	14
12	39	0.5271	249	860	573	673	18
14	8	0.5889	338	910	607	1280	19
16	8	0.6722	458	1050	700	1980	19
			1440	660	440	2420	10

Global Radiation:

Time	(kJ/m2)	Diff.
0.0	0	0
0.5	0	0
1.0	0	0
1.5	0	0
2.0	0	0
2.5	0	0
3.0	0	0
3.5	0	0
4.0	0	0
4.5	0	0
5.0	0	0
5.5	0	0
6.0	0	0
6.5	0	0
7.0	19	19
7.5	68	49
8.0	434	366
8.5	1063	629
9.0	1863	800
9.5	2848	985
10.0	3970	1122
10.5	5226	1256
11.0	6571	1345
11.5	8010	1439
12.0	9418	1408
12.5	10830	1412
13.0	12157	1327
13.5	13349	1192
14.0	14544	1195
14.5	15854	1310
15.0	16626	772
15.5	17184	558
16.0	17758	574
16.5	18220	462
17.0	18584	364
17.5	18672	88
18.0	18683	11
18.5	18683	0
19.0	18683	0
19.5	18683	0
20.0	18683	0
20.5	18683	0
21.0	18683	0
21.5	18683	0
22.0	18683	0
22.5	18683	0
23.0	18683	0
23.5	18683	0
24.0	18683	0

DATE: 22/8/90

COMMENT: Power failure and problems with pump affect flow rates and consistency.

Still Type: Wick 40

Hour	Min	Time Number	Elapsed Time	Output (ml)	Output (ml/m2)	Cmltv. output	Brine (ml)	Cmltv. Brine /m2	Flux (ml/m2/h)
8	30	0.3542	0	0	0	0	0	0	0
10	36	0.4417	126	225	643	643	300	857	714
12	33	0.5229	243	240	686	1329	1250	4429	2183
16	0	0.6667	450	170	486	1814	1200	7857	1135
			1440	0	0	1814	900	10429	156

Still Type: Wick 70

Hour	Min	Time Number	Elapsed Time	Output (ml)	Output (ml/m2)	Cmltv. output	Brine (ml)	Cmltv. Brine /m2	Flux (ml/m2/h)
8	30	0.3542	0	0	0	0	0	0	0
10	37	0.4424	127	225	643	643	1600	4571	2463
12	35	0.5243	245	250	714	1357	2800	12571	4431
16	2	0.6681	452	190	543	1900	1250	16143	1193
			1440	70	200	2100	1000	19000	186

Still Type: Wick 100

Hour	Min	Time Number	Elapsed Time	Output (ml)	Output (ml/m2)	Cmltv. output	Brine (ml)	Cmltv. Brine /m2	Flux (ml/m2/h)
8	30	0.3542	0	0	0	0	0	0	0
10	39	0.4438	129	225	0	0	2200	6286	2924
12	36	0.5250	246	230	657	657	2100	12286	3414
16	4	0.6694	454	150	429	1086	1000	15143	948
			1440	75	214	1300	650	17000	126

Still Type: Wick 150

Hour	Min	Time Number	Elapsed Time	Output (ml)	Output (ml/m2)	Cmltv. output	Brine (ml)	Cmltv. Brine /m2	Flux (ml/m2/h)
0	0	0.3542	0	0	0	0	0	0	0
10	41	0.4451	131	200	571	571	1500	4286	2225
12	38	0.5264	248	225	643	1214	2300	10857	3700
16	6	0.6708	456	110	314	1529	1100	14000	997
			1440	70	200	1729	950	16714	178

Still Type: Basin (for comparison)

Hour	Min	Time Number	Elapsed Time	Output (ml)	Output /m2	Cmltv. output	Temp deg. C
8	30	0.3542	0	0	0	0	10
10	33	0.4396	123	110	73	73	14
12	40	0.5278	250	700	467	540	19
14	15	0.5938	345	1550	1033	1573	21
16	8	0.6722	458	1000	667	2240	21
			1440	815	543	2783	11

Global Radiation:

Time	(kJ/m2)	Diff.
0.0	0	0
0.5	0	0
1.0	0	0
1.5	0	0
2.0	0	0
2.5	0	0
3.0	0	0
3.5	0	0
4.0	0	0
4.5	0	0
5.0	0	0
5.5	0	0
6.0	0	0
6.5	0	0
7.0	21	21
7.5	74	53
8.0	444	370
8.5	1062	618
9.0	1848	786
9.5	2811	963
10.0	4071	1260
10.5	5509	1438
11.0	6959	1450
11.5	8419	1460
12.0	9879	1460
12.5	11347	1468
13.0	12829	1482
13.5	14235	1406
14.0	15560	1325
14.5	16734	1174
15.0	17786	1052
15.5	18676	890
16.0	19390	714
16.5	19905	515
17.0	20223	318
17.5	20303	80
18.0	20303	0
18.5	20303	0
19.0	20303	0
19.5	20303	0
20.0	20303	0
20.5	20303	0
21.0	20303	0
21.5	20303	0
22.0	20303	0
22.5	20303	0
23.0	20303	0
23.5	20303	0
24.0	20303	0

DATE: 23/8/90
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Still Type: Wick 40

Hour	Min	Time Number	Elapsed Time	Output (ml)	Output (ml/m2)	Cmltv. output	Brine (ml)	Cmltv. Brine /m2	Flux (ml/m2/h)
8	30	0.3542	0	0	0	0	0	0	0
10	38	0.4431	128	210	600	600	2250	6429	3295
12	30	0.5208	240	400	1143	1743	1620	11057	3092
14	0	0.5833	330	255	729	2471	1400	15057	3152
16	5	0.6701	455	225	643	3114	2050	20914	3120
			1440	90	257	3371	5500	36629	973

Still Type: Wick 70

Hour	Min	Time Number	Elapsed Time	Output (ml)	Output (ml/m2)	Cmltv. output	Brine (ml)	Cmltv. Brine /m2	Flux (ml/m2/h)
8	30	0.3542	0	0	0	0	0	0	0
10	41	0.4451	131	250	714	714	2120	6057	3101
12	32	0.5222	242	280	800	1514	1200	9486	2286
14	2	0.5847	332	230	657	2171	1600	14057	3486
16	7	0.6715	457	270	771	2943	2400	20914	3662
			1440	110	314	3257	6800	40343	1205

Still Type: Wick 100

Hour	Min	Time Number	Elapsed Time	Output (ml)	Output (ml/m2)	Cmltv. output	Brine (ml)	Cmltv. Brine /m2	Flux (ml/m2/h)
8	30	0.3542	0	0	0	0	0	0	0
10	43	0.4465	133	240	686	686	1750	5000	2565
12	34	0.5236	244	280	800	1486	1200	8429	2286
14	3	0.5854	333	220	629	2114	1250	12000	2831
16	9	0.6729	459	325	929	3043	1750	17000	2823
			1440	75	214	3257	5000	31286	887

Still Type: Wick 150

Hour	Min	Time Number	Elapsed Time	Output (ml)	Output (ml/m2)	Cmltv. output	Brine (ml)	Cmltv. Brine /m2	Flux (ml/m2/h)
0	0	0.3542	0	0	0	0	0	0	0
10	45	0.4479	135	220	629	629	2200	6286	3073
12	35	0.5243	245	280	800	1429	1500	10571	2774
14	5	0.5868	335	250	714	2143	1300	14286	2952
16	10	0.6736	460	220	629	2771	2050	20143	3113
			1440	70	200	2971	5300	35286	939

Still Type: Basin (for comparison)

Hour	Min	Time Number	Elapsed Time	Output (ml)	Output /m2	Cmltv. output	Temp deg. C
8	30	0.3542	0	0	0	0	11
10	48	0.4500	138	215	143	143	19
12	37	0.5257	247	900	600	743	23
14	8	0.5889	338	1250	833	1577	26
16	12	0.6750	462	1300	867	2443	25
			1440	950	633	3077	12

Global Radiation:

Time	(kJ/m2)	Diff.
0.0	0	0
0.5	0	0
1.0	0	0
1.5	0	0
2.0	0	0
2.5	0	0
3.0	0	0
3.5	0	0
4.0	0	0
4.5	0	0
5.0	0	0
5.5	0	0
6.0	0	0
6.5	1	1
7.0	28	27
7.5	102	74
8.0	826	724
8.5	1713	887
9.0	2759	1046
9.5	3964	1205
10.0	5270	1306
10.5	6678	1408
11.0	8125	1447
11.5	9593	1468
12.0	11045	1452
12.5	12444	1399
13.0	13729	1285
13.5	14927	1198
14.0	15999	1072
14.5	16920	921
15.0	17670	750
15.5	18181	511
16.0	18469	288
16.5	18984	515
17.0	19302	318
17.5	19382	80
18.0	19382	0
18.5	19382	0
19.0	19382	0
19.5	19382	0
20.0	19382	0
20.5	19382	0
21.0	19382	0
21.5	19382	0
22.0	19382	0
22.5	19382	0
23.0	19382	0
23.5	19382	0
24.0	19382	0

DATE: 24/8/90

COMMENT: Early finish causes bias against basin still
in comparison with the wick stills.

Still Type: Wick 40

Hour	Min	Time Number	Elapsed Time	Output (ml)	Output (ml/m2)	Cmltv. output	Brine (ml)	Cmltv. Brine /m2	Flux (ml/m2/h)
8	30	0.3542	0	0	0	0	0	0	0
12	32	0.5222	242	480	1371	1371	3750	10714	2996
14	5	0.5868	335	360	1029	2400	1350	14571	3152
16	0	0.6667	450	220	629	3029	1800	19714	3011

Still Type: Wick 70

Hour	Min	Time Number	Elapsed Time	Output (ml)	Output (ml/m2)	Cmltv. output	Brine (ml)	Cmltv. Brine /m2	Flux (ml/m2/h)
8	30	0.3542	0	0	0	0	0	0	0
12	34	0.5236	244	500	1429	1429	3500	10000	2810
14	7	0.5882	337	340	971	2400	2400	16857	5051
16	2	0.6681	452	230	657	3057	2100	22857	3473

Still Type: Wick 100

Hour	Min	Time Number	Elapsed Time	Output (ml)	Output (ml/m2)	Cmltv. output	Brine (ml)	Cmltv. Brine /m2	Flux (ml/m2/h)
8	30	0.3542	0	0	0	0	0	0	0
12	36	0.5250	246	550	1571	1571	3250	9286	2648
14	9	0.5896	339	290	829	2400	1000	12143	2378
16	4	0.6694	454	250	714	3114	1500	16429	2609

Still Type: Wick 150

Hour	Min	Time Number	Elapsed Time	Output (ml)	Output (ml/m2)	Cmltv. output	Brine (ml)	Cmltv. Brine /m2	Flux (ml/m2/h)
0	0	0.3542	0	0	0	0	0	0	0
12	38	0.5264	248	490	1400	1400	4000	11429	3104
14	11	0.5910	341	280	800	2200	1450	15571	3189
16	6	0.6708	456	200	571	2771	2000	21286	3280

Still Type: Basin (for comparison)

Hour	Min	Time Number	Elapsed Time	Output (ml)	Output /m2	Cmltv. output	Temp deg. C
8	30	0.3542	0	0	0	0	12
12	40	0.5278	250	1150	767	767	24
14	13	0.5924	343	1300	867	1633	28
16	8	0.6722	458	1300	867	2500	28

Global Radiation:

Time	(kJ/m2)	Diff.
0.0	0	0
0.5	0	0
1.0	0	0
1.5	0	0
2.0	0	0
2.5	0	0
3.0	0	0
3.5	0	0
4.0	0	0
4.5	0	0
5.0	0	0
5.5	0	0
6.0	0	0
6.5	1	1
7.0	27	26
7.5	89	62
8.0	510	421
8.5	1135	625
9.0	1926	791
9.5	2847	921
10.0	3912	1065
10.5	5135	1223
11.0	6371	1236
11.5	7752	1381
12.0	9176	1424
12.5	10607	1431
13.0	12017	1410
13.5	13374	1357
14.0	14640	1266
14.5	15787	1147
15.0	16799	1012
15.5	17661	862
16.0	18342	681
16.5	0	
17.0	0	0
17.5	0	0
18.0	0	0
18.5	0	0
19.0	0	0
19.5	0	0
20.0	0	0
20.5	0	0
21.0	0	0
21.5	0	0
22.0	0	0
22.5	0	0
23.0	0	0
23.5	0	0
24.0	0	0

DATE: 28/8/90

COMMENT: Late start causes bias against wick stills in comparison with the basin still.

Still Type: Wick 40

Hour	Min	Time Number	Elapsed Time	Output (ml)	Output (ml/m2)	Cmltv. output	Brine (ml)	Cmltv. Brine /m2	Flux (ml/m2/h)
11	0	0.4583	0	0	0	0	0	0	0
13	5	0.5451	125	420	1200	1200	2400	6857	3867
14	42	0.6125	222	240	686	1886	2100	12857	4135
16	5	0.6701	305	140	400	2286	2200	19143	4833
			1290	80	229	2514	5100	33714	902

Still Type: Wick 70

Hour	Min	Time Number	Elapsed Time	Output (ml)	Output (ml/m2)	Cmltv. output	Brine (ml)	Cmltv. Brine /m2	Flux (ml/m2/h)
11	0	0.4583	0	0	0	0	0	0	0
13	8	0.5472	128	428	1223	1223	2750	7857	4256
14	44	0.6139	224	290	829	2051	1800	13000	3732
16	7	0.6715	307	150	429	2480	1750	18000	3924
			1290	95	271	2751	6500	36571	1150

Still Type: Wick 100

Hour	Min	Time Number	Elapsed Time	Output (ml)	Output (ml/m2)	Cmltv. output	Brine (ml)	Cmltv. Brine /m2	Flux (ml/m2/h)
11	0	0.4583	0	0	0	0	0	0	0
13	9	0.5479	129	413	1180	1180	2300	6571	3605
14	45	0.6146	225	260	743	1923	1350	10429	2875
16	9	0.6729	309	135	386	2309	1800	15571	3949
			1290	90	257	2566	6150	33143	1090

Still Type: Wick 150

Hour	Min	Time Number	Elapsed Time	Output (ml)	Output (ml/m2)	Cmltv. output	Brine (ml)	Cmltv. Brine /m2	Flux (ml/m2/h)
11	0	0.4583	0	0	0	0	0	0	0
13	11	0.5493	131	400	1143	1143	2750	7857	4122
14	47	0.6160	227	250	714	1857	2000	13571	4018
16	11	0.6743	311	130	371	2229	2000	19286	4347
			1290	80	229	2457	7000	39286	1240

Still Type: Basin (listed for comparison)

Hour	Min	Time Number	Elapsed Time	Output (ml)	Output /m2	Cmltv. output	Temp deg. C
8	30	0.3542	0	0	0	0	
13	13	0.5507	283	1100	733	733	29
14	49	0.6174	379	1150	767	1500	31
16	13	0.6757	463	1000	667	2167	30
			1440	1150	767	2933	16

Global Radiation:

Time	(kJ/m2)	Diff.
0.0	0	0
0.5	0	0
1.0	0	0
1.5	0	0
2.0	0	0
2.5	0	0
3.0	0	0
3.5	0	0
4.0	0	0
4.5	0	0
5.0	0	0
5.5	0	0
6.0	0	0
6.5	0	0
7.0	0	0
7.5	0	0
8.0	0	0
8.5	0	0
9.0	514	514
9.5	1457	943
10.0	2538	1081
10.5	3741	1203
11.0	5040	1299
11.5	6449	1409
12.0	7893	1444
12.5	9360	1467
13.0	10786	1426
13.5	12176	1390
14.0	13447	1271
14.5	14617	1170
15.0	15617	1000
15.5	16463	846
16.0	17113	650
16.5	17604	491
17.0	17891	287
17.5	17984	93
18.0	17998	14
18.5	17998	0
19.0	17998	0
19.5	17998	0
20.0	17998	0
20.5	17998	0
21.0	17998	0
21.5	17998	0
22.0	17998	0
22.5	17998	0
23.0	17998	0
23.5	17998	0
24.0	17998	0

DATE: 29/8/90

Still Type: Wick 40

Hour	Min	Time Number	Elapsed Time	Output (ml)	Output (ml/m2)	Cmltv. output	Brine (ml)	Cmltv. Brine /m2	Flux (ml/m2/h)
8	30	0.3542	0	0	0	0	0	0	0
10	40	0.4444	130	270	771	771	3000	8571	4312
12	30	0.5208	240	265	757	1529	2200	14857	3842
14	.0	0.5833	330	275	786	2314	1750	19857	3857
16	4	0.6694	454	240	686	3000	2800	27857	4203
			1440	110	314	3314	6100	45286	1080

Still Type: Wick 70

Hour	Min	Time Number	Elapsed Time	Output (ml)	Output (ml/m2)	Cmltv. output	Brine (ml)	Cmltv. Brine /m2	Flux (ml/m2/h)
8	30	0.3542	0	0	0	0	0	0	0
10	42	0.4458	132	260	743	743	2500	7143	3584
12	32	0.5222	242	320	914	1657	1750	12143	3226
14	2	0.5847	332	260	743	2400	1400	16143	3162
16	7	0.6715	457	270	771	3171	2200	22429	3387
			1440	70	200	3371	6250	40286	1102

Still Type: Wick 100

Hour	Min	Time Number	Elapsed Time	Output (ml)	Output (ml/m2)	Cmltv. output	Brine (ml)	Cmltv. Brine /m2	Flux (ml/m2/h)
8	30	0.3542	0	0	0	0	0	0	0
10	44	0.4472	134	250	0	0	2200	6286	2814
12	34	0.5236	244	315	900	900	1700	11143	3140
14	4	0.5861	334	260	743	1643	1450	15286	3257
16	8	0.6722	458	250	714	2357	2100	21286	3249
			1440	60	171	2529	5900	38143	1040

Still Type: Wick 150

Hour	Min	Time Number	Elapsed Time	Output (ml)	Output (ml/m2)	Cmltv. output	Brine (ml)	Cmltv. Brine /m2	Flux (ml/m2/h)
0	0	0.3542	0	0	0	0	0	0	0
10	46	0.4486	136	230	657	657	3000	8571	4071
12	36	0.5250	246	290	829	1486	2050	14429	3647
14	5	0.5868	335	250	714	2200	1700	19286	3756
16	10	0.6736	460	230	657	2857	2600	26714	3881
			1440	70	200	3057	>6000		

Still Type: Basin (for comparison)

Hour	Min	Time Number	Elapsed Time	Output (ml)	Output /m2	Cmltv. output	Temp deg. C
8	30	0.3542	0	0	0	0	16
10	47	0.4493	137	220	147	147	23
12	38	0.5264	248	800	533	680	27
14	7	0.5882	337	1000	667	1347	30
16	12	0.6750	462	1250	833	2180	29
			1440	1000	667	2847	14

Global Radiation:

Time	(kJ/m2)	Diff.
0.0	0	0
0.5	0	0
1.0	0	0
1.5	0	0
2.0	0	0
2.5	0	0
3.0	0	0
3.5	0	0
4.0	0	0
4.5	0	0
5.0	0	0
5.5	0	0
6.0	0	0
6.5	0	0
7.0	30	30
7.5	105	75
8.0	485	380
8.5	1066	581
9.0	1816	750
9.5	2767	951
10.0	3864	1097
10.5	5074	1210
11.0	6361	1287
11.5	7764	1403
12.0	9239	1475
12.5	10734	1495
13.0	12185	1451
13.5	13599	1414
14.0	14915	1316
14.5	16130	1215
15.0	17201	1071
15.5	18126	925
16.0	18776	650
16.5	19048	272
17.0	19290	242
17.5	19391	101
18.0	19399	8
18.5	19399	0
19.0	19399	0
19.5	19399	0
20.0	19399	0
20.5	19399	0
21.0	19399	0
21.5	19399	0
22.0	19399	0
22.5	19399	0
23.0	19399	0
23.5	19399	0
24.0	19399	0

DATE: 30/8/90
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Still Type: Wick 40

Hour	Min	Time Number	Elapsed Time	Output (ml)	Output (ml/m2)	Cmltv. output	Brine (ml)	Cmltv. Brine /m2	Flux (ml/m2/h)
8	30	0.3542	0	0	0	0	0	0	0
11	0	0.4583	150	120	343	343	1300	3714	1623
12	30	0.5208	240	135	386	729	1500	8000	3114
14	0	0.5833	330	205	586	1314	2000	13714	4200
16	0	0.6667	450	185	529	1843	1900	19143	2979
			1440	125	357	2200	>6000		

Still Type: Wick 70

Hour	Min	Time Number	Elapsed Time	Output (ml)	Output (ml/m2)	Cmltv. output	Brine (ml)	Cmltv. Brine /m2	Flux (ml/m2/h)
8	30	0.3542	0	0	0	0	0	0	0
11	2	0.4597	152	155	443	443	1000	2857	1303
12	32	0.5222	242	120	343	786	1050	5857	2229
14	2	0.5847	332	240	686	1471	1500	10143	3314
16	1	0.6674	451	180	514	1986	1250	13714	2060
			1440	100	286	2271	>6000		

Still Type: Wick 100

Hour	Min	Time Number	Elapsed Time	Output (ml)	Output (ml/m2)	Cmltv. output	Brine (ml)	Cmltv. Brine /m2	Flux (ml/m2/h)
8	30	0.3542	0	0	0	0	0	0	0
11	3	0.4604	153	140	400	400	1100	3143	1389
12	34	0.5236	244	120	343	743	1250	6714	2581
14	4	0.5861	334	250	714	1457	1550	11143	3429
16	3	0.6688	453	150	429	1886	1400	15143	2233
			1440	115	329	2214	>6000		

Still Type: Wick 150

Hour	Min	Time Number	Elapsed Time	Output (ml)	Output (ml/m2)	Cmltv. output	Brine (ml)	Cmltv. Brine /m2	Flux (ml/m2/h)
0	0	0.3542	0	0	0	0	0	0	0
11	5	0.4618	155	140	400	400	1270	3629	1559
12	35	0.5243	245	115	329	729	1350	7486	2790
14	6	0.5875	336	225	643	1371	1900	12914	4003
16	5	0.6701	455	130	371	1743	1800	18057	2780
			1440	105	300	2043	>6000		

Still Type: Basin (for comparison)

Hour	Min	Time Number	Elapsed Time	Output (ml)	Output /m2	Cmltv. output	Temp deg. C
8	30	0.3542	0	0	0	0	14
11	7	0.4632	157	160	107	107	18
12	37	0.5257	247	220	147	253	20
14	8	0.5889	338	750	500	753	22
16	7	0.6715	457	750	500	1253	23
			1440	1000	667	1920	10

Global Time	Radiation: (kJ/m2)	Diff.
0.0	0	0
0.5	0	0
1.0	0	0
1.5	0	0
2.0	0	0
2.5	0	0
3.0	0	0
3.5	0	0
4.0	0	0
4.5	0	0
5.0	0	0
5.5	0	0
6.0	0	0
6.5	1	1
7.0	28	27
7.5	122	94
8.0	278	156
8.5	530	252
9.0	955	425
9.5	1730	775
10.0	2431	701
10.5	3347	916
11.0	3983	636
11.5	4688	705
12.0	5697	1009
12.5	7137	1440
13.0	8509	1372
13.5	9919	1410
14.0	11178	1259
14.5	12339	1161
15.0	13377	1038
15.5	14257	880
16.0	14872	615
16.5	15366	494
17.0	15677	311
17.5	15798	121
18.0	15811	13
18.5	15811	0
19.0	15811	0
19.5	15811	0
20.0	15811	0
20.5	15811	0
21.0	15811	0
21.5	15811	0
22.0	15811	0
22.5	15811	0
23.0	15811	0
23.5	15811	0
24.0	15811	0

DATE: 31/8/90

Still Type: Wick 40

Hour	Min	Time Number	Elapsed Time	Output (ml)	Output (ml/m2)	Cmltv. output	Brine (ml)	Cmltv. Brine /m2	Flux (ml/m2/h)
8	30	0.3542	0	0	0	0	0	0	0
10	45	0.4479	135	280	800	800	3000	8571	4165
12	36	0.5250	246	340	971	1771	2250	15000	4000
14	5	0.5868	335	225	643	2414	1750	20000	3804
16	0	0.6667	450	310	886	3300	2700	27714	4487

Still Type: Wick 70

Hour	Min	Time Number	Elapsed Time	Output (ml)	Output (ml/m2)	Cmltv. output	Brine (ml)	Cmltv. Brine /m2	Flux (ml/m2/h)
8	30	0.3542	0	0	0	0	0	0	0
10	47	0.4493	137	290	829	829	2500	7143	3491
12	36	0.5250	246	355	1014	1843	1600	11714	3075
14	5	0.5868	335	270	771	2614	1250	15286	2928
16	0	0.6667	450	260	743	3357	2250	21714	3742

Still Type: Wick 100

Hour	Min	Time Number	Elapsed Time	Output (ml)	Output (ml/m2)	Cmltv. output	Brine (ml)	Cmltv. Brine /m2	Flux (ml/m2/h)
8	30	0.3542	0	0	0	0	0	0	0
10	49	0.4507	139	285	814	814	2300	6571	3188
12	39	0.5271	249	355	1014	1829	1650	11286	3125
14	9	0.5896	339	260	743	2571	1350	15143	3067
16	5	0.6701	455	255	729	3300	2000	20857	3333

Still Type: Wick 150

Hour	Min	Time Number	Elapsed Time	Output (ml)	Output (ml/m2)	Cmltv. output	Brine (ml)	Cmltv. Brine /m2	Flux (ml/m2/h)
0	0	0.3542	0	0	0	0	0	0	0
10	50	0.4514	140	250	714	714	3050	8714	4041
12	41	0.5285	251	325	929	1643	2150	14857	3822
14	10	0.5903	340	260	743	2386	1650	19571	3679
16	9	0.6729	459	235	671	3057	2700	27286	4228

Global Radiation:

Time	(kJ/m2)	Diff.
0.0	0	0
0.5	0	0
1.0	0	0
1.5	0	0
2.0	0	0
2.5	0	0
3.0	0	0
3.5	0	0
4.0	0	0
4.5	0	0
5.0	0	0
5.5	0	0
6.0	0	0
6.5	1	1
7.0	27	26
7.5	81	54
8.0	573	492
8.5	1284	711
9.0	2171	887
9.5	3256	1085
10.0	4470	1214
10.5	5837	1367
11.0	7294	1457
11.5	8771	1477
12.0	10327	1556
12.5	11920	1593
13.0	13475	1555
13.5	14983	1508
14.0	16385	1402
14.5	17692	1307
15.0	18858	1166
15.5	19877	1019
16.0	20698	821
16.5	21318	620
17.0	21318	0
17.5	21318	0
18.0	21318	0
18.5	21318	0
19.0	21318	0
19.5	21318	0
20.0	21318	0
20.5	21318	0
21.0	21318	0
21.5	21318	0
22.0	21318	0
22.5	21318	0
23.0	21318	0
23.5	21318	0
24.0	21318	0

APPENDIX E

Field Test Data from Paulshoek, Namaqualand
(June 1991 - August 1991)

Field Test Results: Joseph's Still, Paulshoek from 31/5/91-31/8/91

Date	Brine Feed (litres)	Distillate (litres)
31 May	25.5	7.5
1 June	24.0	7.0
2 June	20.5	8.5
3 June	20.0	8.0
4 June	20.0	8.0
5 June	15.0	6.0
6 June	18.0	3.0
7 June	19.0	5.0
8 June	19.0	6.0
9 June	20.0	8.0
10 June	20.0	8.0
11 June	20.0	8.0
12 June	20.0	8.0
13 June	20.0	7.0
14 June	20.0	7.0
15 June	20.0	8.0
16 June	20.0	8.0
17 June	20.0	7.0
18 June	20.0	8.0
19 June	20.0	7.0
20 June	20.0	7.0
21 June	20.0	6.0
22 June	20.0	6.0
23 June	20.0	8.0
24 June	20.0	8.0
25 June	20.0	5.0
26 June		
27 June		
28 June		
29 June	storm damage	
30 June		
1 July		
2 July		
3 July	20.0	8.0
4 July	20.0	6.0
5 July	20.0	6.0
6 July	20.0	6.0
7 July	20.0	6.0
8 July	20.0	7.0
9 July	20.0	4.0
10 July	20.0	8.0
11 July	20.0	5.0
12 July	20.0	7.0
13 July	20.0	7.0
14 July	20.0	8.0
15 July	20.0	6.0
16 July	20.0	7.0
17 July	20.0	8.0
18 July	20.0	9.0
19 July	20.0	9.0
20 July	20.0	8.0
21 July	20.0	9.0
22 July	20.0	8.0
23 July	20.0	7.0
24 July	20.0	7.0
25 July	20.0	7.0
26 July	20.0	8.0
27 July	20.0	7.0
28 July	20.0	6.0
29 July	20.0	6.0
30 July	20.0	7.0
31 July	20.0	8.0
1 August	20.0	7.0
2 August	20.0	8.0
3 August	20.0	7.0
4 August	20.0	6.0
5 August	20.0	6.0
6 August	20.0	8.0
7 August	20.0	8.0
8 August	20.0	8.0
9 August	20.0	8.0
10 August	20.0	7.0
11 August	20.0	8.0
12 August	20.0	9.0
13 August	20.0	9.0
14 August		
15 August	20.0	9.0
16 August		
17 August		
18 August		
19 August	storm damage	
20 August		
21 August		
22 August		
23 August	20.0	8.0
24 August	20.0	9.0
25 August	20.0	9.0
26 August	20.0	9.0
27 August	20.0	8.0
28 August	20.0	8.0
29 August	20.0	8.0
30 August	20.0	7.0
31 August	20.0	7.0

Average Distillate	7.3

APPENDIX F

Economic indices and conversion tables for comparison of prices and costs quoted in the literature

APPENDIX G

The relationship between electrical conductivity and total dissolved solids

APPENDIX F

Economic indices for the converting of prices and costs quoted in dated journals to 1991 Rands

Economic indices for the converting of prices and costs quoted in dated journals to 1991 rands

The publications on Solar Distillation reviewed for this work span the period 1948 to 1990. A recurring problem is how to compare prices quoted in dated literature with modern day currency. Fortunately most authors writing in international publications use the US $ to specify prices, or at least give current conversion rates from their own currencies to US $. To convert these dated dollar figures to 1991 rands use has been made of the following: the dollar/rand exchange rate over the period 1947 to 1991; the South African Consumer Price Index (SA cpi) from 1947 to 1991; and the US cpi from 1957 to 1991. These indices were obtained from the South African Reserve Bank.

Two conversion methods can be followed:

A first convert *n*-year dollars to *n*-year rands, then convert *n*-year rands to 1991 rands; or

B first convert *n*-year dollars to 1991 dollars, then convert 1991 dollars to 1991 rands.

The indices are shown in Figures F.1, F.2 and F.3. The conversion factors obtained via conversion routes A and B are both plotted in Figure F.4. The factors are generally similar, but the curve due to conversion method B is smoother, particularly during the mid 1980s when the rand was undervalued by up to 40% against the dollar due to political rather than economic factors. Method B is thus indicated as the more reliable over this period.

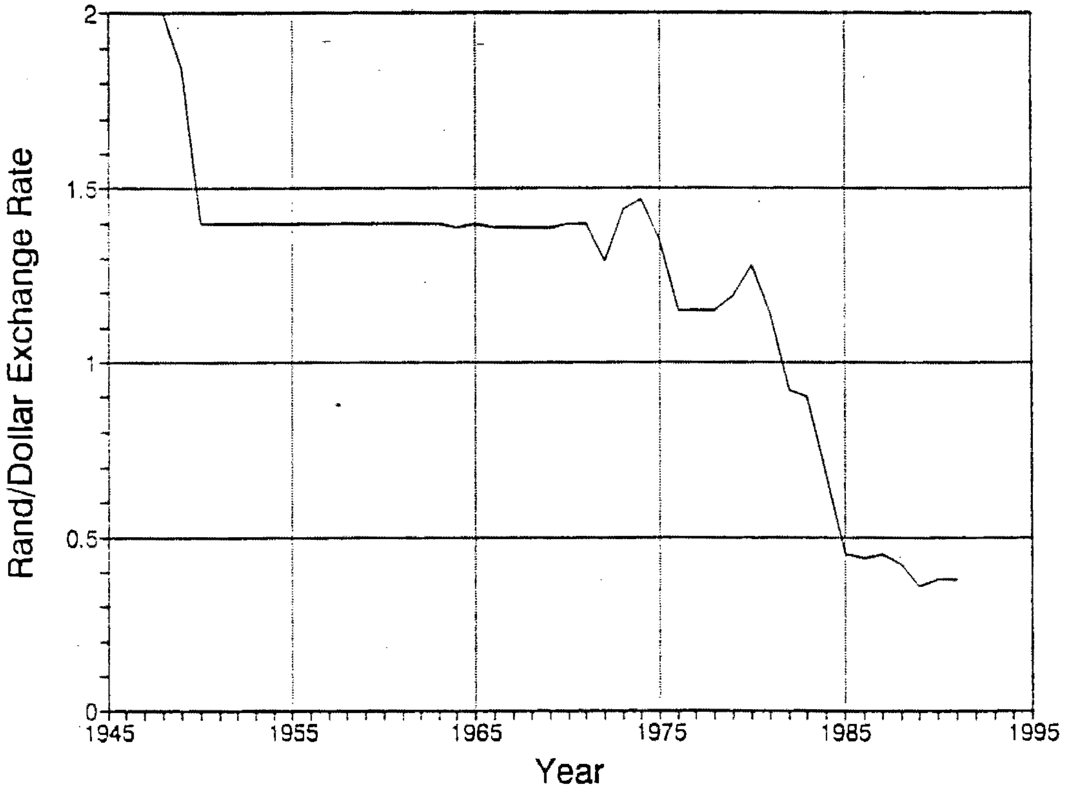

Figure F.1: **Rand/US $ exchange rate, 1947 to 1991 (data from SA Reserve Bank)**

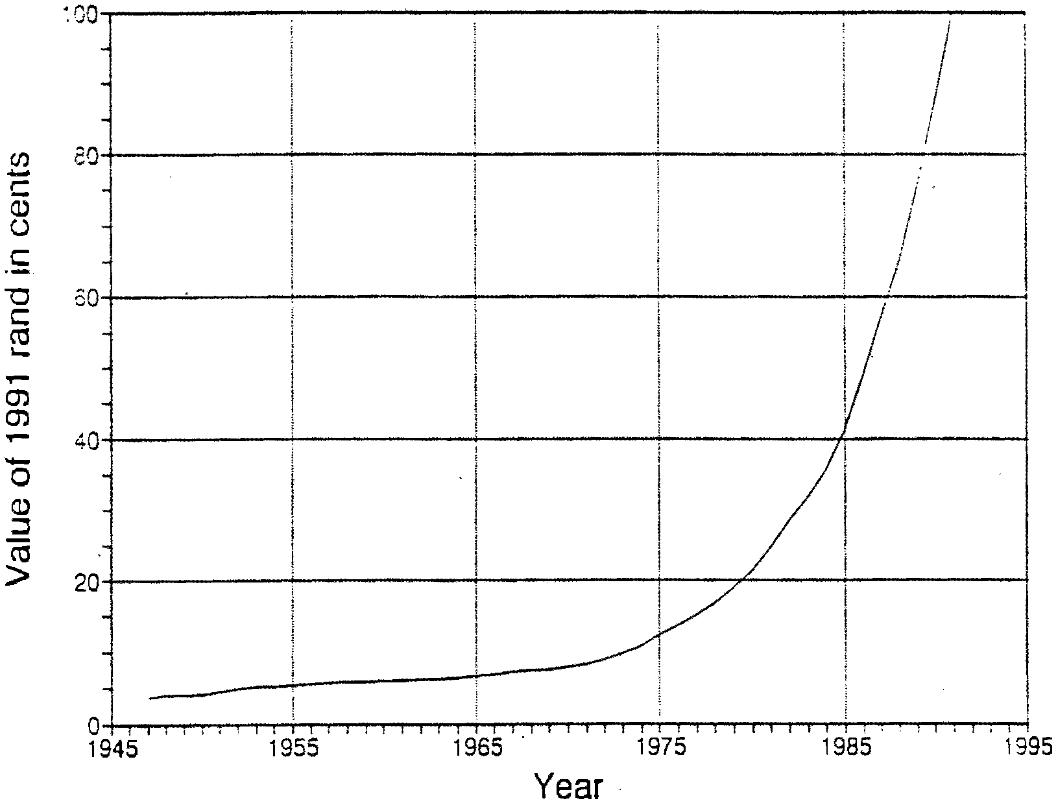

Figure F.2: South African Consumer Price Index from 1947 to 1991 (data from SA Reserve Bank)

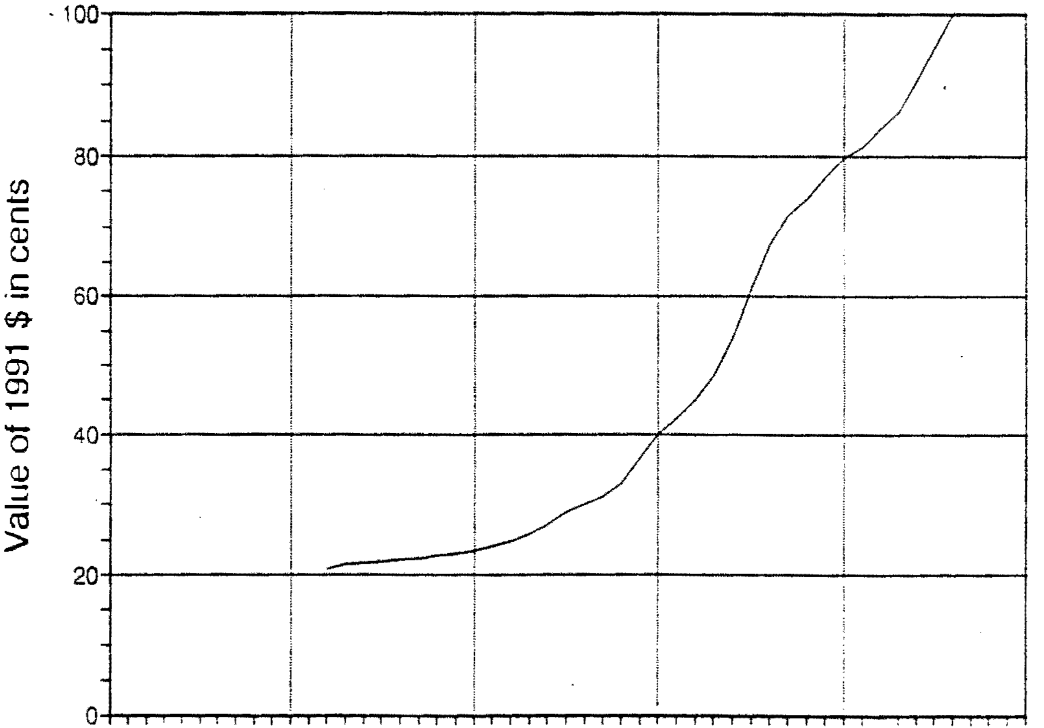

Figure F.3: United States Consumer Price Index from 1957 to 1991 (data from SA Reserve Bank)

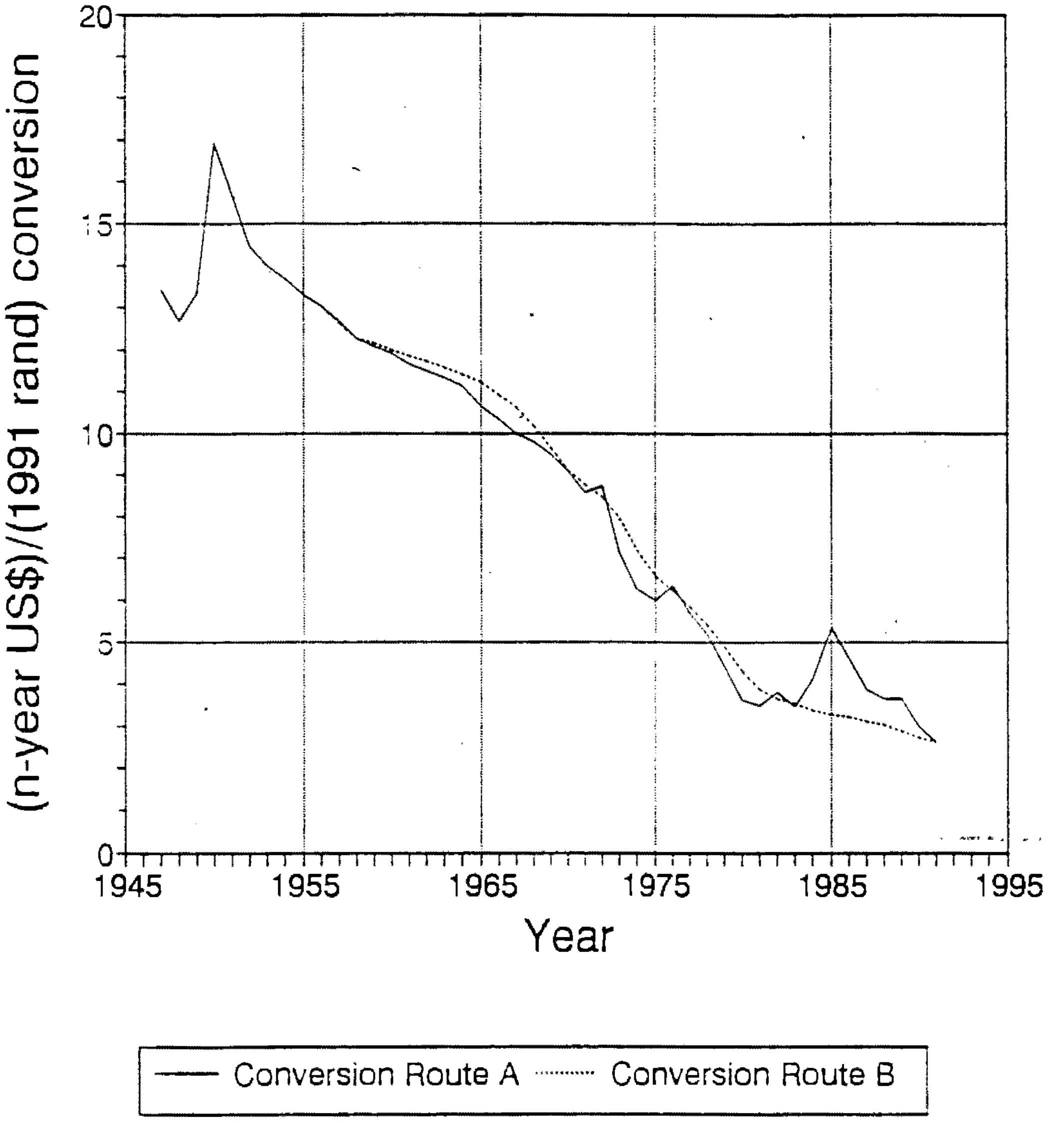

Figure F.4: **Conversion of *n*-year dollars to 1991 rands using conversion methods A and B**

where method A converts *n*-year dollars to *n*-year rands, then *n*-year rands to 1991 rands; and

method B converts *n*-year dollars to 1991 dollars, then 1991 dollars to 1991 rands.

APPENDIX G

The relationship between Electrical Conductivity (EC) and Total Dissolved Solids (TDS)

The relationship between Electrical Conductivity (EC) and Total Dissolved Solids (TDS)

With the desalination industry worldwide tied to the WHO standard of 500 mg/ℓ Total Dissolved Solids (TDS), it is interesting to note some points on the definition and measurement of this parameter. Much of this material is drawn from the paper *Electrical Conductivity and Total Dissolved Solids - what is their precise relationship*, by N.R.G. Walton, which appeared in *Desalination*, volume 72, in 1989.

If TDS = K.EC , then what is K?

Much confusion exists throughout the water industry over this very simple but important question. It may come as a surprise to some workers in the desalination industry to find that there is unfortunately no simple precise relationship between these two parameters although workers in every field of water studies from physical chemistry through electrochemistry, hydrochemistry, soil and irrigation science, hydrology, geochemistry to marine chemistry each claim to have the best approximation.

What they are actually using is a tolerable empirical approximation which appears to hold good within the range of ion concentrations and salinities that their particular subject deals with. Thus the theoretical chemists continue to build on the pioneering works of the early physical chemists, Arrhenius, Ostwald, Debye and Hückel, Onsnager, Kohlrausche et al. from early in this century using ideal solutions and infinite dilutions to formulate absolute definitions for individual ion behaviours, whilst soil and irrigation scientists get more involved with ionic strength effects due to their interest in the balance between monovalent and divalent ions, and engineers - preferring a simple on-site rule of thumb - often simply take the factor of 0,7 so often found on the fixed scales of commercial electrical conductivity - total dissolved solids (EC-TDS) meters and think little more about it.

Definition of Total Dissolved Solids

Superficially this question appears to be self evident, but this hides a number of important points both theoretical and practical. The question of what is "dissolved" and what is not has long been a difficult question in the water industry, since particles, ions and molecules exist throughout an entire size spectrum both individually and in larger polymeric agglomerations, through colloidal suspensions to visible particulate matter. The dividing line between what is truly dissolved and what is in colloidal suspension or agglomeration can only be drawn by reference to a specific filter mesh size.

Since micron-sized colloidal particles are evident under a simple microscope, the line had to be drawn at the sub-micron size and the figure of 0.45 μm has tended to become the internationally accepted standard in the water industry for deciding what is in true solution or "dissolved" matter *and what is "particulate matter". This dividing line came about largely arbitrarily as a matter of practical necessity since 0,45 µm was the smallest pore-size filter paper commercially available in the 1960s and 1970s when these matters were being deliberated internationally.*

Sampling and Analytical Problems

Walton goes on to recommend that samples for TDS analysis should be filtered in-situ at the time of collection, then kept in a refrigerator prior to analysis, which should ideally be within 24 hours of sample collection and filtration. If these measures are not followed, a whole range of physical, chemical and biological activities can take place in the sample bottle [Walton gives five examples: oxygenation leading to precipitation of previously dissolved species like iron and sulphide; degassing of CO_2 can cause $CaCO_3$ precipitation; denitrification; biological utilisation of CO_2, dissolved organic matter and PO_4^{3-} ion uptake; and agglomeration of micro-colloids originally smaller than 0,45 µm].

Assuming that the sampling is carried out correctly, the analysis must still be successfully negotiated. The standard TDS measurement should be carried out by evaporating an accurately weighed water sample in a platinum crucible to dryness at 180°C, followed by cooling in a desiccator and weighing the residue to constant weight.

Walton lists several common theoretical and practical sources of error with this test. One of the more serious ones is the failure to compensate for the loss of CO_2 gas during the precipitation of $CaCO_3$ scale, which can lead to large errors in the TDS evaluation of fresh natural waters. Most of the other errors stem from avoidable, but nevertheless common, laboratory practices.

The point of Walton's discussion here is that because TDS measurements are themselves prone to error, differences of the order of 50% not being uncommon in potable waters, they should not in all cases be held up as an absolute standard against which to judge Electrical Conductivity (EC) readings. There are often times when the use of a good EC reading multiplied by the appropriate K factor is a better way of obtaining the TDS than by analysing for it.

Electrical Conductivity - Definition and Measurement

Electrical conductivity (EC) is the inverse of electrical resistivity. It is defined in terms of the conductance (inverse of resistance) of a given conductor *of area A per unit length ℓ.* For this reason it is also known as the *specific conductance* of the material.

It is measured electrically and specified in units of Siemens per metre, where the Siemens is the mho, or reciprocal of the unit of electrical resistance, the ohm. For practical purposes mS/m or µS/cm are the usual units for the expression of EC.

The EC of an electrolyte or aqueous solution is a summation of the current-carrying ability of every ion present and is dependent upon the number of ions per unit volume of the solution and the mobilities with which each ion is able to move under the influence of the applied electrical potential. Since the temperature dependence of EC is critical (about 2% per 1°C), either the exact temperature of measurement or, more commonly, the EC result corrected to the standard thermodynamic reference temperature of 25°C must be quoted. . . . One should be aware of older meters which may temperature-correct to the previous 20°C standard temperature which will give an immediate 10% error to the EC reading if this fact is not noticed. The writer came across an interesting example in one Middle-Eastern country where alarm was occasioned by the latest annual country-wide well water salinity (EC) survey which indicated a 10% rise in virtually all water well EC readings. It was some time before this universal EC rise was attributed to the change from an old 20°C standard temperature meter to a new 25°C standard meter.

Compact, rugged EC meters are commercially available and are ideally suited to the field measurement of salinity.

Correlation of EC and TDS

Since there is definitely no simple relationship between these parameters across the range of waters encountered in the desalination industry, and since complicated mathematical predictions which suit academics, theoreticians and computers are of little use to the majority of workers in the industry, the best alternative is to produce a series of K values for different ranges of salinities.

The correct way to do this is to take a series of samples of the water in question to a reputable laboratory and measure the EC and TDS a number of times until good precision and accuracy are statistically achieved, and then to take the ratio of the average values to obtain a "best possible" K factor. Of course, all the precautions such as filtration and bicarbonate correction for TDS measurements, and calibration and standardisation of EC measurements as listed in this paper need to be adhered to, to be sure of getting good, accurate results. Only then can the actual K factor for that particular ionic-mix water be relied upon.

However, since most desalination plants utilise fairly predictable water types, the K factors can be approximated in advance as shown in [Table G.1].

The reason for the predictability of the TDS-EC relationship for these water types is due to the overwhelming predominance (ca. 90%) of just two ions in all these waters, namely Na^+ *and* Cl^-*, and the increasing K factor with salinity reflects the hindrance of ionic mobility by the crowding effect of these ions at higher concentrations.*

The major variation of EC with TDS comes with fresh, potable and brackish waters which contain a variety of dissolved salts, sometimes with $Mg(HCO_3)_2$ *or* $Ca(HCO_3)_2$ *predominant and sometimes* $CaSO_4$*,* $NaHCO_3$ *or NaCl as the dominant salt present. The complex ion-pairing and physical (size)* *and electrical charge interactions which take place in the solutions of these salts make any simple TDS-EC relationship impossible. However, many natural waters do contain a fairly well balanced blend of the eight major ions, and so extremes of interaction due to large size or high charge effects are often balanced down so that most natural waters have K values which vary between 0,55 and 0,85. This of course is where the much used value of 0,70 comes in as simply the average between these two extremes.*

Table G.1: Suggested K factors for use with different desalination water types

Water Type	*Typical EC_{25} (μS/cm)*	*K factor*
Distillate	*1-10*	*0,50*
RO permeate	*300-800*	*0,55*
Seawater	*45 000-60 000*	*0,70*
Reject brines	*65 000-85 000*	*0,75*

However, from the desalination point of view, it is generally brackish waters with EC ranging from 2000-20 000 μS/cm which are of interest and these waters rarely have a K factor below 0,60 or above 0,67 due to the chemical evolutionary sequence of most brackish ground waters. Consequently, a good average K value of 0,63 has been found to satisfy most brackish Middle East groundwaters with salinities in the range of 3 000-20 000 mg/ℓ as TDS.

[Figure G.1] gives a generalised view of the change in K factor with increasing salinities for different water types. The dominant HCO_3^- ion concentration of many fresh waters gives the very steep rise in K value at low concentrations, whilst the increasing importance of SO_4^{2-} in brackish waters maintains K-values well above the single mono-valent KCl standard line, whereas the [increase] in K value between 1 000 to 10 000 mg/ℓ TDS is due to the dominance of inter-ion interference causing reduced EC values at higher TDS values. It is in this region where K factors can have the highest variability due to the opposing effects of increased physical resistance and ionic interactions at higher concentrations, and the disproportionate ratio of divalent to monovalent ions. [Figure G.1] also shows that the waters important to the desalination industry occupy very limited fields on the diagram and generally follow the exponential trend of the NaCl line.

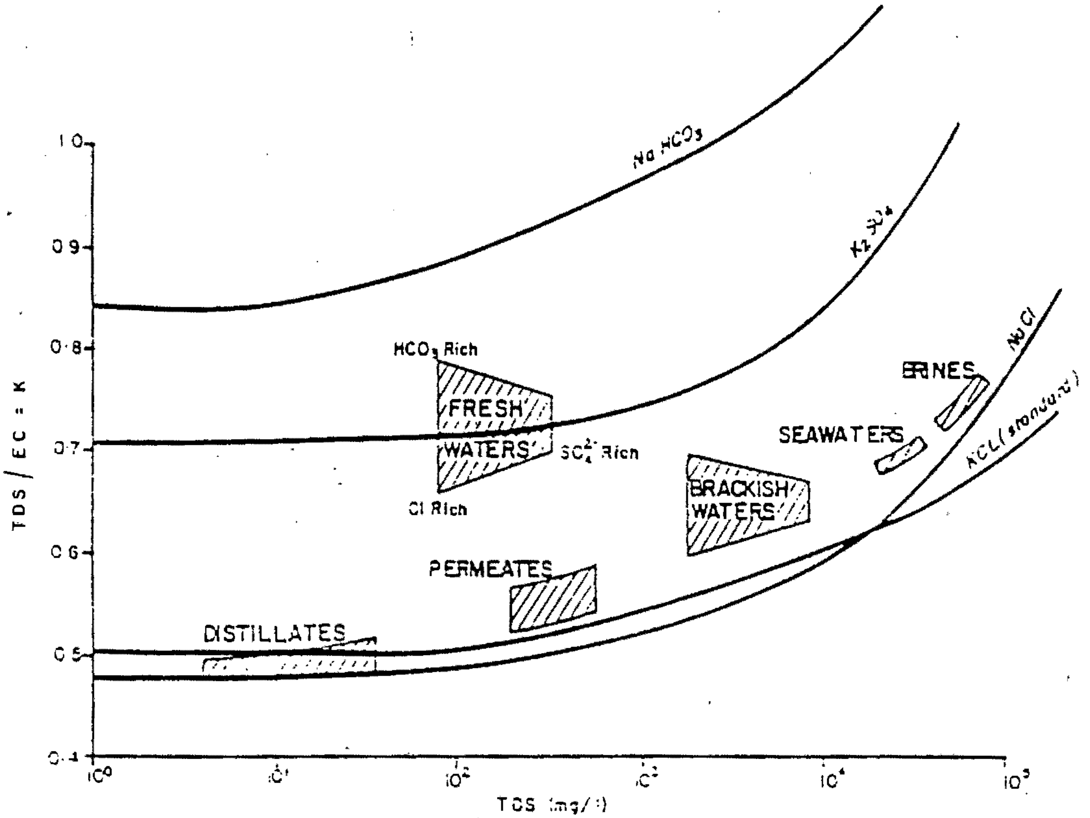

Figure G.1: Plot of TDS against K values showing fields of dominance for different water types (after Walton, 1989)