AN INVESTIGATION OF INNOVATIVE APPROACHES TO BRINE HANDLING

Report to the
Water Research Commission

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EXECUTIVE SUMMARY

Introduction

As a semi-arid country, fresh water is one of South Africa's most important national resources having a direct impact on the health, environmental quality and economic wellbeing of its people. Whilst several factors impact on the availability and quality of fresh water in the region, increasing salinisation of South Africa's public water system was identified as the single most serious pollution threat facing the country as far back as 1970 (Commission of Enquiry into Water Matters, 1970). This situation has only deteriorated in the intervening years since 1970 and the problem has been recognised and addressed in the National Environmental Management Act of 1998 and the Integrated Pollution and Waste Management (IPWM) paper of 2000.

Since then, sustainable development has become the guiding principle in addressing and managing our water resources. This focus on sustainability has resulted in an integrated management process for water resources, pollution and waste in South Africa. Gradually, this resulted in a focus shift from remedial actions towards prevention at the source and sustainable production strategies.

Today, a three-pronged approach is followed resulting in three hierarchical levels of integrated management of pollution, i.e. 1) source-control and prevention in terms of avoidance, reduction, minimisation, 2) impact management in terms of recovery, recycle and re-use and 3) remediation, treatment and disposal (DEAT, 2000).

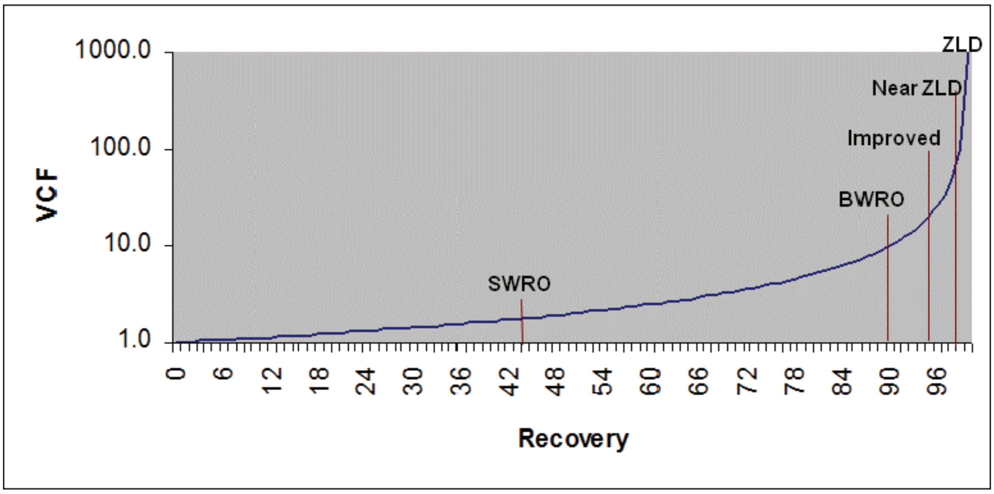
Given the continuing salinisation of our freshwater systems, the principles of resource protection and efficient use are underscored by legislation and resulted in numerous studies by the WRC as the country's water-centred knowledge hub. This, in addition to pro-active measures and innovations of local industry and researchers, resulted in the development of an advanced desalination industry in South Africa, with several large scale in-land industrial desalination systems in operation.

In 2005 the WRC initiated a research project to assess the strategies to manage brine resulting from desalination processes. This report gives expression to this directive and assesses the current status of brine and sludge treatment as well as new, innovative technologies that represent the outcomes of South African technology drivers.

In keeping with steps 1 and 2 of the hierarchy, desalination is becoming increasingly important to sustain water quality in production processes and to protect the environment. Sustainability of brine disposal strategies has become critical and the desalination engineer is more and more compelled to consider new, innovative approaches. Today, typical water recovery rates for different applications are:

Sea water desalination	40-45%
Industrial effluent	70-85%
Brackish water desalination	85-90%

Water not recovered ends up as a concentrated brine stream and as water recovery increases, brine volume decreases. It is generally more economical to run at higher water recovery rates. However, as water recovery increases, the Volume Concentration Factor (VCF) increases, resulting in increased design, operation and maintenance risk. From the diagram below, it is clear that above 90% recovery, VCF increases dramatically with every additional percentage point in water recovery. Today, the major research effort in high recovery systems for in-land brackish water and industrial systems is in the region above 95% water recovery.



Objectives of the Project

The objectives of this project may be summarised as follows:

1. With the increasing focus on energy efficiency, and considering that desalination is a relatively energy intensive process, the first objective of this project was to understand the minimum energy requirements for desalination. This result will be used to guide future research into more energy efficient means of desalination and brine management;

2. The second objective was to collect data about the present brine and sludge volumes in South Africa and to collate these in an appropriate data base. This information was, and will be, used to guide the research in terms of high priority needs and opportunities;

3. Thirdly, the project was to summarise the legal framework within which desalination and disposal of brine and sludge has to take place in South Africa. This should provide an indication as to the present efficiency of legislation as well as any development opportunities in the legal/regulatory arena;

4. Fourthly, the various current alternatives for brine and sludge management was evaluated with a view to identify present best strategies. This review included not only local practises, but international practises as well.

5. Next, the project investigated and identified innovative approaches to brine and sludge management;

6. These innovative concepts were then compared with current best practises in order to identify those concepts which should be investigated further;

7. For the promising concepts, a more detailed evaluation was performed in order to identify those with highest potential;

8. Proof of concept testing was done on the most promising innovative concepts;

9. Future research needs were identified.

Methods

The project was conducted using a combination of desk-top investigations, discussions with industry experts and equipment vendors, visits to plants and discussions with owners & operators of desalination plants as well as bench scale and small scale pilot testing.

Current and Projected Sources of Brine and Sludge

Volumes and sources of brine and sludge were determined through a survey of industry. For this survey, 268 companies were contacted, of which 185 positive responses were received. Despite the good response rate (69%), the development of a detailed database was hampered by either a lack of data within some organizations, or an unwillingness to release detailed data due to commercial and other sensitivities. In addition, industrial effluent and mining water volumes and composition is a dynamic environment, leading to several uncertainties in terms of present, but more importantly, future trends. Therefore, a number of assumptions had to be made in order to arrive at a reasonable data set.

Despite these assumptions, there is sufficient reliable data within the database to enable the following synopsis and trends. Firstly, a summary of current effluent load is provided below:

It should be noted that the study only considered effluent discharged to the in-land environment, and that effluent and salt discharged to the marine environment was not considered. A total of just over 530 000 kl/d of effluent is discharged to inland systems, containing approximately 1060 t/d of salt (refer to the table below). The major industries contributing to the inland volume and salt load are:

- Mining;
- Power generation;
- Petroleum;
- Paper & pulp;
- Steel & metals processing.

Sector	Total effluent			Salt load to environment		
	Total effluent	Total excl marine	Portion excl marine	Total salt	Total salt excl marine	Portion excl marine
	kl/day	kl/day	%	t/day	t/day	% of total excl marine
Paper & Pulp/Wood	272001	89001	16.6	1440	80	7.6
General Packaging	1950	1950	0.4	2	2	0.2
Steel/metals processing	30500	30500	5.7	72	72	6.8
Petroleum	83900	69100	12.9	354	300	28.4
Chemical	13070	11070	2.1	51	44	4.2
Power Generation	132000	132000	24.7	158	158	15.0
Mines	145025	145025	27.1	350	350	33.1
Chemical suppliers	528	528	0.1	0	0	0.0
Dairy	2700	2700	0.5	4	4	0.4
Sugar	8100	3900	0.7	10	2	0.2
Canning	2200	2200	0.4	1	1	0.1
General food	13970	10970	2.1	11	5	0.5
Pharmaceutical & personal care	1430	1430	0.3	1	1	0.1
Animal Nutrition	1205	1205	0.2	1	1	0.1
Poultry & Meat	12100	12100	2.3	8	9	0.8
Beverage	14670	14670	2.7	11	11	1.0
Textile	6000	6000	1.1	13	13	1.2
Waste management	190	190	0.0	5	5	0.5
Fish Processing	220700	200	0.0	7921	1	0.1
Totals	**962239**	**534739**	**100**	**10413**	**1058**	**100**

Taking information directly from industry players and combining that with information from other parallel studies by Golder & Associates, Council for Geosciences, *etc*., the projected general effluent and mine water make volumes may be determined. The brine generation potential for each industry can be estimated from this as indicated in the graph below.

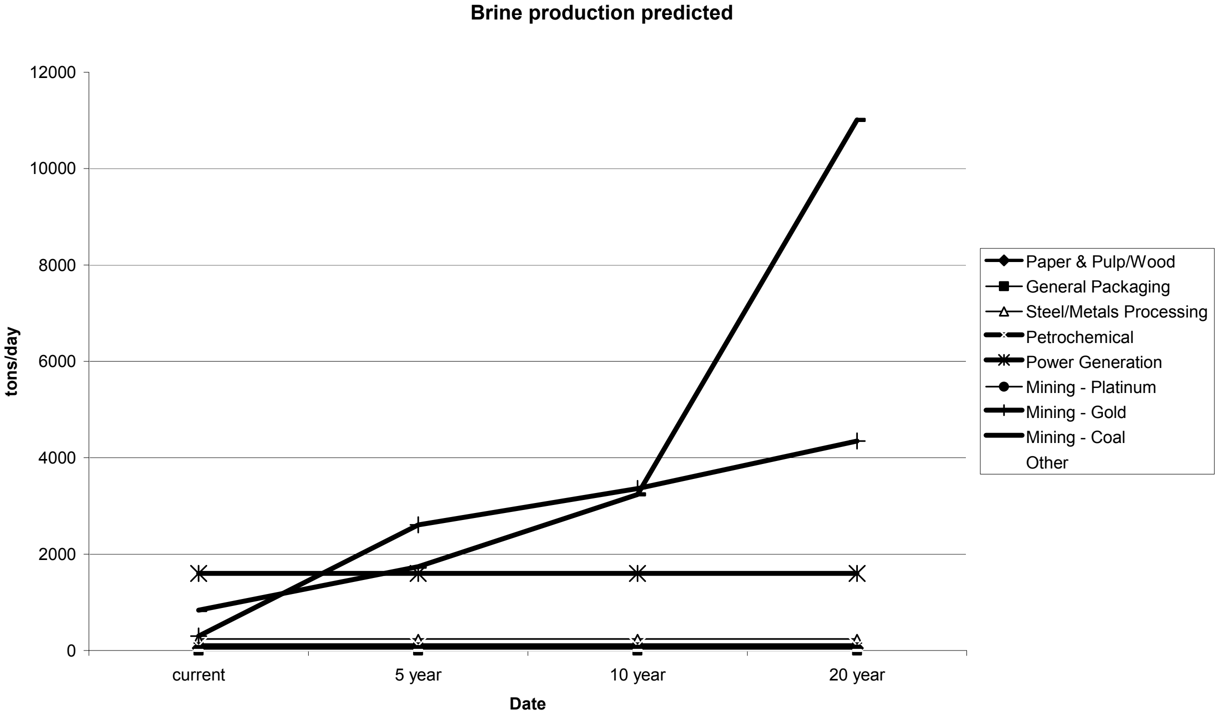
For general industry, effluent volumes are likely to be relatively stagnant despite anticipated future growth. This is mainly as a result of cleaner production techniques and recycling opportunities foreseen. In contrast, volumes in the gold and coal mining sectors are expected to increase significantly over the next 20 years and in particular after 2012. This trend is expected to apply in general to all mining basins.

Despite the uncertainties inherent to the database, the following specific trends could be identified:

- Brine volumes generated as a result of coal and gold mining will probably represent the most important challenge over the medium term. Cumulatively, it is possible that brine volumes could be around 4000 t/d within 5 years, and as much as 15 000 t/d of brine within 20 years.

- In terms of the areas in which brine will be generated, in the short term (depending on future strategies to manage the West and East Rand Basins) brine generation could be relatively evenly split between the Johannesburg area, and the Witbank area;

- The greatest increase in brine generation is expected (in the longer term) to be in the area of the Witbank Coal Fields.



Other factors to be considered in interpreting this data include:

- The East and West Rand basins are generating water primarily from defunct gold mines. It is uncertain as to the extent to which government or the remaining gold mines will be able fund membrane technology treatment in the short term, the increasing value of water notwithstanding. This in turn will influence whether the brine volumes predicted for the Johannesburg area will materialise;

- In the Witbank area, the cost of brine disposal is resulting in considerable effort to minimise the volumes of brine. For mines with low sodium water, these opportunities are significant, and include the generation of water for process purposes in addition to potable water;

- This trend is expected to apply in general to all mining basins.

The similarity in water treatment technologies for water produced by the coal and gold mining industries offers huge benefits to technology developers in optimising processes. It is likely that developments in the field of brine minimisation and management will also be similar, albeit that there will be some differences in the chemistry and nature of the brine.

Legal Framework

Disposal of brine and sludge in South Africa is covered by the following pieces of legislation:

- National Environmental Management Act,1998 (Act 107 of 1998) with relevant EIA regulations;

- Environment Conservation Act, 1989 (Act 73 of 1989);
- National Water Act, 1998 (Act 36 of 1998);

The Department of Water Affairs and Forestry (DWAF) is developing a Waste Discharge Charge System (WDSC) as part of the water pricing strategy in terms of Chapter 5 of the National Water Act. This system has the following objectives:

- Promote sustainable development and efficient use of water resources;
- Promote internalization of environmental costs;
- Recover costs associated with mitigating resource quality impacts of waste discharge;
- Create financial incentives to reduce waste and use water resources more optimally.

Two distinct charges are envisaged:

- Incentive charge: charge that provide a disincentive to discharge waste based on the use of the resource as a means of disposing waste. This forms the basis of the WDCS aim to accomplish the resource quality objectives for a catchment; and
- Mitigation charge: charge to cover the quantifiable cost of administratively implementing measures for mitigation of water discharge related impacts.

Despite excellent legislation, it is unfortunate that the necessary capacity to implement and police these are as yet unproven. Whilst regulatory efforts to address these shortfalls are on-going, policing of the laws will require skilled manpower and determination from the relevant authorities. This, however, is perhaps a much deeper philosophical/socio-economical and political debate which needs discussion outside the scope of this document.

Present brine and sludge strategies

A large number of factors influence brine disposal strategies, including:

- Size of installation;
- Composition of brine;
- Physical and geographical location of the installation;
- Availability of acceptable receiving site;
- Legal/regulatory permissibility;
- Public acceptance;
- Capital and operating costs;
- Ability for future expansion;
- Long term environmental risks;

- Remedial options available in case of failure;
- Economic drivers for primary desalination application.

To date, the most important disposal strategies employed in various regions of the world include:

- Discharge to evaporation ponds;
- Disposal to surface water bodies;
- Disposal through pipelines to municipal sewers;
- Deep-well injection;
- Concentration into solid salts;
- Land application and irrigation of plants tolerant to high salinity (halophytes).

In South Africa, the most frequently used brine disposal options are to lined evaporation ponds, installation of mechanical evaporators and disposal to ash systems. Capital and operating cost as well as long term environmental liability frequently limit successful application of these systems, thus the need for innovative solutions to brine management.

In terms of sludge, the production of a solid sludge is generally preferred above a liquid brine stream due to improved storage/handling characteristics of the former. This forces the desalination engineer to remove as much as possible of dissolved species (mostly multi-valent hardness salts and metals) using low cost precipitation technologies.

Hazard rating of sludge

A major potential drawback of simply removing scaling chemical species without regard for metals and other potentially toxic constituents is the fact that a low quality, mixed sludge is produced with a relatively high hazard rating. An alternative approach may be fractional precipitation of constituents by careful control of process parameters such as pH and temperature.

With this approach, a smaller volume of hazardous sludge may be produced, resulting in the bulk of the sludge having a low hazard rating. A specific example is the removal of heavy metals from feed streams separately from other hardness salts.

Potential for by-product recovery

A further refinement of fractional precipitation is the potential recovery of by-products. A list of potential by-products from South African mine water includes the following:

- Calcium carbonate (limestone of various grades)
- Calcium chloride
- Calcium oxide/hydroxide (lime)
- Calcium sulphate (gypsum)

- Chlorine (gas)
- Ferric oxide
- Magnesium-ammonium-phosphate fertilisers
- Magnesium chloride
- Magnesium hydroxide
- Magnesium sulphate
- Potassium chloride
- Potassium nitrate
- Potassium sulphate
- Sodium chloride
- Sodium nitrate
- Sodium sulphate
- Sulphur (agricultural and industrial grade)

A major benefit of by-product recovery is a reduction in the overall volume of sludge, as well as a reduction in the hazard rating of the sludge produced. However, this has to take place in a techno-economically sustainable manner. A review of imported chemicals into South Africa as well as equivalent volume of water treated (table below) suggests relatively limited opportunity for import replacements. In particular, sulphur appears to be a reasonable opportunity although it is known that applications for high quality calcium carbonate and gypsum are also abundant (import figures, however, do not confirm this due to local sources).

VARIOUS IMPORTED RAW MATERIALS: DTI JAN - DEC 2006

Product	Quantity Imported t	Value of imported product R'000	Unit value of imported product R/t
Gypsum	3,703	2,408	650
Chlorine	38	0.3	8.8
Magnesium hydroxide	2,001	968	484
Ferric oxide	81,970	13,701	167
Calcium chloride	6,219	3,525	567
Calcium carbonate			
Magnesium chloride	1,266	535	423
Magnesium sulphate	6,006	8,269	1377
Potassium chloride	1,576	77	49
Mono ammonium phospate fertiliser	526	103	196
Sodium chloride	4,592	4,936	1075
Sulphur	295,453	681,000	2305
Sodium sulphate	7,671	16,310	2126
Potassium nitrate	79,737	20,603	258
Sodium nitrate	4,913	2,632	536
Total imported	**R'000/a**	**755,067**	

Thus, it is anticipated that recovery of by-products should generally not be viewed as the prime driving force for cost recovery or making such projects economically viable, but rather to eliminate a long term liability from sludge/brine

Process design

A number of factors impact directly on system design and there is not a simple, “one-size-fits-all” solution. Each application has to be evaluated on its own merit to arrive at a site-specific optimum. Despite this, however, several broad principles should improve overall design of most systems:

- Keep all technology as simple as possible;
- Removal of sparingly soluble salts in the solid form is preferred as this generally allows increased water recovery. In addition, storing/transporting salts in the solid form is generally simpler, less costly and safer than storing a concentrated brine solution;
- In general, it is preferable to remove hazardous constituents – such as heavy metals – separately from the bulk of sludge through a process called fractional precipitation as this approach reduces the overall amount, risk and cost of hazardous sludge disposal;
- By-product recovery should be attempted in all cases, as this generally allows high water recovery, whilst reducing long term liability associated with hazardous sludge;
- By-product recovery should not be the prime driver for desalination projects to achieve economic viability. Increased complexity of systems utilising by-product recovery should be carefully evaluated against alternative designs;
- Product water specification may eliminate the requirement for high rejection desalination systems and some salts could be “exported” with the product water. For instance where

a limited amount of sodium chloride can be tolerated in the product water, low rejection nanofiltration membranes may be employed instead of standard reverse osmosis plants. Typical applications include AMD with low levels of sodium and chloride, which is acceptable in potable water applications;

- For relatively small and remote systems, the optimum design philosophy will most likely be a simple process design in order to reduce operational and maintenance complexity;
- For relatively large systems in built-up areas, a more elaborate process design philosophy may be justified to maximize resource utilization efficiency.

Innovative Approaches

The various innovative brine management strategies may be grouped as follows:

- Brine minimization;
- Product recovery;
- Final disposal.

In order to evaluate different innovative concepts against existing alternatives as well as against each other, a conceptual brine was developed and conceptual designs developed for a system to treat 1 Ml/d of brine. Based on this evaluation, the most promising innovative techniques are summarised below.

Brine softening and treatment

The most cost effective manner to manage brine is to reduce the volume thereof as much as possible. Traditionally, the target water recovery for inland desalination system varied between 75 and 85%, resulting in a brine TDS of about 10 000 mg/l-30 000 mg/l. By comparison, brine from seawater RO plants may be as high as 70 000 mg/l. It is clear that if inland desalination plants are operated at similar brine TDS levels, the volume of brine can be reduced by at least 50%. Factors contributing to inland RO plants not being operated at these high TDS levels include:

- Scaling chemistry, including complex and unpredictable synergistic effects;
- Limited understanding of high salinity desalination technology;
- Variable incoming raw water quality;
- Oil, organic material and colloidal matter;
- Commercial risk to contractors having to guarantee plant performance;
- Operational skill and shortage of expert skills in supporting these high recovery systems;
- Lack of inclusion of long term cost for brine disposal in project evaluation, resulting in preference to schemes with lower capital costs.

Many of these concerns may be addressed by advanced and comprehensive pre-treatment, buffering, automated control and using state-of-the-art technology. However, despite encouraging field results from such modern schemes, significant challenges remain in ensuring trouble free operation of desalination systems in cases of complex and variable feed streams. In these situations, design and operation of systems should preferably be performed by specialist teams.

One promising option which appears to be emerging as a preferred way to reduce brine volumes is brine softening and recycle. Several schemes have been proposed in the past, including options such as SPARRO, ICCON, HIPRO, *etc.* The major challenges in recycling of brine are:

- Overcoming the inhibitory effect of anti-scalants;
- Controlling scaling in the membrane units and piping;
- Osmotic pressures.

Modern designs overcome these limitations in a number of ways, most notably as follows:

- The inhibitory effect of anti-scalants may be overcome by two major process routes, including:
    - Selection of the appropriate anti-scalant. Generally two types of anti-scalants are available, *viz.* those interfering with crystal growth (and being incorporated into the crystal structure), and those modifying solubility of certain salts. Generally, the second class of anti-scalant is preferred when attempting to neutralise the effect of anti-scalants;
    - Simple over-saturation. By returning the brine to a slurry reactor and causing super-saturation of the sparingly soluble salts, the anti-scalant is simply overwhelmed and not able to continue preventing precipitation;
- Scaling in membranes may be controlled principally by the following means:
    - Routing of the brine to a slurry reactor where super-saturation is removed. The process have been demonstrated in the SPARRO process;
    - Designing the desalination system in distinct units running sequentially at increasing water recovery. This approach reduces the overall process risk for catastrophic scaling in the system.

In recent years, several innovative pre-treatment schemes for brine treatment were proposed to increase water recovery above 95%. Presently, the technology is being commercially applied. It is recommended that research efforts are supported to consider the following aspects:

- Overcoming and managing the inhibitory effect of anti-scalants;
- Controlling scaling within pipe-lines.

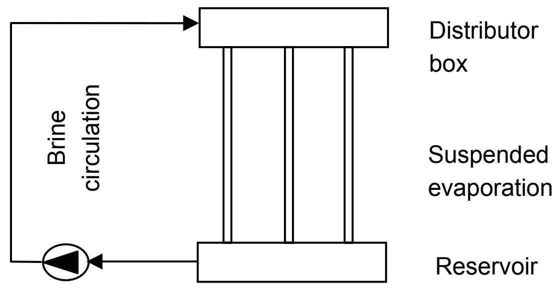
Enhanced evaporation systems

Two promising alternatives were identified, *viz.* WAIV and Dewvaporation.

<u>Wind Aided Intensified eVaporation (WAIV)</u>

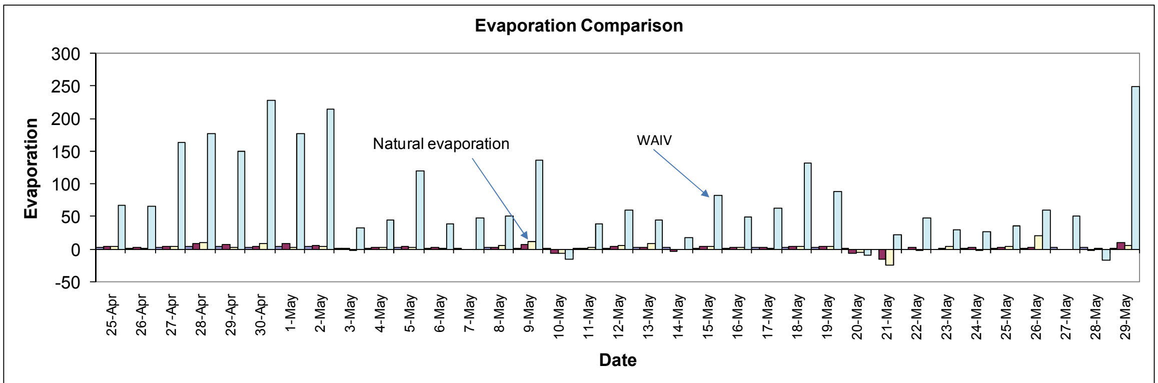
WAIV exploits wind – a naturally renewable energy source – to enhance evaporation above brine ponds through the use of extended vertical surfaces – see figure below. The technology may also be adapted to be used to increase the lifespan of existing evaporation ponds.

The concept was tested using a small scale pilot unit, which have shown that evaporation rates may be increased by as much as 20 to 30 times compared to natural evaporation from open ponds.



The WAIV concept

One of the main benefits of the technology is its perceived level of simplicity and reduced maintenance requirements compared to traditional evaporators. In addition, the technology utilises primarily a constantly available (renewable) energy source for driving evaporation.



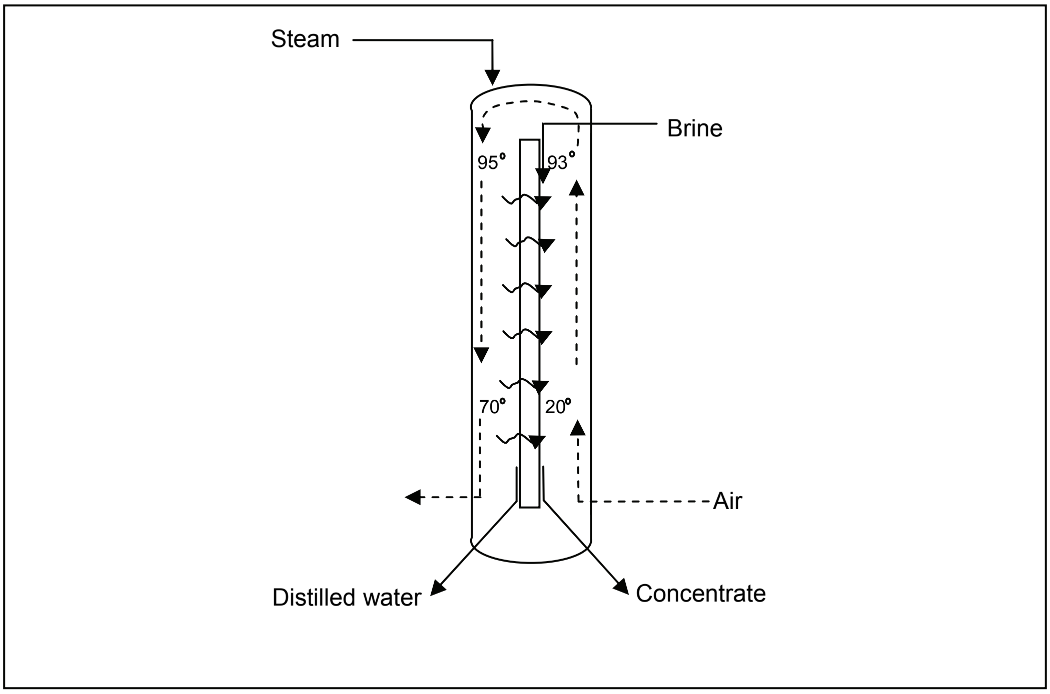
It was further confirmed that the concept is effective in operating under saturated conditions (using sodium chloride only). The pictures above show a general view of the small test unit as well as a view of one of the evaporation surfaces covered with precipitated salt crystals. Despite excellent results, the technology is still in its infancy and concerns include:

- Scaling in pipelines;
- Wind damage to equipment;
- Wind drift losses of saline feed;
- Fog harvesting;
- Salt deposition onto evaporation surfaces;
- Applicability to large scale systems;
- Applicability in areas of increased humidity;
- Theft of construction materials.

It is likely that the technology may reach full scale application in a reasonably short time. As such it is recommended that research into the WAIV technology continues.

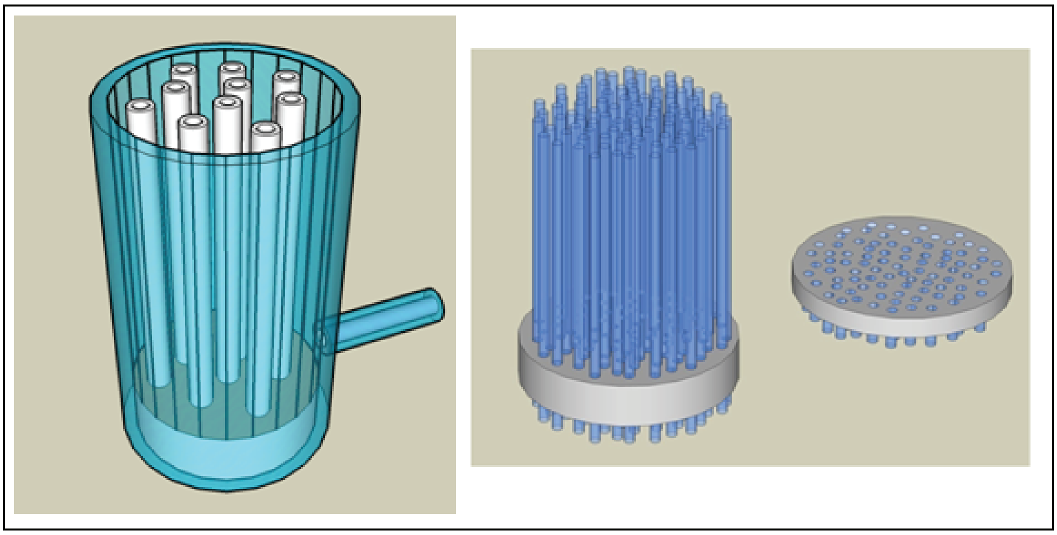
<u>Dewvaporation</u>

This technology is based on the natural cycle of humidification and de-humidification and may utilise waste heat or low energy steam to evaporate brine. Compared to traditional thermal evaporators, evaporation of water in dewvaporation occurs from the surface of the liquid and not from a highly heated metal surface. As such, it is anticipated that scaling will be reduced.

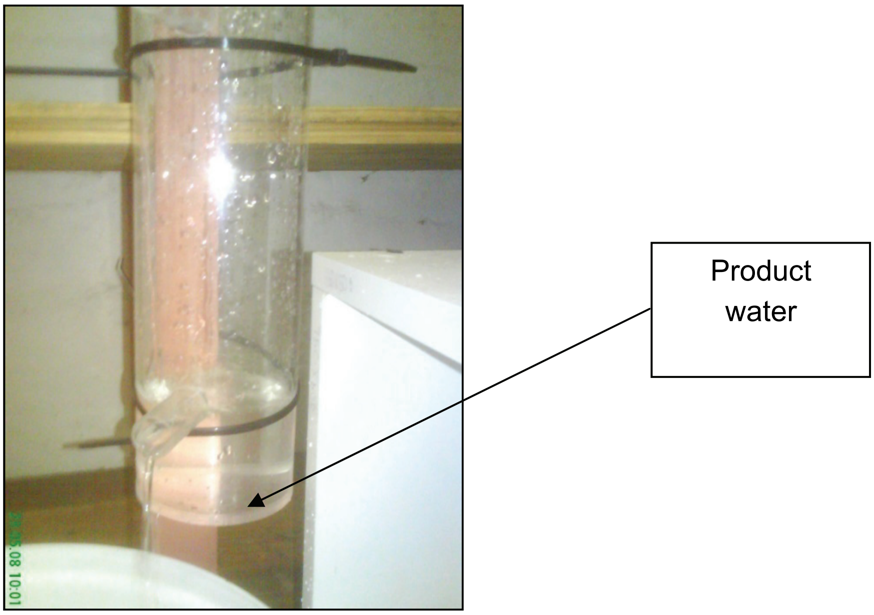


Compared to WAIV, the technology is more complex, but offers the advantage of recovering high quality water from brine streams.

As the process operates below 100ºC, a typical Dewvaporation unit may be constructed from non-corrodible materials (engineering plastics), thus reducing capital and maintenance requirements significantly. An innovative module design was developed, combining the characteristics of a shell and tube heat exchanger as well as that of a capillary ultrafiltration membrane.



Based on this concept, a small scale test module was manufactured and tested on bench scale. It was possible to produce product water of a quality comparable to mechanical evaporators. However, thermal efficiency of the test unit was low due to small size and inherent design limitations of small scale equipment. The picture below shows a general view of the bottom section of the test unit with product exiting the unit.



Whilst conceptual designs show that dewvaporation could hold significant capital and operating cost benefits compared to conventional systems, the technology requires significant additional development to reach pilot scale. The main uncertainties include:

- Materials of construction, particularly relating to wetability and thermal efficiency;
- Scaling control;
- Fluid distribution in the proposed module design;
- Cost associated in harvesting waste heat sources.

It is recommended that research should continue into these areas in order to produce a prototype for long term on-site evaluation.

Freeze desalination

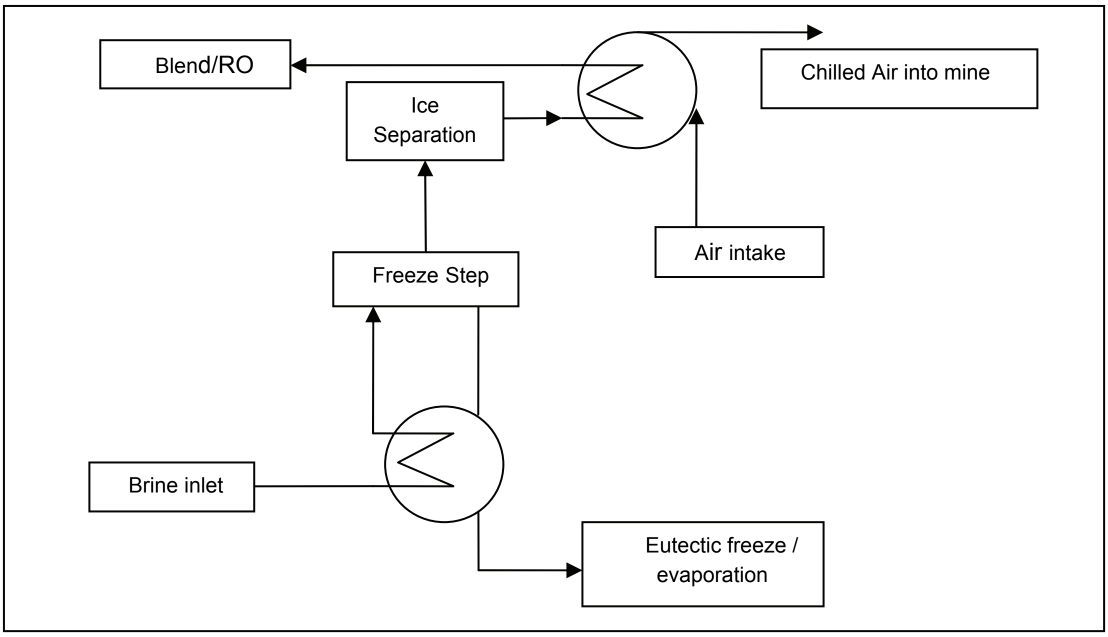
The conversion of saline water to fresh water by freezing is based on the difference between liquid water and ice in terms of salt solubility. Nowhere is freeze desalination so vividly illustrated in nature as in the production of fresh water from ice collected in icebergs.

Two primary approaches are possible, *viz.* direct and indirect freezing, with direct freezing being more efficient. Despite significant research effort in the mid 1950s to late 1980s, freeze desalination was never commercialised successfully, compared to other techniques such as RO and evaporation. The main concerns were inclusion of salt in the ice produced, resulting in the production of low quality product, as well as the efficiency of large vacuum pumps required for low temperature processes.

Lately, and due to the problems and inefficiencies associated with standard evaporative systems, freeze desalination has received increased interest, particularly for the following reasons:

- Reduced energy demands;
- Reduced corrosion at low temperature;
- Reduced risk of scaling at low temperature;
- Improved energy efficiency of large scale vacuum pumps;
- Development of freeze desalination through clathrate formation;
- Possibility of utilising eutectic freeze crystallisation to produce pure water and solid salt by-product in a single unit operation.

A further reason for investigating freeze desalination was that compared to previous efforts to produce potable water from sea water, the present focus was to only partially desalinate brine so that it may be further treated in a standard RO plant. Thus, the main focus of freeze desalination in brine treatment is the removal of the bulk of the osmotic pressure in order to further reduce brine volumes by RO – see illustration below.



In the proposed concept, brine is fed to the freeze desalination unit where the bulk of the salinity is removed. This partially treated brine is routed to an RO unit for polishing, whilst the produced ice may be used to cool deep level workings of a mine by cooling intake air with the ice. The concentrate from the freeze desalination step is routed to a concentrate disposal step, which may include a eutectic freeze unit, or alternatively, a WAIV unit or evaporation pond.

To test the concept, a series of small scale tests using indirect freezing was performed. It was found that 50% desalination could be achieved using a very simple approach from a brine starting at 18900 mg/l. This increased to 87% when residual brine attached to the ice was drained under vacuum.

Actual full scale installations in the fishing industry of South Africa proved a desalination efficiency of more than 99% in a single step, if sufficient draining of residual brine from ice is allowed (I&J on West Coast of South Africa).

To evaluate options to further treat this partially desalinated brine, a theoretical simulation was performed using RO as polishing step and WAIV as final brine disposal step. Whilst the process did not achieve the target energy efficiency of 12 kWh/kl, a theoretical energy efficiency of 19 kWh/kl was achieved at lower potential capital cost than a comparative evaporator/crystalliser. It is anticipated that energy efficiency will improve with direct freeze desalination.

Comparison of innovative options with standard approaches

The following table compares WAIV, dewvaporation and freeze desalination systems with conventional base cases, namely an evaporation pond and a mechanical evaporation/crystalliser unit.

Technology	Capital cost estimate	Operating cost estimate over 20yr project life	Total cost over 20yr project life	Comments
	Rm	Rm	Rm	
Base case - evaporation pond	150-230	1.2	151-230	38.2ha double lined surface area required. This may not be practical on such a scale. The evaluation, however, provides a basis for comparision.
Mechanical evaporation and crystallisation	180	267	447	Costs excludes a final salt store. Also, no provision for disposal of purge stream for crystalliser has been allowed in the cost estimates. These aspects will increase capital costs.
WAIV	100	30.5	130.5	1.9ha of double lined surgace area is required. Whilst this is signficantly smaller than the base case evaporation pond, a 9.2ha final salt store has to be provided. Also, individual WAIV units have to be spaced which increases the overall surface area
Freeze desalination	147.8	90.9	238.7	The costs allows for anintegrated freeze desalination and is based on relatively inefficient indirect ice making equipment, polish RO unit and a final WAIV evaporation pond for final brine disposal.
Dewvaporation	44	84	128	Of all options, Dewvaporation presently holds the largest uncertainty. As such the attractive cost may be overly optimistic.

All three innovative systems compare favourably with traditional brine disposal options, specifically if the overall project life cycle cost is considered over 20 yrs.

The WAIV system offers a saving in capital cost of around R20-R100 million over 20 years when compared to the base case evaporation pond. This is despite the higher projected operating costs. The WAIV system appears to be attractive to small to medium systems, whilst application to larger systems remains to be investigated further. In particular the following should be investigated:

- Application of the WAIV system to large brine flows, with specific reference to spacing requirements in order to reduce overall footprint;
- Application to existing brine disposal ponds which require capacity expansion and the possibility of integrating the WAIV system with these ponds, using existing lined surface areas;
- Effect of wind direction on large systems.

Freeze desalination compares favourably with traditional brine evaporation/crystallisation. The evaluation was performed using relatively conservative assumptions of only 85-90% salt removal and indirect freezing systems. This may be improved further by using direct freezing methods.

Dewvaporation systems compares favourably with traditional evaporation ponds and have the additional benefit of using waste heat as energy source as well as recovery of high quality water. Water recovery is a particular benefit of this technology over WAIV where water is lost to atmospheric evaporation.

Conclusions and Recommendations for Further Research

This report reviewed the present best practises for brine and sludge disposal as well as the legal framework within which this has to be managed. In addition, a review of the potential sources for brine and sludge disposal confirmed the initial expectation that volumes of both will increase in future. In particular, the coal and gold mining industry shows the highest potential for brine generation.

In terms of the potential of by-product recovery, it is clear that with present market conditions and technology, this strategy should not be viewed as an economic justification for desalination. At best, present market/technology conditions allow elimination/reduction of long term environmental liabilities associated with brine and sludge. The most promising by-products which can be produced with relatively little risk appear to be:

- Sulphur;
- Gypsum;
- Precipitated calcium carbonate – high quality.

A number of innovative new approaches were identified with potential application/further development in South Africa. The options thought to have the highest potential are:

- Technologies and concepts based on the WAIV concept;
- Evaporation using a similar approach as Dewvaporation;
- Brine softening and recycling;
- Freeze desalination.

It is recommended that research be continued in the following areas to further develop suitable solutions to local conditions:

- In terms of obtaining a more reliable data base of brine volumes to be generated, the following is recommended:

    - The focus should be on coal and gold mines that have elevated sodium concentrations.

    - Several mines are undertaking additional work on their water balances. Data should be available within the near future that will allow far more reliable predictions to be made. However, mining is a dynamic process, so that there will always be changes in mining strategies that can affect the strategy for water management until such time as the mine is closed. It is unlikely, therefore, that a definitive prediction can be made even with new data. As such, this database should be continually updated.

- In terms of regulatory development, the following is recommended

    - That a national and/or regional approach be considered;

    - Awareness of the environmental impacts and costs of brine management should be increased;

    - Implementation and monitoring of legislation should be improved dramatically.

- In terms of further development of new technologies, the following is recommended:

    - <u>WAIV</u>

        - A demonstration scale unit for WAIV should be developed which can be tested at three sites across the country. These sites should be selected to represent the following whether extremes:

            - Dry, windy conditions;

            - Humid, relatively wind still conditions;

            - Somewhere in-between.

        - Development of strategies to prevent scaling in piping.

    - <u>Dewvaporation</u>

        - A prototype commercial module for Dewvaporation should be developed which is of sufficient capacity to evaluate:

        - Appropriate materials of construction, taking into account wetability, thermal efficiency and mechanical strength;

        - Production cost on a large scale;

        - Total cost of ownership benefits compared to traditional evaporation.

- Brine softening and recycling

  - More work is required for brine softening and recycle in terms of the following:

  - A more fundamental understanding of the impact of anti-scalants in brine treatment processes;

  - Development of strategies to prevent scaling in pipelines.

- Freeze desalination

  - Evaluate direct freeze techniques and re-evaluate financial benefits;

  - Develop a demonstration plant;

  - Continue with development of eutectic freeze desalination as alternative to traditional evaporation and crystallisation.

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LIST OF ABBREVIATIONS & ACRONYMS

AFFA	Agriculture, Fisheries and Forestry – Australia
AMD	Acid Mine Drainage
ARD	Acid Rock Drainage
ART	Acid Rain Test
ASTROP	Advanced Seeded Tubular Reverse Osmosis Process
bar(g)	Bar (Gauge) pressure
BOD	Biological Oxygen Demand
BPEO	Best Practicable Environmental Option
BWRO	Brackish Water Reverse Osmosis
$CaSO_4$	Calcium Sulphate (Gypsum)
CGS	Council for GeoScience
CO_2	Carbon dioxide
CSIR	Council for Scientific and Industrial Research
DEAT	Department of Environment Affairs and Tourism
DME	Department of Minerals and Energy
DTI	Department of Trade & Industry
DWAF	Department of Water Affairs and Forestry
ECA	Environment Conservation Act (Act 73 of 1989)
ECAA	Environment Conservation Amendment Act (Act 50 of 2003)
EFC	Eutectic Freeze Crystallisation
EIA	Environmental Impact Assessment
EPA	Environmental Protection Agency
EU	European Union
GNR	Government Notice Regulations
GRP	Glass Reinforced Polymer
H_2S	Hydrogen Sulphide
HDPE	High Density PolyEthylene
HERO	High Efficiency Reverse Osmosis
HIPRO	High Performance Reverse Osmosis
HSR	Hydrothermal Swing Reactor
ICCON	Internal Causticisation Concentrate Recycle
IDA	International Desalination Association
IPWM	Integrated Pollution and Waste Management (White Paper)
IRR	Internal Rate of Return
LCZ	Lower Convective Zone
MCPA	Minnesota Pollution Control Agency
MDG	Millennium Development Goals
Mgd	Million gallons per day
Ml/d	Mega Litre per day (volumetric flow)
MVR	Mechanical Vapour Recompression
MWD	Mine Water Drainage
NaCl	Sodium chloride
NCZ	Non-Convective Zone
NF	Nano-Filtration
NPV	Net Present Value
OSW	Office of Saline Water (Department of Interior, USA)
PCC	Precipitated Calcium Carbonate
PVC	Polyvinyl Chloride polymer
RH	Relative Humidity
RO	Reverse Osmosis

SALT	Strong Acid Leach Test
SH	Specific humidity
SPARRO	Slurry Precipitation and Recycle Reverse Osmosis
SPLP	Synthetic Precipitation Leaching Procedure
SRF	Secondary Refrigerant Absorption
SWRO	Sea Water Reverse Osmosis
TCLP	Toxicity Characteristic Leaching Procedure
TDB	Dry Bulb Temperature
TDS	Total Dissolved Solids
TWB	Wet Bulb Temperature
UCZ	Upper Convective Zone
UIC	Underground Injection Control
USDW	Underground Source of Drinking Water
USEPA	United States Environmental Protection Agency
UV	Ultra Violet
VAT	Value Added Tax
VCF	Volume Concentration Factor
VFVA	Vacuum Freeze Vapour Adsorption
VFVC	Vacuum Freeze Vapour Compression
WAIV	Wind Aided Intensified eVaporation
WDCS	Waste Discharge Charge System
WEFTEC	Environment Federation Technical Exhibition and Conference
WISA	Water Institute for Southern Africa
WRC	Water Research Council
WSSD	World Summit on Sustainable Development
ZLD	Zero Liquid Discharge

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CHAPTER 1

1. INTRODUCTION

1.1 General Pollution and Water

Water is one of South Africa's most important national resources. In a water-scarce South Africa, the availability of water will determine our country's people's health and sustainable development in the years to come. However, pervasive salinisation of South Africa's fresh water bodies threatens this resource. As far back as 1970, the creeping salinisation of South Africa's public water system was identified as the single most serious pollution threat facing the country. (Commission of Enquiry into Water Matters, 1970). This situation has only deteriorated in the intervening years since 1970 and the problem has been recognised and addressed in the National Environmental Management Act of 1998 and the Integrated Pollution and Waste Management (IPWM) paper of 2000.

Concurrently, a global paradigm shift has occurred in the approach to addressing pollution since the 1992 Rio Earth Summit. This paradigm shift has also been enshrined in the United Nations' Millennium Development Goals of 2000 and the World Summit on Sustainable Development (WSSD) of 2002 in Johannesburg, South Africa.

Also in South Africa, addressing pollution has changed from an end-of-pipe approach in combating effects and remediation, to that of an integrated approach to the whole waste life-cycle. The focus has therefore changed to that of sustainability, prevention and source control. Sustainable development has become the guiding principle in addressing and managing scarce water resources. This change was formulated in the National Environmental Management Act, 1998 (Act 107 of 1998), the IPWM white paper of 2000 and subsequent waste management bills (DEAT, 2006). An integrated management approach is therefore now part of South Africa's legislation and industry.

The integrated approach to waste management, resulting in a hierarchical approach, is schematically depicted in **FIGURE 1** below. The inverted triangle shows the diminishing brine volumes in following the brine life-cycle. The opposite cost triangle shows the corresponding cost escalation as brine is addressed later in the brine life-cycle. An integrated approach dictates that waste is first addressed at the source and prevented by avoidance, reduction and minimisation of brine, or salt load. The second step is to manage the impact by recovery, recycle and re-use of brine streams and thirdly, the remediation, treatment and disposal of brines.

The WRC has been an integral part of research into, and addressing pollution and waste control in giving expression to the philosophy of the IPWM white paper of 2000. In accordance with its mandate as the country's water-centred knowledge 'hub' building sustainable water research capacity in South Africa, the WRC is focusing on water resource management, water use and waste management. In 2005 the WRC instituted a research project to assess the current brine handling strategies and review future technologies. The current report forms part of the WRC review of new innovative technologies – available and future – to address salinity and brine streams as early as possible in the brine life-cycle.

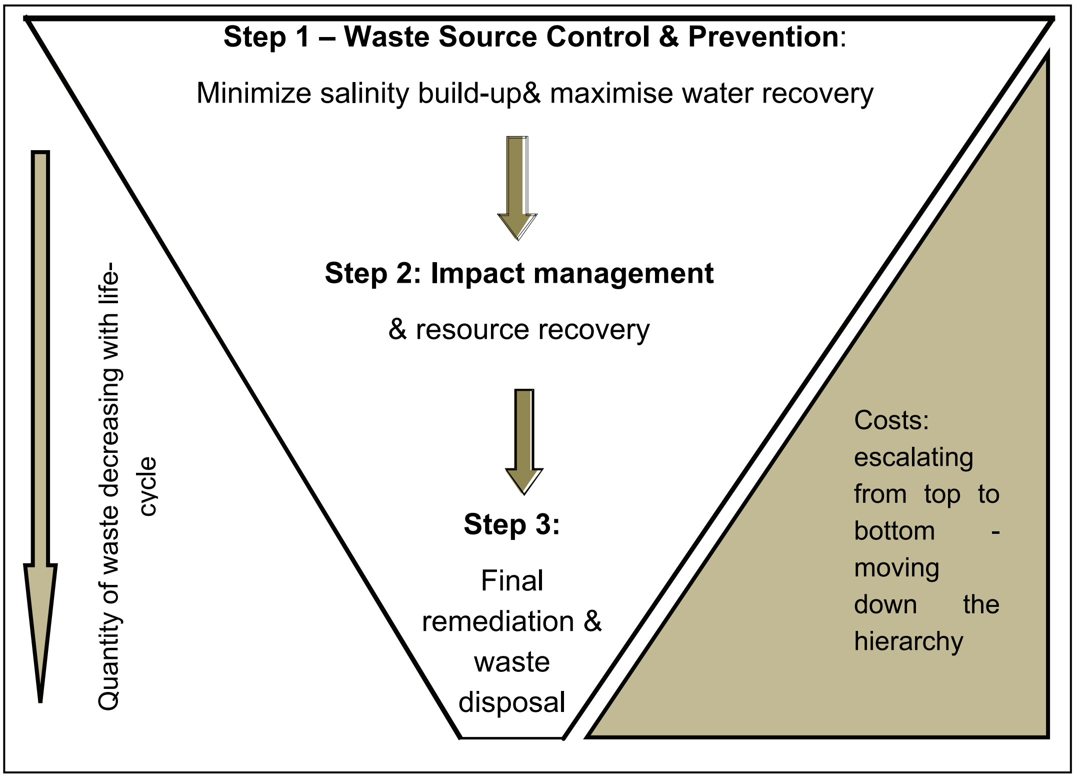


FIGURE 1. GENERIC HIERARCHY FOR WASTE (AND, SALINITY) CONTROL

1.2 Salinity Control and Water Treatment

As water resources deteriorate with global population growth, desalination is becoming increasingly part of daily water treatment requirements. Already, desalination is represented in virtually all industries, ranging from pure water applications in the pharmaceutical/medial/electronics industry to the production of potable water from brackish or sea water. It is included in the treatment of complex industrial effluents and even the reclamation water from tertiary sewage.

Inevitably, salinity control measures result again in a concentrated waste stream (brine) containing the unwanted salts to be disposed of. When the volumes of these highly saline brines are small, disposal to municipal sewer is often acceptable. However, for higher salt load applications or in more sensitive environments, different disposal strategies have to be developed. These may range from relatively unsophisticated systems such as lined evaporation ponds to complex unit operations such as mechanical vapour recompressed evaporation and crystallisation.

The hierarchy for waste disposal as discussed above can be adapted to salinity control as shown in **FIGURE 1**. Starting from the top of the inverted triangle, one starts by considering opportunities to minimize salinity build-up, both in terms of volume of saline streams as well as total mass of salts. This step is the most important activity in minimizing overall costs and represents the most sustainable route. It is also highly site and process specific with operators of each process / site having to adopt a holistic approach to optimize life cycle costs.

Once salinity build-up has been minimized, a desalination plant is frequently required to protect the environment from saline waste and recover as much as possible water for re-use. This step correlates with the second step in the integrated management approach of impact minimisation. Experience has shown that treatment and final disposal of brine and salts can amount to as much as 50% of the overall cost of a desalination facility, thus it is imperative to design the desalination facility for maximum water recovery.

To off-set some of the costs associated with brine/salt disposal, significant development effort is being directed at brine beneficiation and resource recovery. To date, these developments have been met with limited commercial success, owing to the fact that brine inherently consists of a watery solution of low value waste products with limited marketability. In addition, markets for by-products frequently do not form part of the core focus of owners of the desalination facility, thus requiring a different commercial model. However, as environmental pressures continue to rise, technology and markets develop, more innovations in this regard may be expected, which may lead to very exiting secondary developments in desalination strategies.

Finally, in all desalination processes, it is realistic to expect a small waste or purge stream. These streams are frequently highly concentrated and should be managed in a careful and sustainable manner. Presently, the standard practise is to dispose of these salts to evaporation dams or formal waste disposal sites. Associated salt/waste disposal costs can frequently be prohibitive.

1.3 Project Focus

In the broadest sense, this project considers innovative means for the management of brine. Such brines can originate from almost any salinity control activity, such as:

- Process bleed streams;
- High salinity effluents;
- Cooling tower blow down;
- Boiler blow down;
- Concentrate from desalination facilities, such as:
    - Ion exchange regeneration effluent;
    - Concentrate from membrane based desalination processes;
    - Concentrate from mechanical evaporation plants;

Despite the diverse methods for salinity control, reverse osmosis – more than any other technology at present – frequently forms the basis for active strategies to control salinity build-up in process facilities or for protecting the environment. In South Africa, this can be clearly observed in cases such as the treatment of acid mine drainage, cooling tower blow down at power stations and at major industrial installations. Therefore, in order to address the major concerns of industry and to create a singular focus for the project, the following relatively narrow definitions were adopted to guide the research in this project:

Desalination Refers exclusively to the use of reverse osmosis (RO) for salinity removal from water and waste water;

Brine Refers to a concentrated watery solution, typically containing 1-6% of dissolved low value salts, emanating from the RO process;

Sludge Refers to a suspension of solids, typically from 1 to 10% of solids, but varying significantly, depending on the nature of the solids.

1.4 Brine Disposal – a Global Perspective

Since its introduction in the late 1950s, the use of desalination technology has increased exponentially and on a global scale. For the past 20 years, growth in desalination of brackish and seawater for potable and process purposes has rarely been less than 10% per annum. Today, it is estimated that more than 45 million cubic meters desalinated water is produced daily from saline water and waste waters (IDA, 2006). Of this, the vast majority (83%) is seawater desalination applications, whilst the rest (about 8000 Ml/d) are brackish/wastewater applications.

Presently, desalination is the fastest growing segment of the water treatment industry globally (Pankratz, 2006). The desalination market is expected to expand on average by about 12% per annum between 2006 and 2010, accelerating to above 15% after 2015 (Gasson, 2006). See Figure 2 for projections made in the IDA Desalination Yearbook, 2006- 2007. There are many reasons for this growth, the major being:

- New technology breakthroughs and technical developments;
- Improved understanding of underlying chemistry – particularly in the area of highly saline feeds;
- Increased population, coupled with a gradual decrease in fresh water quality and availability.
- Economies of scale – particularly in large infrastructure projects;
- Improved energy efficiencies;
- Better materials of construction;
- Project delivery innovations, including financial engineering and outsourcing to specialist operating firms;

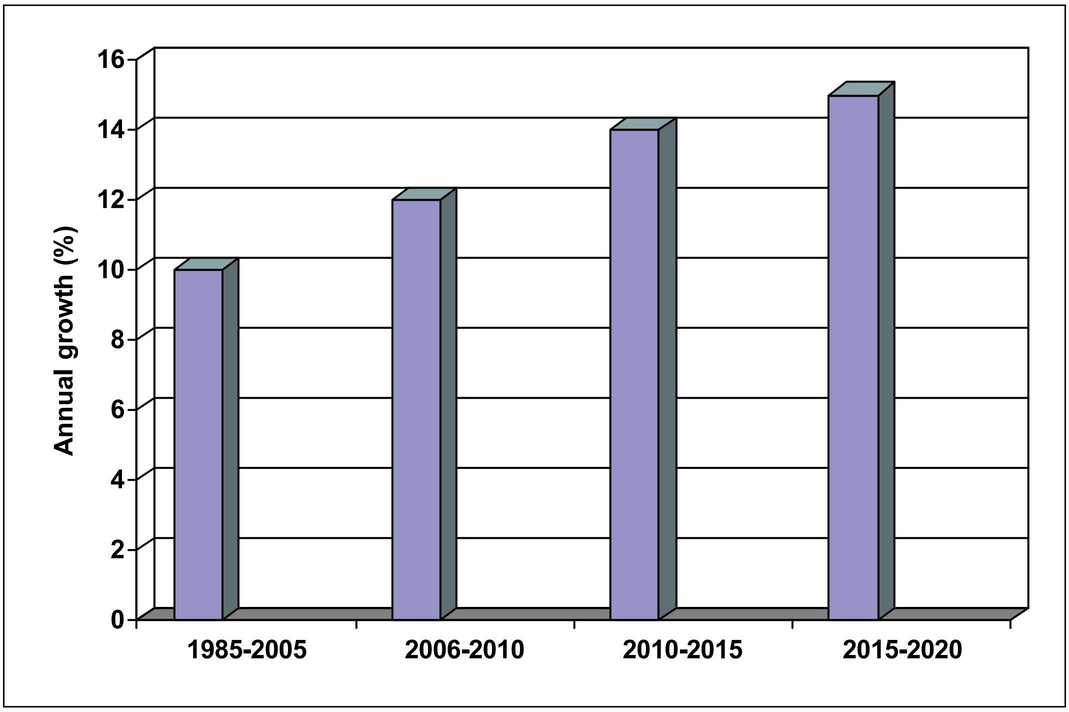


FIGURE 2. PROJECTED GROWTH IN DESALINATION MARKET (IDA, 2006)

Disposal of salts removed in desalination processes will thus become increasingly important, particularly with regard to inland desalination processes. This was clearly illustrated as far back as 2001 by Black & Veatch engineers in a paper presented at WEFTEC, which concluded that brine disposal has become one of the most important areas of research in desalination technology and that new technologies are urgently required to improve the overall economics of brine disposal (Scalan, 2001).

1.5 Brine Disposal – a Southern African Perspective

In Southern Africa, the first desalination plants were installed in the early 1980s, and mostly on relatively small brackish water reverse osmosis plants to produce potable water. Since then, a large number of membrane desalination plants were installed, ranging in capacity from only a few kiloliters per day to several mega-litres per day. Today, the major desalination applications in the region may be summarised by **TABLE 1**.

TABLE 1: SUMMARY OF PRESENT DESALINATION MARKET IN SOUTH AFRICA

Potable water applications	**Industrial water applications**

• Small units (**100s** of kl/d)
• Remote areas
• Design strategy:
  • Simplicity
  • Cost
	• Medium sized (Ml/d range)
	• Built-up areas – high land cost
	• Support infrastructure available
	• Design strategy:
	  • Efficient resource use
	  • Environmental protection

Sea water desalination • Poorly developed • Presently small plants only • Potential for few large regional plants • Marine brine disposal • Excluded from study	**Brine disposal** • Most desalination plants in-land • Water scarce country • Pressure to balance environmental protection and socio-economic development.

1.5.1 Potable water applications

These plants are generally relatively small in size – typically producing not more than a few 100 kl/d of potable water from brackish borehole water. The plants tend to be in remote villages dotted throughout the South African region with relatively low population density and rainfall. A significant number of these installations have been reported to date, and considering the relatively fast development and low annual rainfall of several of the SADC countries, it is expected that the number of these installations will increase in the foreseeable future. As such, these applications were included in the study.

1.5.2 Industrial applications

These plants typically vary in size from a few 100 kl/d to several 1000 kl/d and are primarily used for producing high quality process water or treatment of contaminated effluent from industrial/mining activities. Installations are generally situated in developed areas within economically significant regions of South Africa. Considering the size, number and locations of these plants, this is the most important category of installation in terms of this project.

1.5.3 Sea water desalination

This is not a well developed application in the region due to sufficient alternative water sources at present. To date, less than 10 seawater installations are operational in the region, all of which are very small in global terms. However, it is expected that more desalination plants will be built over the next decade due to development and environmental pressures. To illustrate, a 50 Ml/d seawater desalination is presently under construction close to Walvis Bay in Namibia. This plant should be operational in 2009.

Generally, desalination installations situated on the coastline discharge brine into the near shore and desalination industry specialists agree that, whilst not without risk, this is the most appropriate disposal method. As such, this type of installation is excluded from the present study.

1.5.4 Brine disposal

South Africa faces a unique situation in that most industrial and mining activities are situated in-land, thus requiring specific brine disposal strategies. As South Africa is a water scarce country, it is the responsibility of engineers and owners of desalination plants to ensure that water recovery is maximized. Furthermore, regulators should balance the requirements of protecting the environment with demands to develop the region and create additional job opportunities.

1.6 Project Aims

In 2005, the WRC initiated a research project to address some of the above issues. The objectives of this project may therefore be summarised as follows:

1. Evaluate the current and projected sources of brine and sludge. This information was used to guide the research in terms of high priority needs and opportunities;

2. Summarise the legal framework within which desalination and disposal of brine and sludge has to take place in South Africa. This should provide an indication as to any development opportunities in the legal/regulatory arena;

3. Evaluate present brine and sludge management strategies with a view to identify present best strategies. This review included not only local practises, but international practises as well.

4. Investigate and identify innovative approaches to brine and sludge management;

5. Compare innovative concepts with current best practises in order to identify those concepts which should be investigated further;

6. Perform a more detailed evaluation on promising innovative concepts in order to identify those which should be investigated further;

7. Perform proof of concept testing on the most promising innovative concepts;

8. Identify future research needs.

1.7 Project Approach

Brine management is a global challenge receiving much attention with a large number of researchers working concurrently on a variety of solutions. Already the pace of new innovations in the field published has increased significantly, with several proprietary process flow schemes developed on a regular basis. Each application with its particular circumstances is unique. Whilst the project aimed at identifying the major trends and technology options, the project team acknowledges that many opportunities may exist which may not necessarily have been specifically dealt with in this report. Rather, it is hoped that this document will contribute to further technological development.

Brine management, treatment and disposal are real life, urgent problems, for a number of industries in South Africa. Therefore, the project took a pragmatic approach, rather than adopting a more theoretical focus, with a primary objective being the identification of high priority opportunities coupled with longer term sustainability.

Firstly in chapter 2, and in order to understand the energy requirements for different brine treatment options, the minimum energy required for desalination was calculated from first principles. This was considered important in the light of the global focus on energy efficiency and associated carbon dioxide production.

Secondly in chapter 3, and in line with the "market focus" of the project, a review of the present and expected brine sources was undertaken. This was followed by a review of sludge disposal techniques which could be applied to desalination sludge.

Thirdly in chapter 4, the legal framework in which desalination and brine management has to take place in South Africa is summarised. Regulating authorities have an important responsibility to review, manage and approve responsible desalination initiatives, and should balance environmental protection requirements with development and commercial needs.

Chapter 5 details a literature and market study that was then undertaken to identify present strategies for brine and sludge management/disposal in order to identify present best practices and identify innovative approaches. From this, a selection of innovative techniques which compared favourably to present best practises for the bulk of South African brines was selected. These can be viewed in chapters 6 and 7. In order to compare these innovative options, a conceptual design was performed for a 1 Ml/d brine treatment plant, and the anticipated life cycle cost compared to brine ponds and mechanical evaporation/crystallisation (chapter 8).

Finally, proof of concept testing was conducted for several of the most promising techniques. This served to provide more information regarding initial process assumptions as well as further highlighting additional opportunities and research needs. The proof of concept can be viewed in chapter 9. This report is concluded in chapter 10 with a discussion of the main findings emanating from this project and in chapter 11 with recommendations for further research and implementation of its findings.

CHAPTER 2

2. MINIMUM ENERGY REQUIREMENTS AND MODELLING CAPABILITY

Process efficiency of desalination processes is generally measured in terms of water recovery and salt removal rate. However, in order to understand and compare the energy efficiency of various desalination processes, a more fundamental understanding of the minimum theoretical energy requirements for desalination is required. For the purpose of this document, the minimum desalination energy may be calculated as follows (adapted from a study by Van der Ham (1999) into eutectic freeze crystallization).

Notation used:

$\dot{Q}$	Heat	[J/s]
$\dot{W}$	Work	[J/s]
ϕ	Flow rate	[mol/s]
H	Enthalpy	[J/mol]
S	Entropy	[J/mol/K]
G	Gibbs Energy	[J/mol]
$\overline{G}_i$	Partial Gibbs Energy of component i in a mixture [J/mol]	
G^0	Gibbs Energy at standard state [J/mol]	
x_i	Mole fraction of component i in a mixture	
a_i	Activity of species i	
γ_i	Activity coefficient of species i	
u_M	molality based activity coefficient for species 'M'.	
$\overline{G}(m)_M^\infty$	molality based partial Gibbs energy for species 'M' at infinite dilution.	

2.1 Theory

The calculation of the minimum work requirements first requires a definition of the separation process. The feed to the process is always one liquid aqueous stream at room temperature and pressure. The output flow of the process always consists of one liquid, 100% pure water stream at room temperature and a "concentrate" stream. The state of the concentrate stream is defined as its thermodynamic stable condition at room temperature, ambient pressure and actual composition of the concentrate. This means that the state of the concentrate can vary with the amount of water that is present in the concentrate stream. For example, full separation of an aqueous sodium chloride solution result in one pure water stream and one pure sodium chloride stream. At room temperature and pressure, this pure sodium chloride stream has only one possible stable state: as a solid salt.

This means that the concentrate that remains after the water is removed is usually either a concentrated liquid steam or the pure, solid salt. In this work, both types are designated ‘concentrate’. In **FIGURE 3**, the separation process is depicted. The energy balance for this process (the first law of thermodynamics) may be written as follows:

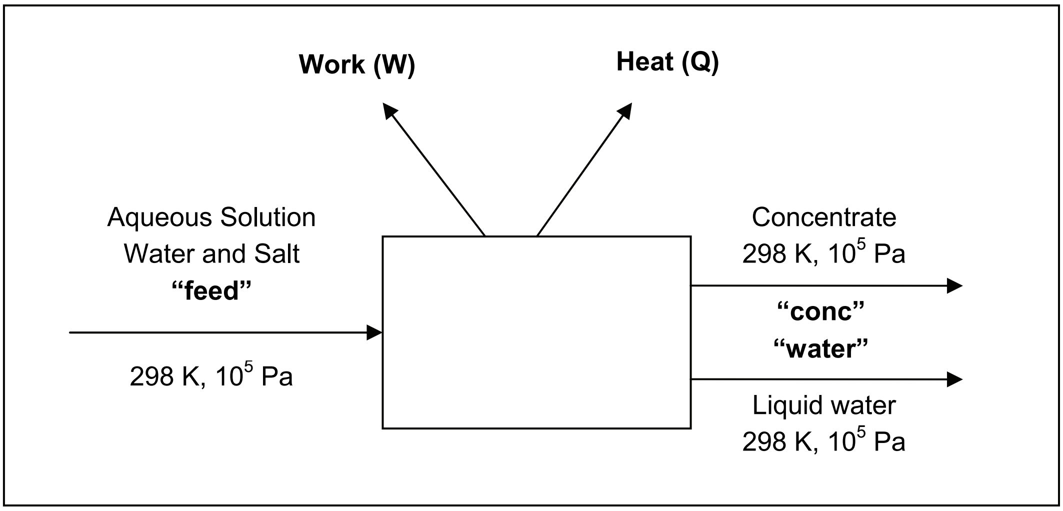


FIGURE 3. PROCESS FOR SEPARATION OF AN AQUEOUS SOLUTIONS INTO PURE, LIQUID WATER AND CONCENTRATE.

$$(\phi_{conc}H_{conc} + \phi_{water}H_{water}) - \phi_{feed}H_{feed} = \dot{Q} - \dot{W} \tag{2.1}$$

The notation of work and heat follow the convention that work is brought about by the process and heat is absorbed by the process. Historically, this convention came from “heat pumps”, devices that converts heat into work, such as a power plant converting steam into electricity. As mentioned above, the separation process is always accompanied by a work requirement rather than a work production. This means the sign of W is always negative in this study. The sign of Q is negative when heat is produced during separation and positive if absorbed.

The second law of thermodynamics dictates that any “real” process is accompanied by an increase in ‘total’ entropy. ‘Total’ entropy is the sum of the entropy changes in the observed system and the entropy change of the surroundings. For the process in **FIGURE 3**, the surroundings can only change by means of heat exchange from the process to the surroundings. Therefore, the total entropy is given by equation 2.2.

$$\dot{S}_{total} = (\phi_{conc}S_{conc} + \phi_{water}S_{water}) - \phi_{feed}S_{feed} + \frac{\dot{Q}_{surroundings}}{T_0} \geq 0 \tag{2.2}$$

Because all heat transferred from the process equals the heat taken up by the surroundings, $\dot{Q}_{surroundings} = -\dot{Q}$.

For a reversible process, there is no overall entropy generation and the equality applies in equation 2.2:

$$\dot{Q} = T_0\left(\left(\phi_{conc}S_{conc} + \phi_{water}S_{water}\right) - \phi_{feed}S_{feed}\right) \qquad (2.3)$$

Combining this with the first law (2.1) and using G = H – TS, leads to:

$$\dot{W} = -\left(\phi_{conc}G_{conc} + \phi_{water}G_{water} - \phi_{feed}G_{feed}\right) \qquad (2.4)$$

In a system with two components, water and solute, the values of G can be obtained using:

$$G = x_{water}\overline{G}_{water} + x_{solute}\overline{G}_{solute} \qquad (2.5)$$

With:

$$\overline{G}_i - \left[\frac{\partial(nG)}{\partial n_i}\right]_{P,T,n_j} \qquad (2.6)$$

For any "real" mixture, $\overline{G}_i$ is related to its composition by:

$$\overline{G}_i = G_i^0 + RT\ln(a_i) \qquad (2.7)$$

G_i^0 represents the Gibbs energy of pure species, i, in its standard state at fixed pressure P^0 and T^0 of the solution.

Using $a_i = \gamma_i x_i$ and substitution of (2.7) into (2.5):

$$G = x_{water}\left(G_{water}^0 + RT\ln\gamma_{water}x_{water}\right) + x_{solute}\left(G_{solurw}^0 + RT\ln\gamma_{solute}x_{solute}\right) \qquad (2.8)$$

The use of equation (2.7) imposes an important restriction on γ_i in view of the meaning of G_i^0. If G_i^0 is the molar Gibbs energy of pure i at [P^0,T^0], the partial Gibbs energy must be equal to the Gibbs energy of the pure specie as its fraction becomes unity:

$$x_i = 1 \Rightarrow \overline{G}_i = G_i^0 \qquad (2.9)$$

Therefore:

$$x_i = 1 \Rightarrow \gamma_i = 1 \qquad (2.10)$$

2.1.1 Separation of a binary feed into pure products

For a "conc" stream, this leads to x_{solute} = 1 and x_{water} = 0 and for the "water" stream to x_{solute} = 0 and x_{water} = 1. Or: $G_{water} = G^0_{water}$ and $G_{conc} = G^0_{solute}$. With complete separation, the molar balances are $\phi_{water} = x_{water}\phi_{feed}$ and $\phi_{conc} = x_{solute}\phi_{feed}$. Equation (2.4) then becomes:

$$\frac{\dot{W}}{\phi_{feed}} = -\left(x_{solute}G^0_{solute} + x_{water}G^0_{water} - \left[x_{solute}\left(G^0_{solute} + RT\ln\gamma_{solute}x_{solute}\right) + x_{water}\left(G^0_{water} + RT\ln\gamma_{water}x_{water}\right)\right]\right)$$

Where:

$$\frac{\dot{W}}{\phi_{feed}} = x_{solute}RT\ln\gamma_{solute}x_{solute} + x_{water}RT\ln\gamma_{water}x_{water} \tag{2.11}$$

2.1.2 Separation of aqueous electrolyte solutions

In electrolyte systems, the use of equation (2.7) raises a problem in the choice for the standard state G^0_i for the solute. For water, the standard state is the Gibbs energy of liquid water at the desired temperature (298K) and pressure (P^0). For a salt, e.g. sodium chloride, the standard state would be pure NaCl at 298K and P^0, which is an unstable condition. The standard state for solutes is therefore taken as the partial Gibbs energy for a hypothetical solution in which all interactions between ions due to their charge, size and other relevant properties are absent. Because electrolyte solutions are non-ideal systems due to the strong ion-ion and ion-water interaction the partial Gibbs energy of the solute approached the standard state only when its concentration approaches zero, i.e. at infinite dilution:

$$\overline{G}_{solute} = \overline{G}^{\infty}_{solute} + RT\ln\left(\gamma_{solute}x_{solute}\right) \tag{2.12}$$

With:

$\overline{G}^{\infty}_{solute}$: partial molar Gibbs energy of a solute at infinite dilution

$$x_{solute} = 0 \Rightarrow \gamma_{solute} = 1$$

The use of the mole fraction x_{solute} also raises a problem with electrolytes. Salts are always water soluble to a certain extent and dissociate at least partially into two solutes, cations and anions. It is an experimental impossibility to measure the $\overline{G}_{solute}$ varying the mole fraction of one ion while keeping its counter ion fraction constant.

For a completely dissociated salt $M_{v1}X_{v2}$ the partial molar Gibbs energy is related to the Gibbs energy of the cation and anion:

$$\overline{G}_{MX} = v1\overline{G}_M + v2\overline{G}_X \tag{2.13}$$

We now introduce a concentration scale more convenient in electrolyte modelling: molality (mol/kg water), symbol m. The partial Gibbs energy of a cation 'M' is now related to its molality as:

$$\overline{G}_M = \overline{G}(m)_M^\infty + RT\ln(u_M m_M) \tag{2.14}$$

For the anion 'X':

$$\overline{G}_X = \overline{G}(m)_X^\infty + RT\ln(u_X m_x) \tag{2.15}$$

It is important to note that although the activity coefficient is different for different concentration scales, the partial Gibbs energy of the dissolved salt is not. Equation (2.13) becomes:

$$\overline{G}_{MX} = \overline{G}^\infty(m)_{MX} + v1RT\ln(m_M x_M) + v2RT\ln(m_X x_X) \tag{2.16}$$

With:

$$\overline{G}_{MX}^\infty = v1\overline{G}_M^\infty(m) + v2\overline{G}_X^\infty(m)$$

Or:

$$\overline{G}_{MX} = \overline{G}_{MX}^\infty(m) + RT\ln\left(m_M^{v1} m_X^{v2}\right) + RT\ln\left(u_M^{v1} u_X^{v2}\right) \tag{2.17}$$

The mean molality and mean activity coefficient are now defines as:

$$m_\pm = \left(m_M^{v1} m_X^{v2}\right)^{1/v} \tag{2.18}$$

$$u_\pm = \left(u_M^{v1} u_X^{v2}\right)^{1/v}$$

With $v = v1 + v2$. Equation (2.17) becomes:

$$\overline{G}_{MX} = \overline{G}_{MX}^\infty(m) + vRT\ln(m_\pm u_\pm) \tag{2.19}$$

2.1.3 Minimal work of separation for water extraction from brines

The process involves three streams: the feed, a concentrated liquid product and pure water. Equation (2.5) for these three streams:

$$G_{feed} = x_{w,F}\left(G_w^0 + RT\ln a_w\right) + x_{s,F}\left(\overline{G}_{MX}^\infty + RT\ln\left(u_{\pm,F} m_{\pm,F}\right)\right) \tag{2.20}$$

$$G_{water} = G_w^0 \tag{2.21}$$

$$G_{conc} = x_{w,C}\left(G_w^0 + RT\ln a_w\right) + x_{s,C}\left(\overline{G}_{MX}^\infty + vRT\ln\left(u_{\pm,C} m_{\pm,C}\right)\right) \tag{2.22}$$

Define ζ as the ratio of the mole flow of water produced to the mole flow of feed:

$$\zeta = \frac{\phi_{water}}{\phi_{feed}} ; \zeta \langle \ x_{w,F} \tag{2.23}$$

Using ζ , we can eliminate $x_{w,C}, x_{s,C}, \phi_{conc}$ and ϕ_{water}.

$$\phi_{water} = \zeta \ \phi_{feed}$$

$$\phi_{conc} = (1-\zeta)\phi_{feed}$$

$$x_{s,C} = \frac{1}{1-\zeta} x_{s,F} \tag{2.24}$$

$$x_{w,C} = \frac{1-\zeta - x_{s,F}}{1-\zeta}$$

To get:

$$-\frac{\dot{W}}{\phi_{feed}} = (1-\zeta - x_{s,F})RT \ln a_{w,C} + x_{s,F} RT \ln a_{MX,C} - \left[(1-x_{s,F})RT \ln a_{w,F} + x_{s,F} RT \ln a_{MX,F}\right] \tag{2.25}$$

With:

$$a_{MX,F} = (u_{\pm,F} m_{\pm,F})^{v} \tag{2.26}$$

$$a_{MX,C} = (u_{\pm,C} m_{\pm,C})^{v}$$

2.1.4 Example: Concentrating a 1% NaCl feed to 26% saturated brine

The work example is defined with weight % as concentration scale; the concentrations must first be converted to molalities. The results from the conversion and the activities are given in **TABLE 2**

TABLE 2. MOLALITY AND ACTIVITY COEFFICIENTS FOR 'FEED' AND 'CONC' STREAMS.

Stream	**Concentration**			
	W%	**M**	**xs**	**Activity coefficient u**
'Feed'	1			
Na+		0.17	0.0031	0.741532
Cl-		0.17	0.0031	0.741532
'Conc'	26			
Na+		6.01	0.0979	0.989757
Cl-		6.01	0.0979	0.989757

For NaCl, a 1-1 salt, $v = 2; u_{\pm} = u_X = u_M$ and $m_{\pm} = m_X = m_M$. Substitution of these values in equation (1.22) gives the activities of the solutes. The water activities are calculated directly with the Pitzer model.

TABLE 3. CONCENTRATION DEPENDANT TERMS OF (25L) FOR WATER AND SOLUTE FOR THE FEED AND 'CONCENTRATE' STREAMS.

Stream	$RT \ln a_{MX}$	$RT \ln a_w$
Feed	-10179.9	-14.27
Concentrate	8837.5	-683.89

The mole fraction of the 'feed' and 'conc' stream, $x_{s,F}$ and $x_{s,C}$, are given in **TABLE 2**

Table 2. The ‘yield’ ζ as defined in equation (23) equals $\zeta = 1 - {x_{s,F}}/{x_{s,C}} = 0.96823$. Substitution into equation (2.25) results in:

$$-\frac{\dot{W}}{\phi_{feed}} = 53.8 \quad \frac{J}{mol\ feed} \tag{2.27}$$

Expressed as work per kg of produced water: $-\dot{W} = 3077\ J/kg$ water.

In comparison, existing desalination techniques use significantly more energy, for example:

- Reverse osmosis can be used to concentrate a salt stream to a maximum of about 7% (typical brine from seawater desalination plants). Above this, osmotic limitations prevent further concentration. The energy requirements to achieve 7% salt in solution will be approximately 4500J/kg water. Using energy recovery devices, some of the residual energy in the brine stream may be recovered. In this instance, the net energy requirement may be reduced to about 2800-3200 kJ/kg water. This excludes transfer pumps and other energy consumers typically required on a desalination plant.

- To increase the salt concentration from 7% to 26% NaCl requires the use of thermal evaporation. Here, several options are available. The most energy efficient configurations will include concepts such as mechanical vapour recompression at significant additional capital cost. Despite this, the net energy requirement will still be in the region of 10 000-15 000 kJ/kg water.

It is clear that existing desalination techniques have poor energy efficiency, typically ranging from 15-25% compared to the theoretical amount.

CHAPTER 3

3. CURRENT AND PROJECTED SOURCES OF BRINE

For the purposes of this study, it was initially proposed that all brine and sludge produced in the country should be considered, excluding sewage sludge. With this as basis, a range of industries and mining operations were consulted to determine where various waste streams are produced, the typical volumes, and the nature of the waste streams.

From this data, high priority industries and geographical regions were identified in order to direct research into appropriate brine management techniques.

Within the time frame and available project budget, it was not possible to calculate water balances and potential surpluses for mines or industries that had not already undertaken some background work. While every effort was made to consult with as many companies as possible, in some cases the project was hampered by either a lack of data or an unwillingness to release that data. In such instances, some broad assumptions have been made, and these are documented in the data presented in Appendix A.

3.1 Methodology

Industries targeted as part of this study that are known to produce brine or sludge, or that have the potential to, are:

- Paper & Pulp/Wood
- General Packaging
- Steel/Metals Processing
- Petrochemical
- Power Generation
- Mining – Platinum
- Mining – Gold
- Mining – Coal
- Other

Industries under “Other” include:

- Chemical suppliers
- Manufacture of dairy products

- The sugar industry
- Canning
- General food
- Animal nutrition
- Poultry and meat
- Juice processing
- Textile
- Waste management
- Fish processing

Information on the current, 5-year, 10-year and 20-year volumes was determined by contacting individuals within the various industries. Fortunately, work in the mining industry was been undertaken in parallel with this study, and information was obtained for the Olifants River catchment from a project commissioned by Anglocoal and BHP Billiton undertaken by Golder & Associates. Similarly, the Council for GeoScience (CGS) provided information in a broad overview for the Western basin of the mining around Johannesburg.

It will be appreciated that there are numerous factors that affect the volumes of brine and sludge that may result from a particular industry or process. For example, in the mining industry: -

- While water make is largely a function of the area of disturbance, it is strongly influenced by rehabilitation issues (such as rehabilitation backlogs, the thickness of capping of spoils), the nature of mining (opencast, underground, stooping), and numerous other factors, so that a detailed knowledge of each mine is required to predict the long term water make;

- Many options remain in terms of managing a water make, such as using storage within mined out areas, and the water use of the mine itself (particularly coal washing activities);

- Within the gold mining industry, decisions around reworking of old tailings can require significant volumes of water, thus potentially utilising the water make generated through mining;

- Once a treatment plant becomes part of the overall water management strategy, the volumes and nature of the brine and sludge are highly dependent on the water chemistry (particularly if the water is high in sodium or not), and the final water requirements. If process water (for the coal washing plant) is to be produced by the water treatment plant, the volumes of brine may decrease significantly, since the water quality requirement for process water is significantly poorer than that required for potable purposes.

The assumptions used in determining brine volumes are thus relatively broad, and until each industry is able to provide reliable site specific data, the volumes will probably remain relatively uncertain. However, it is considered that the data is the best estimate at this particular point in time.

3.2 Key Assumptions

- Where detailed water balances are not available, operational water make from active opencast mines would be around 20% of rainfall, reducing to around 12 to 14% post closure. For underground mines, a water make of 2% of rainfall was assumed (bord and pillar);

- From water treatment plants, an efficiency of 95% has been used to determine the volumes of brine from mining applications;

- For industry, only available data was used on brine production, since the efficiency likely to be achieved will be very site specific;

- Sludge volumes were estimated at 10% of the brine volume (where detailed information was not available).

3.3 Presentation of Results

Overall, 268 companies were contacted. From this, a total of 185 positive responses were received (69%).

TABLE 4 summarises in broad terms the anticipated present effluent and salt load from the various industries contacted.

TABLE 4: SUMMARY OF CURRENT ESTIMATED EFFLUENT & SALT LOAD FROM SURVEY

Sector	Num-ber of res-pon-dents	Total effluent			Salt load to environment		
		Total effluent	Total excl marine	Portion excl marine	Total salt	Total salt excl marine	Portion excl marine
		kl/day	kl/day	%	t/day	t/day	% of total excl marine
Paper & Pulp/Wood	12	272001	89001	16.6	1440	80	7.6
General Packaging	8	1950	1950	0.4	2	2	0.2
Steel/metals processing	20	30500	30500	5.7	72	72	6.8
Petroleum	14	83900	69100	12.9	354	300	28.4
Chemical	15	13070	11070	2.1	51	44	4.2
Power Generation	13	132000	132000	24.7	158	158	15.0
Mines	17	145025	145025	27.1	350	350	33.1
Chemical suppliers	6	528	528	0.1	0	0	0.0
Dairy	5	2700	2700	0.5	4	4	0.4
Sugar	7	8100	3900	0.7	10	2	0.2
Canning	2	2200	2200	0.4	1	1	0.1
General food	16	13970	10970	2.1	11	5	0.5
Pharmaceutical & personal care	5	1430	1430	0.3	1	1	0.1
Animal Nutrition	3	1205	1205	0.2	1	1	0.1
Poultry & Meat	5	12100	12100	2.3	8	9	0.8
Beverage	24	14670	14670	2.7	11	11	1.0
Textile	3	6000	6000	1.1	13	13	1.2
Waste management	3	190	190	0.0	5	5	0.5
Fish Processing	7	220700	200	0.0	7921	1	0.1
Totals	**185**	**962239**	**534739**	**100**	**10413**	**1058**	**100**

From **TABLE 4** it is estimated that 962 239 kl/d of effluent is released into the environment. Of this, approximately 430 000 kl/d (44%) is discharged into the marine environment, leaving 534 739 kl/d of effluent which has to be managed/discharged inland. Mining (27.1%), power generation (24.7%), paper & pulp (16.6%), petroleum (12.9%) and steel/metals processing (5.7%) discharges 87% of all effluent.

It is estimated that a total of 10 413 t/d of salt is discharged to the environment, of which the vast majority (almost 90%) is discharged directly into the marine environment. This leaves 1 058 t/d of salt discharged at various inland locations. Of this, the mining sector (33.1%), petroleum (28.4%), power generation (15%), paper & pulp (7.6%) and steel/metals processing industries (6.8%) releases approximately 91% of the inland salt load.

Industries discharging into the marine environment were excluded from the present study. The main industries discharging into the marine environment are the fish processing industry and paper & pulp processors.

It is therefore clear that the major industries for which desalination presently is, or in future may become necessary, are:

- The mining sector;
- Power generation – specifically inland, water cooled coal fired power stations;
- Petroleum sector – dominated by the large inland synfuels facilities;

- Inland paper & pulp processors;
- Steel/metals processing facilities.

The mining sector may be further sub-divided into platinum, gold and coal as the major sources. This is important as the major ore bodies occur in geographically different locations which impacts on the quality and composition of the underground water.

TABLE 5 below, summarises the current, 5-year, 10-year and 20-year volumes of water, brine and sludge produced, and predicted to be produced, by each industry.

TABLE 5. SUMMARY OF WATER, BRINE AND SLUDGE MAKE BY INDUSTRY.

	Water (Ml/day)				Brine (tons/day)				Sludge (tons/day)			
Category	**current**	**5 year**	**10 year**	**20 year**	**current**	**5 year**	**10 year**	**20 year**	**current**	**5 year**	**10 year**	**20 year**
Paper & Pulp/Wood	270	270	270	270	50	50	50	50	5	5	5	5
General Packaging	1	1	1	1	0	0	0	0	0	0	0	0
Steel/Metals Processing	1	1	1	1	240	240	240	240	24	24	24	24
Petrochemical	6	6	6	6	100	100	100	100	10	10	10	10
Power Generation	32	32	32	32	1600	1600	1600	1600	160	160	160	160
Mining - Platinum	0	0	0	0	13	13	16	21	3	3	4	6
Mining - Gold	10	87	112	145	300	2610	3360	4350	30	261	336	435
Mining Coal	28	58	108	367	840	1740	3240	11010	84	174	324	1101
Other	27	27	27	27	0	2	2	2	0	0	0	0

The above information is presented graphically and discussed further below.

3.3.1 Water Make

The predicted water make for the various industries and mining activities are given in **TABLE 5.** These figures indicates the current and predicted future water make requiring treatment, that is, after the expected uses by the various industries, use of storage, etc. However, the data is a first order assessment, and does not necessarily account for all of the site specific options that may be implemented by the different mines or industries to minimise the volume to be treated.

Most industries are predicted to have a constant water production over time, the argument being that although capacity increases will occur, improvements in efficiency will probably result in a stable water consumption rate. However, the gold and coal mining sectors show increases in water treatment volumes within the next decade, but particularly in 10 to 20 years from now.

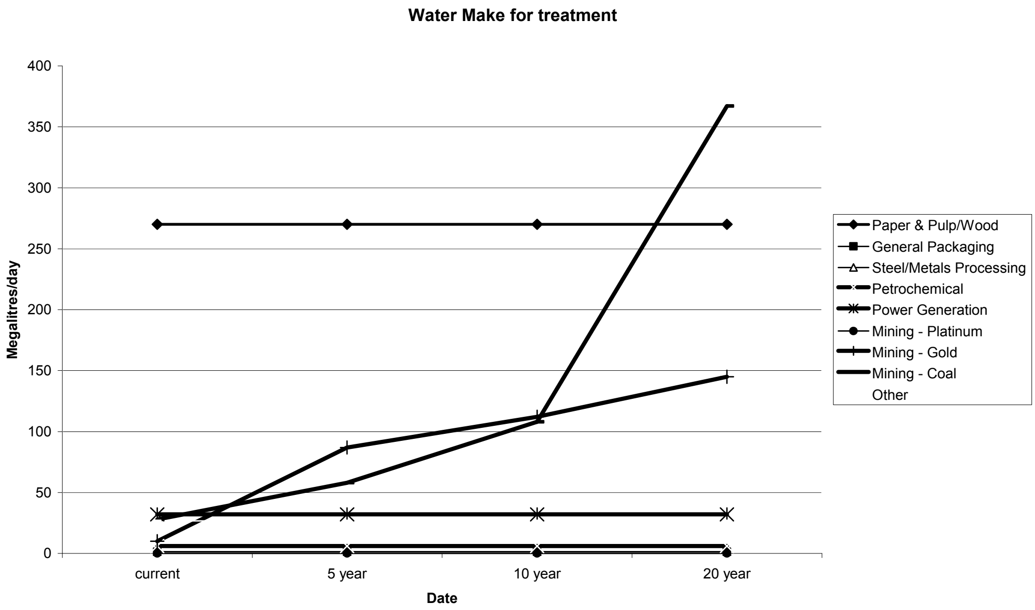


FIGURE 4. THE WATER MAKES BY INDUSTRY CURRENTLY, AND PREDICTED FOR 5-, 10- AND 20 YEARS TIME.

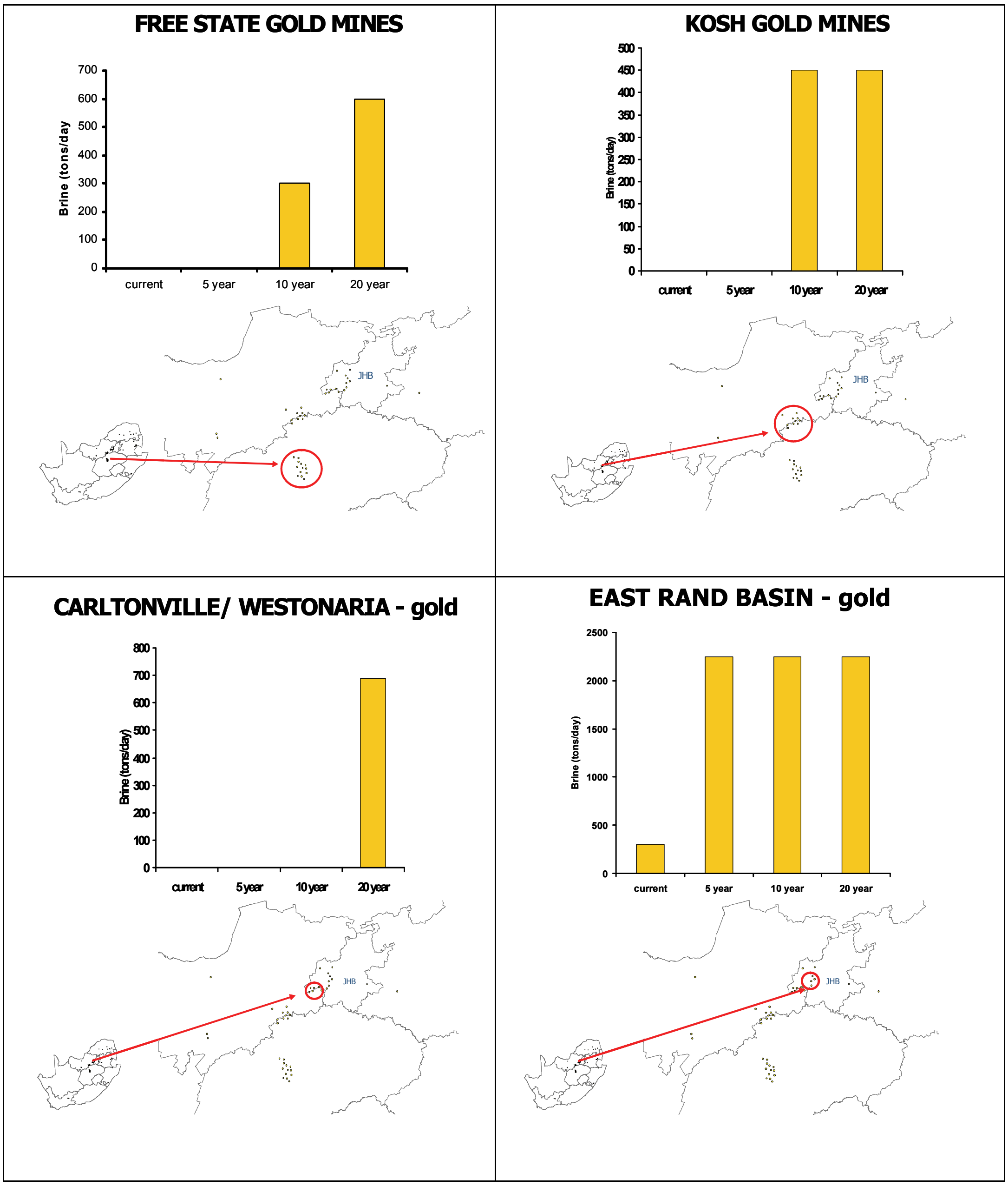
The location of the water make requiring treatment is directly linked to the predicted brine make locations, which are shown in **FIGURE 5** and **FIGURE 6.** This data indicates that there will be an initial increase in water treatment for gold mining from the defunct mines around Johannesburg (both the western and eastern mining basin), while as might be expected, the coal mining industry water treatment will be centred around the Witbank area. The coal mining is influenced by the following:

- Many mines have to date been able to utilise storage associated with mining to manage their overall water balances. Particularly underground bord and pillar mines have a relatively low water yield while forming significant storage compartments.

- Opencast mines, with significantly higher water generation than underground bord and pillar mines are more problematic to manage in terms of water. However, a combination of water reuse, controlled releases within the Loskop Dam catchment, and some storage opportunities within mined out blocks has resulted in limited water treatment to date. This situation is changing rapidly as water make increases above the water use requirements, controlled releases become less due to water quality issues, and areas used to store water (above or below ground) become full.

- A further significant factor has been the increase in opencast mining over the last few decades, greatly increasing the area of disturbance and the associated water make.

- It is important to note that in certain areas, the volumes are approximate values as highlighted previously. For example, in the case of Majuba and the Ermelo mines, the water make has been derived from approximate areas of disturbance and potential associated water make, but without any detailed knowledge of what strategies are being proposed to manage the water make, and the likely time to decant for the areas. The possibility of additional treatment for the Secunda coal field is also not excluded, but will be highly dependent on mining plans and available storage over the next few decades.



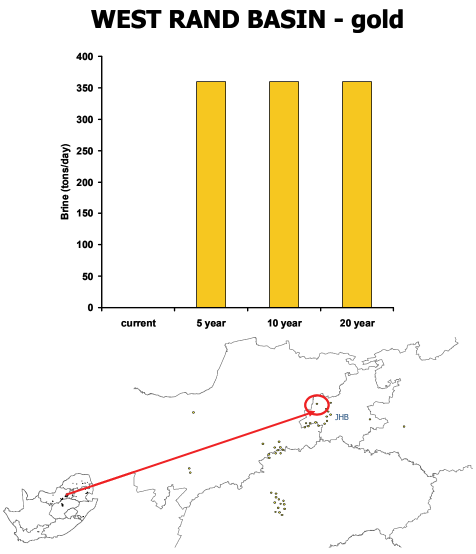
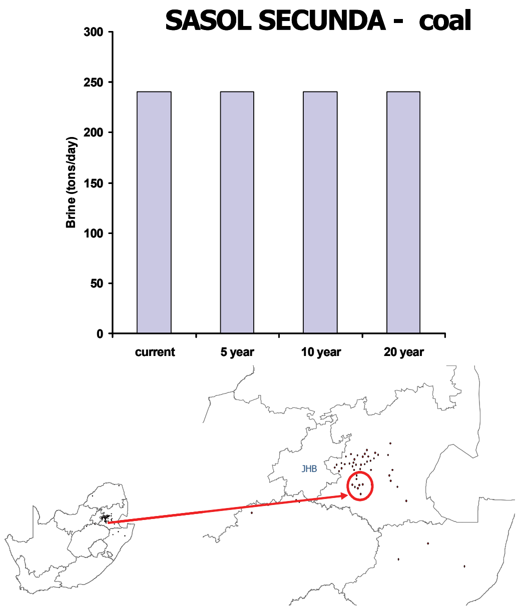
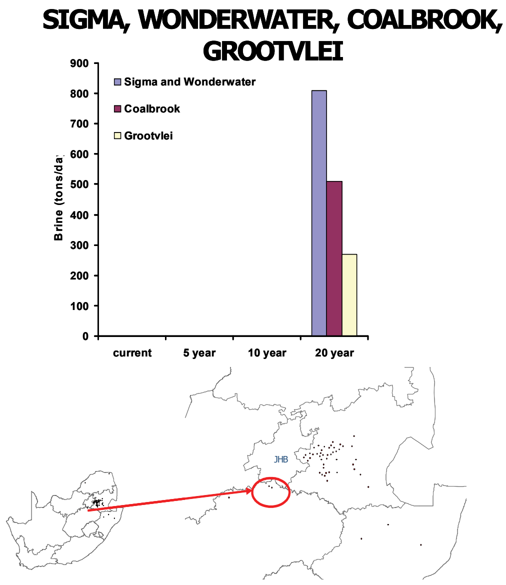


FIGURE 5. MAPS AND GRAPHS DEPICTING PREDICTED BRINE PRODUCTION IN THE GOLD MINING SECTOR.





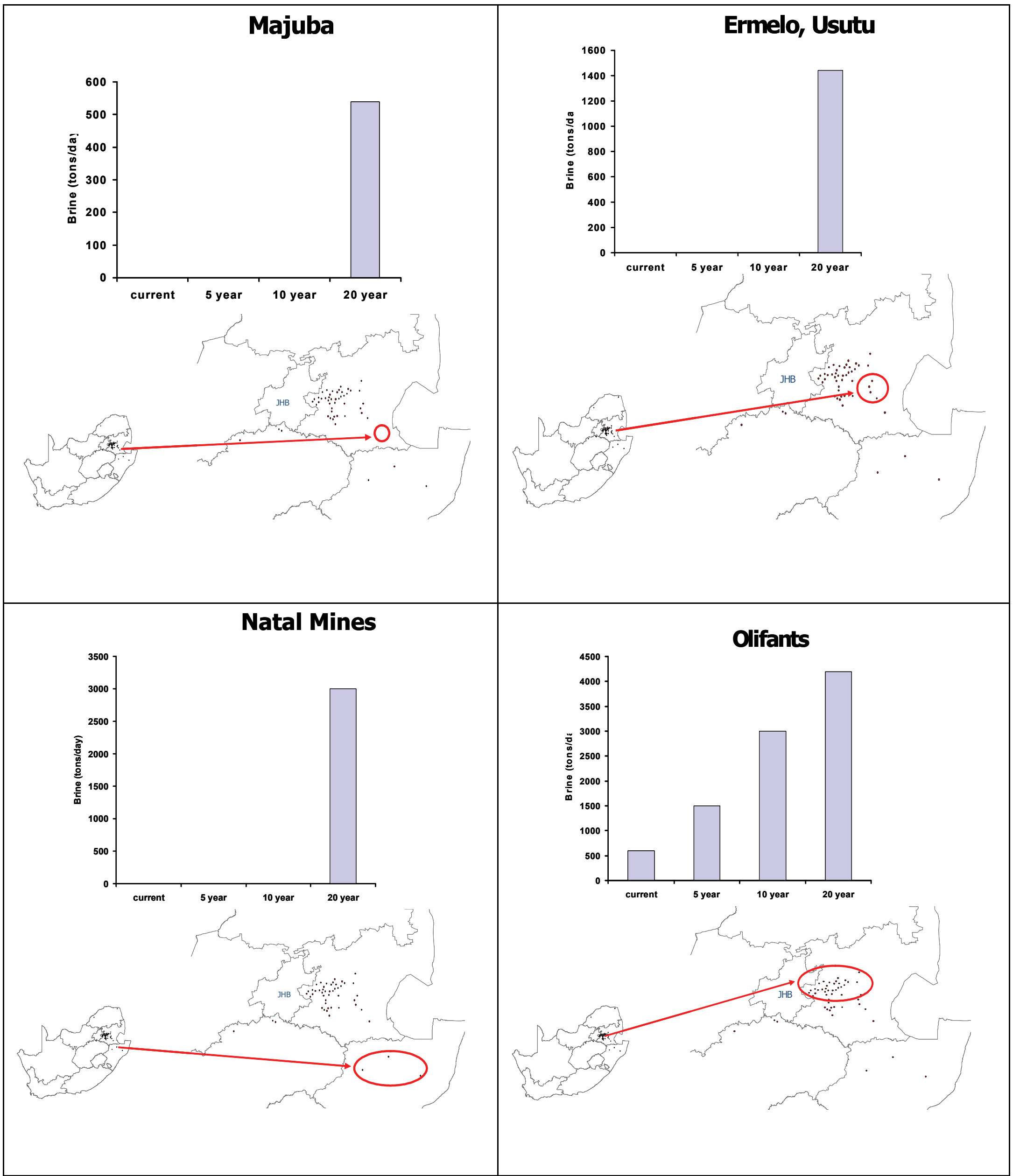


FIGURE 6. MAPS AND GRAPHS DEPICTING PREDICTED BRINE PRODUCTION FOR THE COAL MINING SECTOR.

3.3.2 Brine production

Brine production figures are given below (**FIGURE 7**).

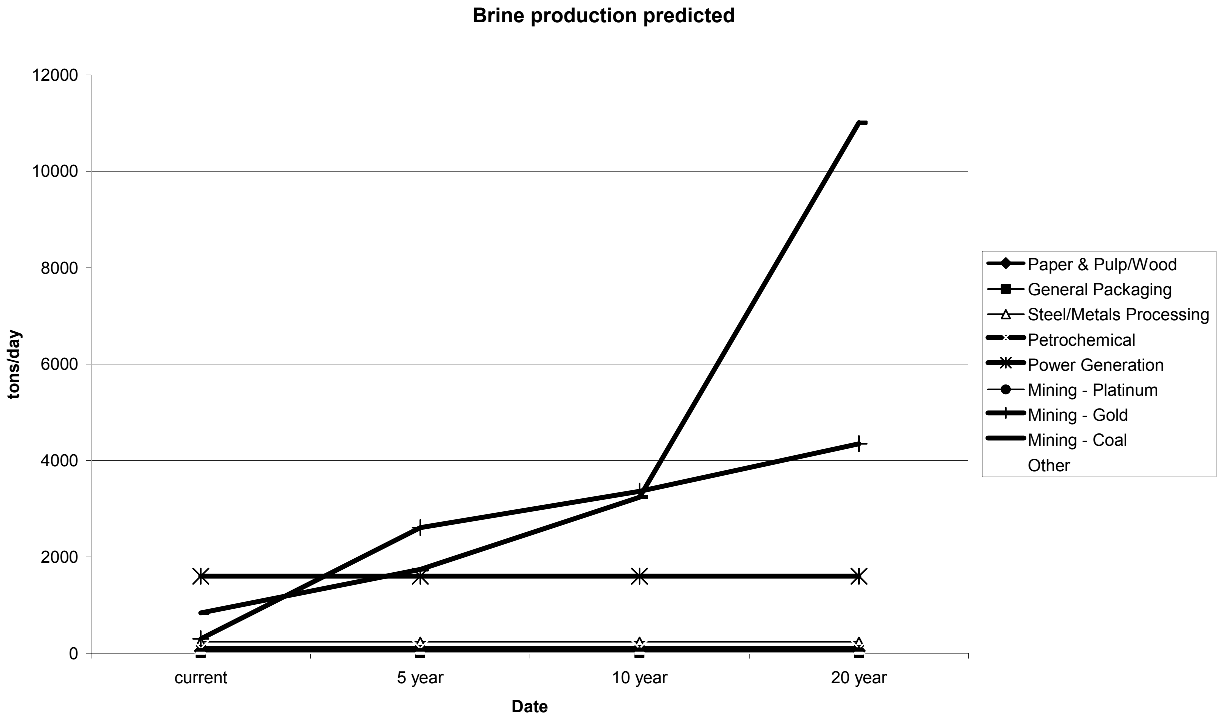


FIGURE 7. THE BRINE PRODUCTION BY INDUSTRY CURRENTLY, AND PREDICTED FOR 5-, 10- AND 20 YEARS TIME.

Most industries (excluding mining) are predicted to have a constant brine production over time. It is interesting however to note that:

- The paper and pulp industries are major producers of waste water, but generate very small volumes of brine. This is ascribed to the high organic content of the waste stream;
- In line with the expected water make increase, gold and coal mining show an increase in brine volumes. In particular, the coal mining sector is expected to increase brine production by nearly four times between this decade and the next;
- Gold mining activities are declining in some areas which is leading to an increase in decant of AMD if left unchecked;
- AMD is potentially a source of potable water but if not treated, could become an environmental disaster;
- An important point to make is that in the field of water treatment, 10 to 20 years is a long period of time. Even since the initial work undertaken for this study, efficiencies in the water treatment plants appears to have improved with an emphasis from the technology suppliers on reducing brine volumes. Efficiencies appear to be ca. 95-98% for some of the low sodium / chloride mine water, but this will not necessarily be the case for all mine water;

- The option of producing multiple streams of water as final product also influences the volumes of brine, particularly if not only potable water is to be produced. Where water is required for coal washing, it becomes possible to generate no brine, depending on the proportion of potable water produced compared to process water.

3.3.3 Sludge production

For the mining industry, the sludge volumes are highly dependent on the divalent ions and metals that can be precipitated upstream of membrane treatment systems.

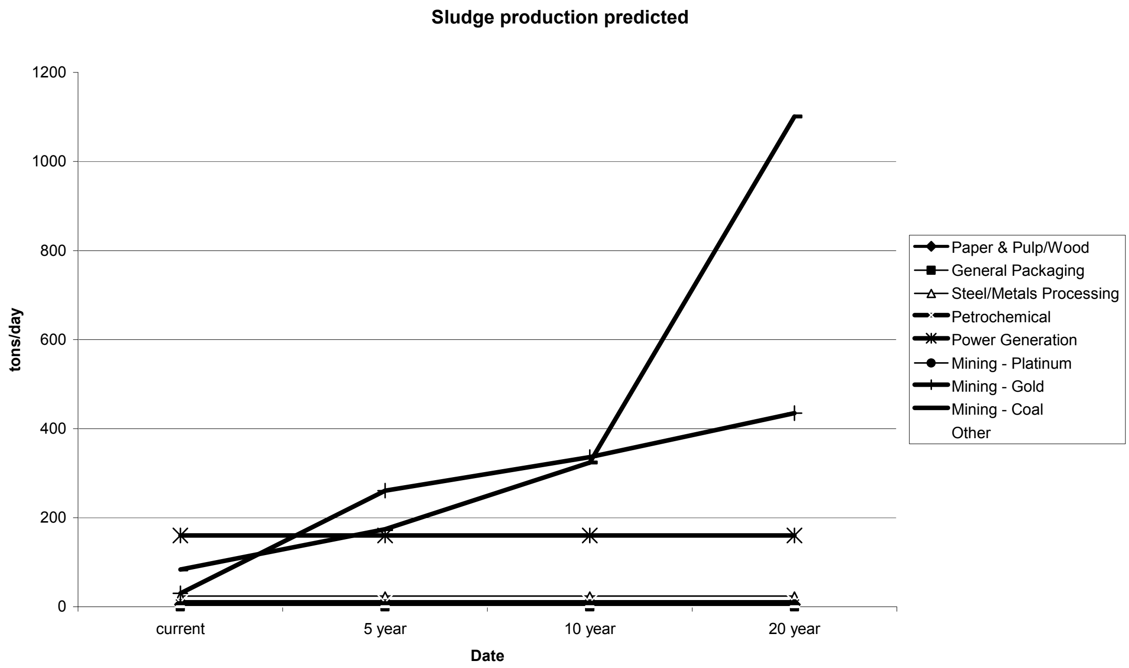


FIGURE 8. THE SLUDGE PRODUCTION BY INDUSTRY CURRENTLY, AND PREDICTED FOR 5-, 10- AND 20 YEARS TIME.

The initial estimate of sludge volumes was that, where there was no detailed information, they would be around 10% of the brine volumes. However, the estimate is very site specific, and in instances where high efficiencies are achieved thus reducing the brine volumes, the volumes of sludge appear to be very similar to those of the brine.

However, since the initial estimates have been based on an efficiency of 95%, it is considered reasonable that sludge volumes will be of the order of 10% to 20% of the brine volumes. It is also reasonable that some of this material will be marketable. Typically, for water from the coal mining industry (predicted to be a large producer of sludge), the low metal precipitate is largely gypsum, with opportunities in the building industry, use in mines as a dust-suppressant to minimise explosion risk, and various other opportunities.

Based on this, sludge volumes are estimated at 10% of the brine volumes, this being the potential volume to be managed rather than the total produced.

3.4 Discussion of Results

Given that numerous assumptions have had to be made in compiling the predictive data base, it is reasonable to question the reliability of the values generated. However, there is sufficient reliable data within the database to enable the following trends to be identified:

- The current volumes of brine estimated are around 3000 t/d. Of this, power generation is the major contributor. However, the use of ash dams as a salt sink means that most of these salts do not end up in brine ponds. Eskom and Sasol have research projects currently evaluating the capacity of ash dams to assimilate brine;

- With time it is clear that coal and gold mining will become the major source of water required to be treated. Of these two, coal mining will become the predominant contributor, largely due to the use of dragline mining techniques within the industry;

- When comparing the areas of disturbance, one would intuitively expect coal mining to become the predominant contributor of brine;

- When extrapolating the current trend, it indicates a doubling of brine volumes every 5 years in the coal mining area, from just under 1 000 t/d currently to around 10 000 t/d in 20 years time;

- When extrapolating the trend for gold mining, it is expected that significant volumes will be generated in the next 5 years in the West and East Rand basins, with some 2 600 t/d potentially being generated. The trend is not expected to increase as dramatically as for coal over the following 15 years. The volume is expected to roughly double from year 5 to year 20;

- Given the progress being made in water treatment technology, it is unlikely that the trend of brine volumes doubling every 5 years will prevail in the longer term. This is further discussed in chapters 6 and 7. Nevertheless, increases in brine volume of several thousand tons/d are likely, and this will present a challenge in terms of management;

- A particular focus that may be required in future work is to identify areas within the coal fields that are high in sodium, since these appear to be the most problematic areas at present in terms of brine minimisation;

- The trends appear to indicate that the areas around Witbank are the most significant in terms of coal mining. However, these are also the areas for which the most reliable data is available;

- As may be expected, for gold mining the current focus is on the old mining areas in and around Johannesburg, but with time the centre of gravity in terms of water generation will move to the west, and then towards the Free State mining basins.

3.5 Summary

In broad terms it can be concluded that:

- Brine volumes generated as a result of coal and gold mining will show an increasing trend over the short to medium term.

  Cumulatively, it is possible that volumes of brine from coal and gold mining activities will be generating around 4000 t/d of brine within 5 years, and as much as 15 000 t/d of brine within 20 years.

  However, technological developments and opportunities for water with low sodium concentrations make it reasonable to conclude that the volumes of brine predicted here are at the upper bound of what will eventually materialise;

- In terms of the areas in which brine will be generated, in the short term (depending on future strategies to manage the West and East Rand Basins) brine generation could be relatively evenly split between the Johannesburg area, and the Witbank area;

- However, the greatest area of increasing brine generation is expected (in the longer term) to be in the Witbank Coal Fields;

Other factors to be considered in interpreting this data include:

- The East and West Rand basins are generating water primarily from defunct gold mines. It is uncertain as to the extent to which government or the remaining gold mines will be able fund membrane technology treatment in the short term, the increasing value of water notwithstanding. This in turn will influence whether the brine volumes predicted for the Johannesburg area will materialise;

- In the Witbank area, the cost of brine disposal is resulting in considerable effort to minimise the volumes of brine. For mines with low sodium water, these opportunities are significant, and include the generation of water for process purposes in addition to potable water;

The similarity in water treatment technologies for water produced by the coal and gold mining industries offers huge benefits to technology developers in optimising processes. It is likely that developments in the field of brine minimisation and management will also be similar, albeit that there will be some differences in the chemistry and nature of the brine.

In terms of obtaining a more reliable data base in terms of brine volumes to be generated, the following is recommended:

- The focus should be on coal and gold mines that have elevated sodium concentrations.

- Several mines are undertaking additional work on their water balances. Data should be available within the next year that will allow far more reliable predictions to be made. However, mining is a dynamic process, so that there will always be changes in mining strategies that can affect the strategy for water management until such time as the mine is closed. It is unlikely therefore that a definitive prediction can be made even with new data.

- For the purposes of providing direction for the current study on innovative brine disposal and management options, the current data base is probably adequate in that it highlights the future trends for the major industries with brine production potential.

CHAPTER 4

4. LEGAL FRAMEWORK

The disposal of waste in South Africa (of which brine and sludge form a part) is covered by the following legislation:

4.1 National Environmental Management Act, 1998 (Act 107 of 1998)

The principles of waste avoidance, minimisation and re-use are enshrined in the National Environmental Management Act, 1998 (Act 107 of 1998). The act is intended to ensure that pollution and degradation of the environment is avoided and where it cannot be avoided, minimised and remedied or mitigated. The act is concerned with avoiding and minimising negative impacts on the environment and people's environmental rights. An Integrated Environmental Management approach is contained within the act to ensure that any development is sustainable. The concept of the Best Practicable Environmental Option (BPEO) is indicated as the preferred approach to environmental management.

4.1.1 EIA Regulations

The new EIA Regulations (Chapter 5 of the National Environmental Management Act, 1998) were published in Government Notice Regulations 385, 386 and 387 on 21 April 2006. An application for environmental authorisation for listed activities is required in terms of these Regulations. Distinction is made between activities requiring basic assessment and those requiring a comprehensive assessment (i.e. scoping and EIA). In terms of brine and sludge disposal: -

- A <u>Basic Assessment</u> is required for activities listed in GN R386 of 2006, or further activities identified by the Minister/MEC. These are regarded as smaller scale activities of which the impacts are generally known and can be managed. Some listed activities related to waste disposal include:

  (1)(o) Construction of facilities/infrastructure (including associated structures or infrastructure) for recycling, re-use, handling, temporary storage or treatment of general waste with a throughput capacity of 20 m^3 or more, but less than 50 tons daily average measured over a period of 30 days;

  (1)(s) Construction of facilities/infrastructure (including associated structures or infrastructure) for treatment of effluent, wastewater or sewage with an annual throughput capacity of 2 000-15 000 m^3;

  (23) Decommissioning of existing facilities/infrastructure, other than facilities/infrastructure that commenced under an authorisation issued in terms of GN385, for: -

  (d) Disposal of waste,

  (f) Recycling, handling, temporary storage or treatment of general waste with a daily throughput capacity of

20 m^3 or more, or

(g) Recycling, handling, temporary storage or treatment of hazardous waste;

(24)(c) Re-commissioning or use of any facility/infrastructure, excluding facilities/infrastructure that commenced under an authorisation issued in terms of GN385, after a period of 2 years from closure or temporary closure for facilities for any purpose/activity, which require permission, authorisation, or further authorisation, in terms of legislation governing the release of emissions, pollution, effluent or waste prior to the facility being re-commissioned;

(25) The expansion of or changes to existing facilities for any process/activity, which requires an amendment of an existing permit or license, or a new permit or license in terms of legislation governing the release of emissions, pollution, effluent.

- Scoping and environmental impact assessment is required for activities listed in GN R387 of 2006, or further activities identified by the Minister/MEC. Some listed activities related to waste disposal include:

(1) Construction of facilities/infrastructure (including associated structures/infrastructure) for –

(e) Any process/activity which requires a permit or license in terms of legislation governing the generation or release of emissions, pollution, effluent or waste and which is not identified in GN R 386;

(f) Recycling, re-use, handling, temporary storage or treatment of general waste with a throughput capacity of 50 tons or more daily average measured over a period of 30 days;

(g) Use, recycling, handling, treatment, storage or final disposal of hazardous waste;

(o) Final disposal of general waste covering an area of 100 m^2 or more, or 200 m^3 or more of airspace;

(q) Incineration, burning, evaporation, thermal treatment, roasting or heat sterilisation of waste or effluent, including cremation of human or animal tissue;

(r) Microbial deactivation, chemical sterilisation or non-thermal treatment of waste or effluent.

4.2 Environment Conservation Act, 1989 (Act 73 of 1989)

Section 20(1) of the Environment Conservation Act, 1989 (Act 73 of 1989) (ECA), states that no one may provide, own or operate a disposal site without a permit issued by the Minister of Water Affairs. However, in terms of the Environment Conservation Amendment Act, 2003 (Act 50 of 2003) (ECAA), the responsibility for the issuing of permits in terms of section 20(1) of the ECA was transferred to the Minister of Environmental Affairs and Tourism. In terms of section 20(6) of the ECA, the issuing of a permit is subject to the concurrence of the Minister of Water Affairs and Forestry. The permit should also include the conditions contained in the Record of Decision from the Minister of Water Affairs and Forestry.

The process for applying for a permit and the investigations that needs to be conducted as part of this process is contained in the *Minimum Requirements for Waste Disposal by Landfill*. This document also sets out the requirements for the management and operation of disposal sites. The *Minimum Requirements for the Handling Classification and Disposal of Hazardous Waste* provides the South African waste classification system and the requirements for disposal of all hazardous waste. The *Minimum Requirements for Water Monitoring at Waste Management Facilities* indicates the requirements for water quality monitoring at disposal sites. Authorisation, construction and operation of sludge treatment and disposal facilities should comply with these requirements.

4.3 National Water Act, 1998 (Act 36 of 1998)

The purpose of the National Water Act, 1998 (Act 36 of 1998) is to ensure the protection, use, development, conservation, management and control of South Africa's water resources.

Section 19 of the Act requires that pollution of the water resource be prevented, or that the effects of pollution be remedied through the implementation of appropriate measures by the person who owns, occupies, controls or uses the land.

Section 21 defines water uses which have to be licensed in terms of the Act. The water uses related to the disposal of waste are:

- The discharge of waste or water containing waste into a water resource through a pipe, canal, sewer, sea outfall or other conduit (section 21(f));
- The disposal of waste which may detrimentally impact on a water resource (section 21(g)); and
- The disposal of water which contains waste from, or which has been heated in, any industrial or power generation process.

The Department of Water Affairs and Forestry (DWAF) is developing a Waste Discharge Charge System (WDCS) as part of the water pricing strategy in terms of Chapter 5 of the National Water Act. This system has the following objectives, that is, to:

- Promote sustainable development and efficient use of water resources;

- Promote internalization of environmental costs;
- Recover costs associated with mitigating resource quality impacts of waste discharge;
- Create financial incentives to reduce waste and use water resources more optimally.

Two distinct charges are envisaged:

- Incentive charge: charges that provide a disincentive to discharge waste based on the use of the resource as a means of disposing waste. This forms the basis of the WDCS aim to accomplish the resource quality objectives for a catchment; and
- Mitigation charge: charge to cover the quantifiable cost of administratively implementing measures for mitigation of water discharge related impacts.

4.4 Discussion of acts

The above acts, in conjunction with other policy documents, i.e. IPWM of 2000, Draft Waste Management Bill of 2006, Municipal Service Act, map out a road to integrated management of pollution and waste in South Africa.

The strong points of these policies are as follows:

- In the desalination industry, technology development is driven by a number of factors. Some of these are that South Africa is a semi-arid country, a significant part of our industry is in the resources sector, economic pressures, energy costs, etc. The current progressive legislation existing in South Africa is a further technology driver, and promotes technology that will answer to the sustainability objectives set out in relevant acts.
- The hierarchical approach to treatment of brine and waste is advocated in these acts which drive the industry towards sustainability.
- Classification of different kinds of waste and pollution as well as addressing smaller scale activities is adequately addressed in the EIA regulations.
- The documentation required by the legislation is very good, though burdened by significant bureaucratic processes.
- The legislation discussed above is some of the best legislation in the world in terms of its completeness and the progressive nature of it.

However, implementation of these laws still needs to be proven. To date, it is questionable if the policing of the law is adequate. The necessary capacity to implement and police the excellent legislation is as yet unproven and it is hoped that the regulatory environment will nurture capacity building and skills development matching such progressive documents. This however, requires a much deeper philosophical/socio-economical and political debate which is outside the scope of this document.

CHAPTER 5

5. CURRENT BRINE MANAGEMENT STRATEGIES

5.1 Factors influencing brine management strategy

On a global scale, brine disposal strategies vary significantly from region to region as well as between different treatment plants in the same region. A number of factors determine the preferred brine disposal option, including:

- Size of installation;
- Composition of brine;
- Physical and geographical location of the installation;
- Availability of acceptable receiving site;
- Legal/regulatory permissibility;
- Public acceptance;
- Capital and operating costs;
- Ability for future expansion;
- Long term environmental risks;
- Remedial options available in case of failure;
- Economic drivers for primary desalination application.

To date, the most important disposal strategies employed in various regions of the world included:

- Discharge to evaporation ponds;
- Disposal to surface water bodies;
- Disposal through pipelines to municipal sewers;
- Deep-well injection;
- Concentration into solid salts;
- Land application and irrigation of plants tolerant to high salinity (halophytes);

These are reviewed in more detail below.

5.2 Evaporation ponds

Solar evaporation is a well established method for removing water from a concentrated solution and has been used for centuries to recover salt from seawater.

It is generally the preferred disposal strategy in sparsely populated, arid regions where applications are mostly for (small) installations producing potable water from brackish boreholes. Factors driving installation of evaporation ponds in these areas include:

- Relatively small size of installation;

- Climatic conditions which are conducive to steady and relatively rapid evaporation rates;

- Low cost of land;

- Ease of construction, operation and maintenance;
- Except for feed pumps, no mechanical equipment or energy is required.

Often the remoteness of these installations is the major consideration in designing the overall desalination process, and often water recovery will be sacrificed in favour of a simpler and less complex design.

Evaporation ponds may be lined or unlined, although unlined ponds are only feasible in the most arid regions with relatively small installations and even then there is a risk of groundwater contamination. An example of this includes installations in Oman, Jordan and the UAE. In these countries, brine is often disposed of by discharge to wadi beds – a dry riverbed that contains water only during times of heavy rain (Mohamed, 2005). However, this practise is presently under scrutiny as studies in Gulf countries, India and elsewhere has shown significant impacts on the quality of groundwater.

Despite the advantages of evaporation ponds, they are not without disadvantages – particularly for larger installations in built-up areas:

- Land requirements increases rapidly where evaporation rate is low or the disposal rate is high. Generally, these areas have a higher population density with commensurately higher cost of land;
- To prevent contamination of ground water an impervious liner of clay or synthetic membranes such as PVC or Hypalon is required, increasing the cost further. Liners have to be mechanically strong to withstand stresses and mechanical damage during periodic salt cleaning;
- Seepage from poorly constructed evaporation ponds can contaminate underlying potable water aquifers. Seeping generally occurs along the liner joints and when mechanical damage has been inflicted to the liner. On-going monitoring is required to allow early detection of salt leakages in the liner;
- Wildlife management and protection adds to supervisory requirements;
- It is often difficult to control public access and use of fencing is not always a feasible option in low income areas due to theft of fencing materials for sale as scrap;
- There is little economy of scale;

FIGURE 9. LINED EVAPORATION POND

5.3 Mechanical evaporation

The use of mechanical evaporation techniques is well established with several major references operating throughout the world. These systems are mainly used in larger desalination systems of which the following classes are most important:

- *Production of potable water from sea water.* These systems typically form part of large, integrated infrastructure projects and are particularly popular in the Middle East with relatively warm sea water (design temperature greater than 25ºC) and increased feed salinity (36000-44000 mg/l). Thermal desalination processes presently enjoy roughly the same market share for seawater desalination as reverse osmosis (IDA, 2006). Whilst the principles of evaporation are similar as for other systems, these projects are typically custom designed and discharge of brine into the marine environment. It will therefore not be considered further in this report.

- *Final precipitation of product.* Evaporation, crystallisation and drying are standard unit operations in the chemical process industries, recovering a very wide range of products and by-products. Whilst these systems fall outside the scope of this report, it is important to note that experience gained in these applications served as basis for the introduction of the processes in the disposal of brine.

- *Treatment of concentrated industrial effluent.* These systems are typically implemented as part of a zero liquid discharge strategy in large scale industrial desalination applications. Here, the primary focus of design is the optimal use of basic resources and environmental protection. Thermal processes are largely employed in integrated systems – typically to reduce RO brine to solids. These are the only systems to be considered further.

In the case of industrial effluent treatment, mechanical evaporation/crystallisation offers the major advantage of producing a solid product – either as individual salt streams or as a mixed waste for landfill disposal. In addition, mechanical evaporation is viewed as a positive extreme in recycling and the maximum efficient use of the water source (Svensson, 2005).

Due to the nature of zero-liquid discharge facilities, it is often possible to reduce the time requirement for permitting, and generally communities are supportive of the technology (Svensson, 2005). In contrast to open evaporation ponds, it can be located in virtually any major industrialised area with vastly reduced land requirement.

Several large scale industrial treatment systems are in operation throughout the world. Ericsson (1995) describes a system at Debiensko (Poland) in which evaporation, crystallisation and fluid bed drying are combined with other unit operations such as chemical neutralisation, precipitation of hardness salts and RO to recover potable water, gypsum and sodium chloride from contaminated mine water in Poland. In South Africa (Burger, 2004) describes a similar system operated by Sasol to recover process water, gypsum, sodium carbonate and sodium chloride in an integrated process using several unit operations. In this system, mechanical evaporation treats brine from the RO process to produce solids by-products for sale.

Despite the significant benefits of mechanical evaporation of brine, there are several disadvantages, of which the most important are:

- Energy intensive, with associated production in greenhouse gases
- High capital cost resulting from the use of exotic materials;
- High maintenance requirements and low process availability;
- Skilled labour requirements;
- High operating costs.

Ericsson (1995) estimated the energy costs for the Debiensko zero liquid discharge project at approximately 0.4 kWhr/m^3 feed for the pre-treatment section, 4-5 kWhr/m^3 feed for the RO section and approximately 44 kWhr/m^3 feed for the concentration/crystallisation/drying steps. The significant energy cost for the thermal processes therefore demand that overall feed rate to this section of the plant be minimized in order to reduce the overall energy cost. This implies careful consideration of the overall process design in addition to careful supervision and control during operation.

Significant corrosion and erosion problems are created by the treatment of brine in thermal evaporations systems. Therefore, only high-grade construction materials may be used to minimize maintenance requirements and increase plant life. Typical construction materials include:

- Titanium grade 2 and 12 alloy for heat exchanger tubes and plates;
- High molybdenum steel for evaporator and crystallizer bodies – typically 254 SMO and AL6XN stainless steels;

Use of these materials significantly increases construction costs and does not automatically guarantee corrosion free operation. In addition, regular de-scaling operations and other maintenance requirements reduce overall plant availability.

As cost considerations generally rule out redundancy in these systems, alternative strategies have to be found to prevent total shut-down of the entire desalination system in case of maintenance outages on downstream evaporation/crystallisation units.

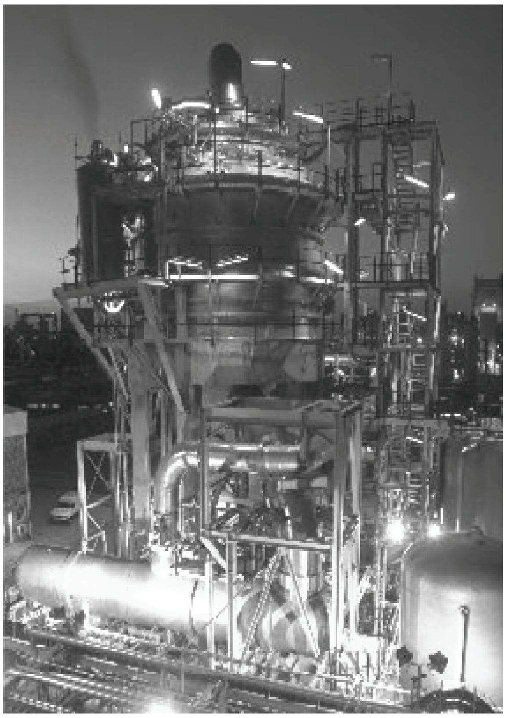


FIGURE 10. LARGE SCALE INDUSTRIAL BRINE EVAPORATOR/CRYSTALLISER (BURGER ET AL., 2004)

An important consideration in the application of mechanical evaporation is marketability of by-products – particularly with varying incoming streams such as low quality industrial effluents. This factor is described more fully later when the recovery of by-products from brine is considered.

Experience has shown that whilst several income streams may be possible, integrated zero-liquid discharge effluent treatment projects are rarely attractive as stand-alone investments. Instead, these projects tend to be strategic in nature – often with support from government or environmental agencies (Ericsson, 1996) or as part of an integrated industrial complex where the cost of capital repayment and operation represents a relatively small portion of the overall income stream.

5.4 Surface water & sewer discharge

Discharging of brine into surface water is generally only acceptable when large and rapid dilution factors can be demonstrated, and when the risk of downstream concentration impacts is minimal. This option may include discharge to:

- Sanitary sewer;
- Industrial sewer;
- Lakes & lagoons;

- Brackish lakes;
- Rivers;
- Ocean.

When available, this option is often the simplest solution in terms of equipment required and is frequently the lowest cost option. It is generally a useful option for desalination installations close to the ocean, or where inland accumulation of salts in water bodies is of limited concern.

The primary environmental concerns with this disposal option include impact on benthic life, salinity build-up and specific ion toxicity. Environmental considerations will vary significantly from site to site and will invariably be subject to a permitting process.

Sanitary sewer discharge of a small volume of brine usually represents a low risk/cost disposal method with limited permitting requirements. In addition, this option has the benefit of lowering the BOD of the domestic sewage (Ahmed, 2000). However, the increase in TDS may have a negative effect on micro-organisms in the treatment plant and may leave the treated effluent unsuitable for productive applications such as irrigation. Therefore, the adequacy of sewer capacity and wastewater treatment plant capacity to accept brines from desalination plants must be carefully considered.

As a general rule, brine cannot be discharged into lower salinity water if the resulting salinity is more that 10% higher than the upstream receiving waters (Mickley 2001). Due to the nature of RO brine, disposal to surface waters other than the ocean will thus rarely be feasible, unless adequate mixing with other water, such as treated sewage is possible. Even then, salinity build-up in dams and lakes downstream of the discharge point has to be carefully considered.

Marine environments generally require dilution to within 3-5% of background salinity to prevent acute toxicity (Clarke, 2006). Marine discharge of brine is generally not acceptable in sensitive areas such as estuaries, close to coral reefs, *etc.*

If discharge is directly to surface water, a mixing zone will be required to minimize the area of impact. Due to increased density, brine has negative buoyancy which impacts on diffuser design.

Often, the raw water feed to the desalination plant will contain heavy metals, radio-activity, *etc.* which will be concentrated in the desalination process. Often, the bulk of these contaminants are removed as part of the pre-treatment to the desalination plant. However, when brine contains appreciable levels of these contaminants, brine treatment prior to discharge may have to be performed to limit environmental impacts.

The costs for surface water discharge are influenced by a great number of site specific factors. The key factors that determine the costs of brine discharge to surface water are (Mickley, 2004):

- Conveyance costs to transport the concentrate from the desalination plant to the discharge point;

- Costs for outfall construction and operation – particularly if the brine is corrosive or highly scaling;

- Fee payable to the waste water treatment plant if brine is discharged to sewer;

- Costs associated with the monitoring of the environmental effects of the brine discharge on the surface waters.

5.4.1 Applications

- Europe

Most of Europe has an abundance of large rivers. Desalination by reverse osmosis is thus not frequently applied on a large scale. Where applied, it is mostly to remove such substances as colour, odour, hardness or microbial contaminants. Surface water discharge of brine is the most commonly used disposal strategy and large rivers are frequently used to transport salts to the ocean (Squire, 2000).

- Middle East and Australia

In the Middle East and parts of Australia, surface water discharge of brine is mostly used at seawater desalination plants where the brine is discharged to sea. Generally no surface water is available to discharge brine into resulting in large scale use of evaporation ponds.

- USA

Mickley (2001) conducted an extensive survey of membrane utility plants in the USA and

TABLE 6 shows the surface water and sewer disposal statistics for 102 utility desalination plants covered in his work. The majority of the plants surveyed treats brackish borehole water for potable purposes.

TABLE 6: USE OF SURFACE WATER AND SEWER DISPOSAL OF BRINE IN THE USA (MICKLEY, 2001)

Disposal Option	Distribution
Surface water disposal	45%
Disposal to sewer	42%
Deep well injection	9%
Evaporation ponds	2%
Spray irrigation	2%
TOTAL	**100%**

Of the plants surveyed, 30.2% was larger than 3 million gallons per day (mgd) (that is larger than roughly 11.3 mega litres per day (Ml/d)), 22.6% ranged between 1 and 3 mgd (3.8-11.3 Ml/d), 24.5% between 0.3 and 1 mgd (1-3.8 Ml/d) and the rest (22.7%) smaller than 0.3 mgd (1 Ml/d).

Unfortunately, Mickley does not identify ocean discharges specifically in his work, and it is not clear which of the plants surveyed discharges indirectly to the ocean *via* municipal sewer. However, FIGURE 11 shows that larger installations mainly use surface, sewer or sub-surface injection as disposal option. Alternatives such as evaporation and land application simply become impractical due to cost, land requirements and environmental risks.

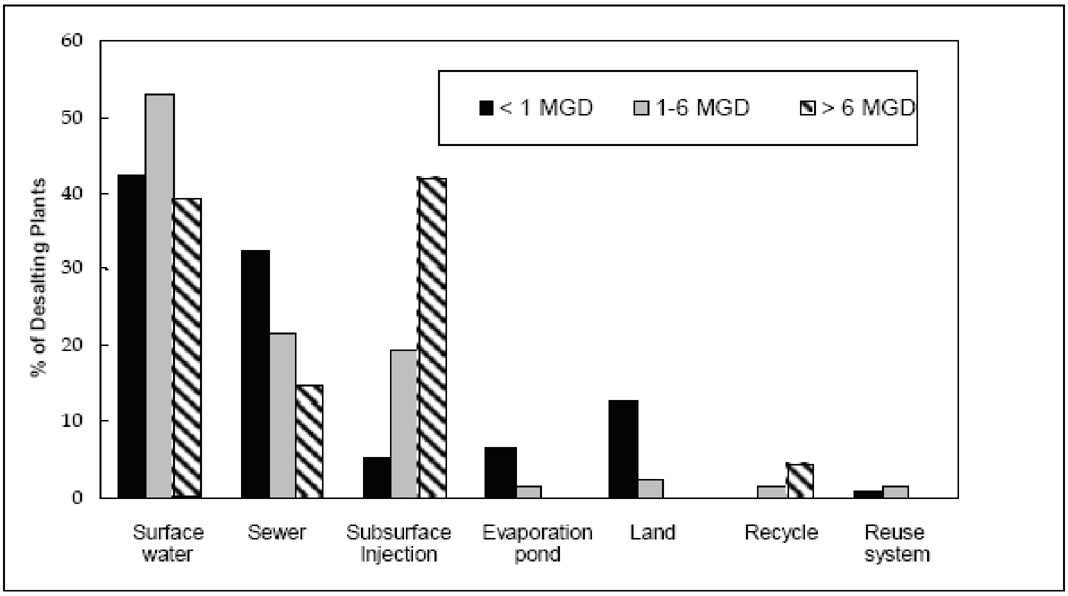


FIGURE 11. BREAK DOWN OF DISPOSAL OPTIONS IN THE USA (MICKLEY, 2001)

- South Africa

In South Africa surface water and sewer discharge for inland desalination plants is only used for small to very small installations. Discharge of larger amounts of brines will result in salinity build-up of river and dam systems.

5.5 Land application

Whilst this is not a frequently applied option, it may be considered in areas where water conservation of great importance such as in remote, desert environments (Younos, 2005). In these regions, smallish desalination plants are generally used to provide potable water for villages, whilst brine may be re-combined with (brackish) raw water for irrigation purposes.

For this approach to work effectively and be sustainable, the following important factors should be considered (Ahmed, 2000, Svensson, 2005):

- Control of total salinity;

- Site selection;
- Risk of uncontrolled groundwater contamination;
- Pre-application treatment;
- Hydraulic loading rates;
- Land requirements;
- Selection of vegetation;
- Surface runoff control.

Irrigation of concentrate may be considered as indirect ground water discharge for a portion of the flow. The brine should thus be free of substances that pose a serious danger to the public health and safety or impair the reasonable beneficial use of adjacent waters (Kimes, 1995).

For irrigation, the quality of brine must satisfy crop and soil requirements and it is not uncommon to use relatively large tracts of land to control soil salt loading. Crops such as salt tolerant grasses and halophytic trees are generally chosen for this type of application (Svensson, 2005).

Although some plants can still extract water from brine for their physiological functions, this only serves to concentrate salts even further in the remaining solution. This salt still needs to be disposed of. Land application will thus represent a sustainable use of brine only in special circumstances where excess salt is removed from the system.

FIGURE 12. FURROW IRRIGATION OF HALOPHYTIC TREES IN EGYPT (SVENSSON, 2005)

5.6 Deep well injection

Whilst not directly comparable with underground mined out areas, experience gained elsewhere with injection wells provides some valuable insights into the possible use of mined out areas as brine storage sites.

The practice of deep-well injection of liquid waste has been employed since about 1930, when oilfield brine re-injection started in the USA (Hirschberg, 1994). Today, it has become standard practice in the oil industry, and in the USA alone – where the largest amount of injection wells may be found – are some 300 000 injection wells (Mickley, 2001).

Injection wells are a disposal option in which liquid wastes are injected into porous subsurface rock formations. Depths of the wells typically range from 300 m to 2500 m. The rock formation receiving the waste must possess the natural ability to contain and isolate the waste. Paramount in the design and operation of an injection well is the ability to prevent movement of wastes into or between underground sources of drinking water (Mickley, 2001).

As fluid movement in the injection zone is very slow (as it should be), injection wells may be considered a storage method rather than a disposal method – the wastes remain *in-situ* indefinitely if the injection programme has been properly planned and executed

Because of their ability to isolate hazardous wastes from the environment, injection wells have evolved as the predominant form of hazardous waste disposal in the USA. In 1984, the United States Environmental Protection Agency (USEPA) reported that almost 60% of all hazardous waste disposed of in 1981 was injected into deep wells (Mickley, 2001). This translates to more than 35 000 Ml of hazardous waste in a single year! By contrast, only 35% of this waste was disposed of in surface impoundments and less than 5% in landfills.

Despite the vast quantity of waste being disposed of in this manner on an on-going basis, there are at least five ways waste may migrate and contaminate groundwater (Strycker, 1987):

- Escape through the well bore into an underground source of drinking water because of insufficient casing or failure of the injection well casing due to corrosion or excessive injection pressure;

- Escape vertically outside of the well casing from the injection zone into an underground source of drinking water;

- Escape vertically from the injection zone through confining beds that are inadequate because of high primary permeability, solution channels, joints, faults, or induced fractures;

- Escape vertically from the injection zone through nearby wells that are improperly cemented or plugged, or that have inadequate or leaky casing;

- Contaminate groundwater directly by lateral travel of the injected wastewater from a region of saline water to a region of fresh water in the same aquifer.

Mickley (2001) lists the major drawbacks of this technology as being the following:

- Complex and detailed process involved in selection of a suitable well site;
- Costs involved in conditioning the waste brine in order to prevent well clogging;
- Possibility of corrosion and subsequent leakage in the well casing;
- Seismic activity which could cause damage to the well and subsequently result in ground water contamination;
- Uncertainty of the well half-life which can only be estimated using mathematical simulation techniques.

As a result of the growing concern over contamination of groundwater in the United States, the Underground Injection Control (UIC) regulations were developed and included in the Drinking Water Act of 1979. These regulations were intended to strengthen existing regulations of the different states as well as establish minimum federal standards reflecting good engineering practices.

5.6.1 Classification of injection wells

In the USA, injection wells are classified into five classes (CFR, 1989 a,b). Class I wells include:

- Wells used by generators of hazardous wastes or by owners or operators of hazardous waste management facilities to inject hazardous wastes beneath the lowermost formation containing an underground source of drinking water;
- Other industrial and domestic disposal wells that inject fluids beneath the lowermost formation containing an underground source of drinking water.

Classes II to V include wells for many specific uses and different fluids. Only Class I wells are pertinent to the disposal of brine.

Class I injection wells include both industrial and municipal disposal wells that inject fluid beneath the lowermost formation containing an underground source of drinking water. Industrial disposal wells include those facilities that inject industrial wastes regardless of their corrosivity, toxicity or hazard to health. Municipal waste disposal wells are not nearly as numerous as industrial waste disposal wells. Increasingly stringent controls on discharges of sewage effluents into surface water bodies have forced municipalities to seek more effective means of waste treatment and disposal. Currently the largest, most numerous and most sophisticated municipal Class I injection wells are southern Florida, where the favourable hydrogeology makes the use of wells for subsurface injection of wastes possible.

Municipal wastewater is primarily sewage effluent that has received a minimum of secondary treatment. Municipal wastewater may contain minor contributions from non-municipal or industrial sources. For the purposes of the UIC programme in

Florida, municipal sewage effluent that contains less than 5 percent of its operating capacity contribution from non-municipal sources is considered municipal wastewater (Kimes, 1995).

Of particular importance to the classification of municipal wells is an exclusion that eliminates the tubing and packer requirement. (*A packer is a device that is placed inside the innermost casing string and holds the base of the tubing through which the fluid is injected in place. The annular space between the tubing and casing string is filled fluid, most commonly water mixed with a corrosion-inhibitor. The packer in conjunction with the tubing protects the casing from injection pressures, isolates the casing from the injection fluid and provides an additional opportunity for monitoring through the tubing-and-casing annulus.)* The tubing and packer represent additional capital outlay of some 10-15%, whilst operating and monitoring costs are expected to be higher (Kimes, 1995).

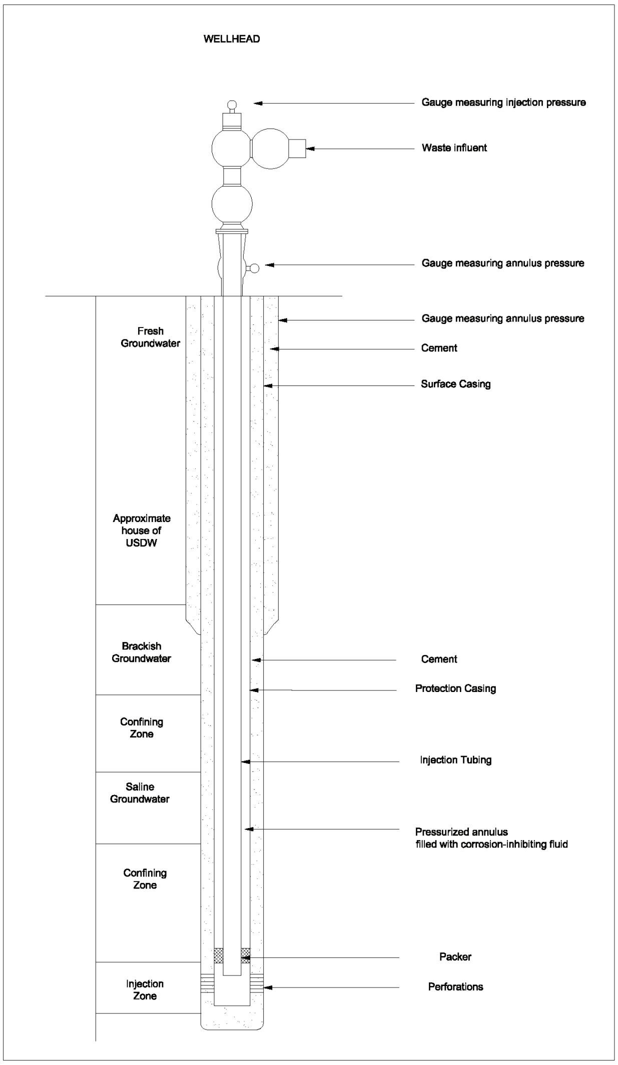


FIGURE 13. SCHEMATIC DIAGRAM OF A TYPICAL CLASS I INJECTION WELL (HIRSCHBERG, 1994).

5.6.2 Injection well design and siting criteria

Ideally, injection wells must inject water into saline ground waters that have no potential to be used as drinking water sources. The definition of a drinking water source in the USA is ground water containing TDS less than 10,000 mg/l (Kimes, 1995).

The rules and regulations acknowledge that the appropriate siting of a Class I wells are of paramount importance, and they provide a very detailed and specific set of siting criteria (Hirschberg, 1994). These may be summarized as follows:

- Injection has to take place below the lowermost known underground source of drinking water (USDW).
- The area where the well is to be located has to be geologically suitable. This requires a regional analysis of the geology, structure, hydrogeology, and seismicity; and on a local scale, all of the above, and also aquifer hydrodynamics, and an assessment of potential mineral resources.
- The injection zone should have sufficient lateral extent, permeability, porosity, and thickness to be able to store the injected waste safely for a long enough time, without the risk of fluid movement into a USDW; and the confining zone should be laterally sufficiently continuous and free of transmissive faults or fractures to prevent fluid movement into a USDW. It should contain at least one formation of sufficient thickness and with lithological and stress characteristics capable of preventing vertical propagation of fractures.
- Proof has to be provided that one of the following conditions applies:
    - there is at least one sequence of permeable and less permeable strata between the confining zone and the base of the lowermost USDW; or
    - the hydraulic head in the injection zone is, and remains, lower than that in the lowermost USDW; or
    - there is no USDW present.

5.6.3 Applications

- USA

Florida is the region with the largest number of deep injection wells – particularly due to its excellent geologic formations to support deep well injection and relative abundance of brackish water desalination plants (Svensson, 2005).

Southern California is underlain by a series of groundwater-bearing strata of cavernous limestone and dolomites separated by thick and impervious layers of marls and dense limestone. Groundwater in the deeper strata, generally at depths greater than 400 m is highly mineralized. At a depth of approximately 1000 m cavernous dolomite exists. This zone is called the Boulder Zone of the Oldsmar Formation. Water quality is poor at this depth and the zone has extremely high permeability and the capacity to receive large amounts of waste under low injection pressures. The Boulder Zone is isolated from overlying aquifers by thick, dense layers that act as barriers to fluid exchange, thus protecting the water quality from the overlying aquifers. Consequently, a number of Class I municipal injection wells have been developed in the area. The water of this zone is similar to seawater at about 35 000 mg/l (Mickley, 2001).

- Australia

In Australia, the only known Class I well for hazardous waste is at Kwinana, in Western Australia. This bore was installed in the early 1980s for the disposal of chemical waste.

In Australia, there are about 220 other wells for brine disposal and enhanced oil recovery, most of them on Barrow Island, in Western Australia. About 30 wells are known to be used for storage of hydrocarbons for later recovery. A few experimental wells are at present being used in Queensland in trial methane production from coal seams, and the hydraulic fracturing of these seams.

About 40% of Western Australia is underlain by sedimentary basins and several potential class I deep-well injection zones and areas have been identified in the Perth, Carnarvon, and Eucla Basins, using three major site-selection criteria for an initial screening.

- Middle East

Despite the large number of desalination plants in the region, no injection wells for brine disposal could be found in the Middle East, although membrane concentrate is often disposed of in shallow unlined bores (Mohamed *et al.*, 2005). This type of disposal has a significant environmental consideration and improper disposal has the potential for polluting the groundwater resources and can have a profound effect on subsurface soil properties.

- South Africa

South Africa currently has no known injection wells apart from some exploratory work on the West Coast and thus very little expertise in the construction and operation of these wells. To evaluate the applicability of deep well disposal in South Africa, the site selection criteria listed earlier should be considered carefully.

When injection wells are used to dispose of concentrate in the USA and Australia, it is usually co-disposed with municipal effluent to reduce the capital cost. This improves the economical viability of deep well disposal, but as South Africa is a water scarce country, municipal water is seen as a potential water source for industrial and irrigation use.

Instead of deep well injection, mined-out areas may potentially be used to store brine. However, underground water movement in the area will complicate this application significantly and it is doubtful if it will be possible to demonstrate a fail-safe disposal of brine in the majority of cases. A detailed review of mined out areas for brine storage is outside the scope of this project and should ideally be considered as a stand-alone project for detailed investigation.

5.7 Summary

Currently, the most important brine disposal options are:

- Discharge to evaporation ponds;
- Disposal to surface water bodies;
- Disposal through pipelines into municipal sewers;
- Deep-well injection;
- Concentration into solid salts;
- Land application and irrigation of plants tolerant to high salinity (halophytes).

In South Africa, discharge to surface water bodies, into municipal sewers and irrigation applications are not practical options, but for low salt load applications. Deep-well injection has not been explored in detail, and could still offer a disposal option. Variation on this theme – such as storage of brine in underground mined out areas has been proposed, although long term risks are difficult to quantify.

The most frequently used brine disposal options are discharge to lined evaporation ponds an concentration by mechanical evaporation into solid salts.

CHAPTER 6

6. INNOVATIVE APPROACHES TO BRINE MANAGEMENT

As shown in paragraph 5.1, a number of factors influence the design of brine disposal strategies. Small, remote desalination systems demand a low maintenance, simple to operate system, compared to large industrial applications, which require a different approach to maximize resource utilisation, minimize cost and contain long term environmental liability.

However, probably the most challenging application is in the case of acid mine drainage from defunct mines, where insufficient funds are available to finance desalination and brine disposal operations. This challenge could however be turned into an opportunity provided the political will is present to unite industry and the legislator in addressing brine.

Present design approaches to desalination and salt disposal is often simply too costly to implement and a completely new approach is required to the management of salinity in these systems.

This chapter reviews the major trends in brine disposal strategies in an attempt to identify the best opportunities for local requirements.

6.1 Brine minimization

Often, precipitation chemistry limits water recovery significantly below the mechanical limits of RO equipment. If precipitation limits are removed (or moved) through properly designed pre-treatment systems, water recovery can in general be increased significantly, resulting in reduced brine volumes and consequently lower disposal costs. This concept has been the focus area of many workers (CSIR, 1996) and processes such as SPARRO, GYPCIX, SAVMIN and many others to remove sparingly soluble salts have been proposed since the early 1980s. More recently different process configurations such as the HERO, HSR, ICCON, AQUA-K, HIPRO and others were developed to recover potentially valuable materials and improve overall water recovery rates and process economics. The different approaches to brine minimization are depicted by FIGURE 14. In this summary, metals and multi-valent salts are removed upstream of the RO process, which ultimately is used merely as a concentrating step for mono-valent salts.

In an extreme illustration of what can be achieved by continuously removing scaling chemistry, Gunther (2006) presented a process option in which sparingly soluble salts are sequentially removed in a slurry reactor. The project is presently under construction near Witbank and aims to recover 97% of the incoming saline mine water as high quality potable water. This is a remarkable achievement in that a mere 10 years earlier, water recovery rates varying between 65% and 90% were quoted by for the same application.

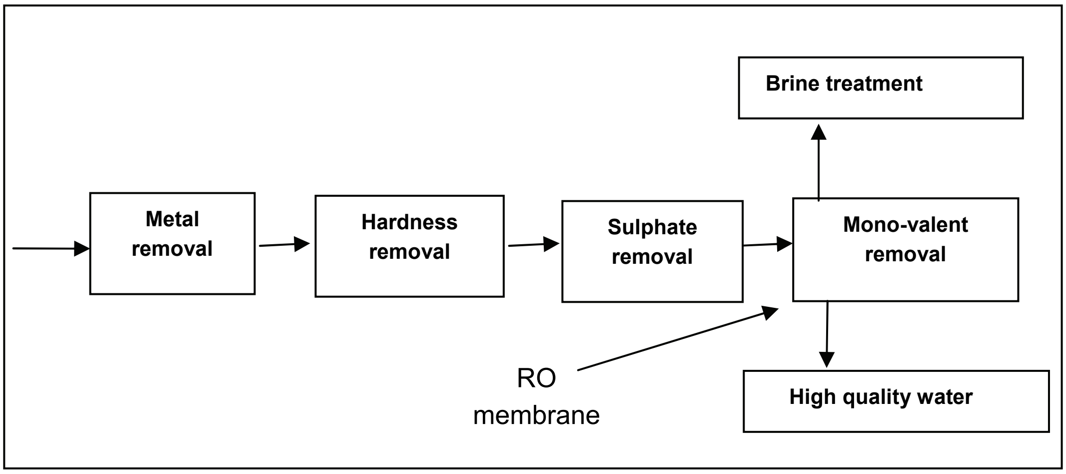


FIGURE 14. STAGE-WISE REMOVAL OF SALTS IN SALINE STREAMS (VAN DER MERWE, 2003)

This process presented by Gunther is an innovation on the earlier SPARRO concept (Juby, 1992 and 1998) which uses a slurry reactor in combination with tubular reverse osmosis membranes to continually remove hardness salts. The main concern with the SPARRO process, however, was erosion of tubular membranes by precipitated crystals, as well as relatively high capital and operating costs of the tubular membrane configuration. The Emalahleni project (Gunther, 2006) overcomes these concerns by a dedicated slurry reactor and using modern membrane configurations such as capillary ultra-filtration and spiral wound modules.

Brine minimization through advanced pre-treatment is rapidly gaining in popularity as it generally results in improved overall process economics and may in extreme cases eliminate a final RO step (and thus brine generation).

6.2 By-product recovery

A major potential drawback of simply removing scaling chemistry without regard for metals and other potentially toxic constituents is the fact that a low quality, mixed sludge is produced with a relatively high hazard rating. An alternative approach may be fractional precipitation of constituents by careful control of process parameters such a pH and temperature. Again, much research has been done by a number of workers to produce a large variety of by-products from the raw feed water into the RO plant as illustrated by the following list (Van der Merwe, 2003):

- Calcium Carbonate (various grades)
- Calcium Chloride
- Chlorine (gas)
- Ferric Oxide
- Gypsum
- Magnesium Chloride
- Magnesium Hydroxide

- Magnesium Sulphate
- Magnesium-ammonium-phosphate fertilisers
- Potassium Chloride
- Potassium Nitrate
- Potassium Sulphate
- Sodium Chloride
- Sodium Nitrate
- Sodium Sulphate
- Sulphur (agricultural and industrial grade)

Whilst recovery of by-products can facilitate a practical use for many of the low value salts present in brine streams, to date these schemes have been met with limited commercial success, globally, due to a number of factors, such as:

- Capital and operating cost associated with equipment and processes to produce by-products.
- Practical challenges to produce by-products to the required consistency and quality standards demanded by markets, from a feed stream which is essentially a variable quality/quantity waste stream;
- Drying, size reduction/classification, packaging, quality control, distribution, warehousing and generally other overheads associated with delivery of by-products to the market;
- Supply/demand balance and associated commodity price cycles of these by-products;
- Access to markets from a geographical as well as strategic marketing perspective;
- Ability and willingness of owners of desalination plants to become involved in operations of such relatively complex plants;
- Ability and willingness of owners of desalination plants to accept responsibility for marketing of by-products;

Many of these limitations can be overcome by appropriate commercial, legal and business structures which may involve outsourcing, strategic alliances, *etc.* However, global experience to date has shown that these schemes are more effective at reducing long term liability than by providing a competitive investment alternative. In all instances technical achievement, no matter how significant, should be subjected to a robust business analysis prior to investment.

Nevertheless, by-product recovery is an increasingly attractive option in many installations and more process options are being proposed regularly. It is anticipated that further developments in this regard will take place as environmental and cost pressures increase. Whilst it may not always improve process economics significantly, one of the main benefits will be to reduce long term liability associated with storage/disposal of waste salts.

6.3 Selective brine treatment

Nederlof (2005) suggested that in some applications the whole brine may not be the problem and that selected brine treatment may yield it suitable to environmental release. His work focused on applications in water rich countries, such as Europe, where desalination is used primarily to remove hardness, taste, colour and microbial contaminants from groundwater. The approach may therefore not be directly applicable in the local context, but the concept of selected brine treatment is still of value and is therefore briefly discussed.

Nederlof describes applications where parameters such as sulphate, chloride, phosphate, iron and anti-scalants are the prime contaminants of concern:

- Anti-scalant is an important consideration in brine treatment as, on the one hand, it interferes with precipitation kinetics and thus removal of multi-valents salts, whilst on the other hand, it adds to phosphate content of brine. As discussed earlier, brine disposal in Europe often involves discharge to large rivers or water bodies, thus anti-scalants may introduce phosphates into the environment which promotes eutrofication of surface water bodies. Experience in the Netherlands has shown that aeration of brine, followed by rapid sand filtration is effective in removing a part of the anti-scalant from the brine. Removal was particularly effective when poly-phosphates were used as anti-scalant;

- In selected applications, multi-valent salts may be precipitated from the brine stream (for instance to remove metals) prior to discharge into the environment;

- Many desalination systems in Europe treat anaerobic boreholes. As such, aeration of the brine may be required to increase oxygen levels prior to discharge. Such aeration will assist in iron and anti-scalant removal.

6.4 RO vs. NF

Nano-filtration (NF) is an interesting membrane process in that it does not have the same salt rejection efficiency as reverse osmosis. In particular, mono-valent salts such as sodium chlorides are “selectively passed” with rejection rates as low as 50-75% compared to typical rejection rates in excess of 99% for reverse osmosis membranes.

When the level of mono-valent salts such as sodium chloride is relatively low (say below 200 mg/l) nano-filtration potentially affords an opportunity to pass some sodium chloride to the permeate (product water). Whilst the product water should still conform to the required standards, the concentration in the brine stream may be significantly lower, which in turn may provide opportunities for increased water recovery and alternative disposal methods.

This approach has already been used in the Netherlands to minimize the concentration of sulphates and chlorides in plants producing potable water from boreholes (Nederlof, 2005).

Whilst this option offers an interesting alternative, its application for control of brine composition will be very site specific.

6.5 Enhanced evaporation processes

Several processes have been proposed to improve performance of evaporation ponds. Most of these efforts are directed at increasing the heat transfer area by spraying the brine over evaporation ponds, introducing turbulence or running brine over the exposed sides of the lining of the pond. Whilst all of these efforts offer relatively low cost solutions, they do not significantly change the required surface area needed. In the case of spraying the brine over the pond, there is the additional concern of wind drift losses and contamination of adjacent areas.

Two concepts which merit additional discussion have recently been reported in literature. These are the WAIV and Dewvaporation processes.

6.5.1 WAIV

A system to increase evaporation from ponds was developed by the Ben Gurion University in Israel (Gilron *et al.*, 2003). This new technology, described as the WAIV process (Wind Aided Intensified eVaporation), involves circulation of brine over vertically suspended "wetable surfaces," designed to increase the effective

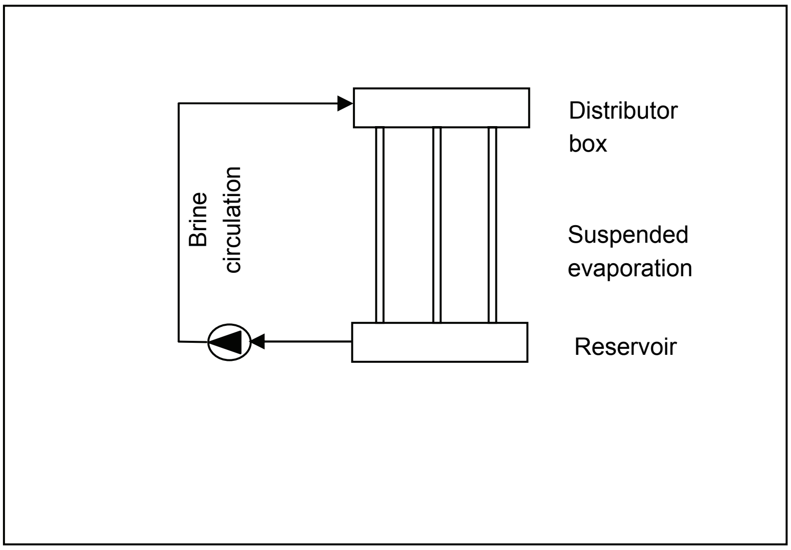


FIGURE 15. ILLUSTRATION OF WAIV CONCEPT

evaporative surface area. The surfaces were suspended as shown in Figure 17 and were wetted by circulation of water from the top as well as capillary forces.

Packing densities of 20 m^2/m^2 has been achieved, resulting in significantly increased evaporation rates per unit area of land. The evaporation surfaces may consist of non-woven geo-textiles, woven netting or other materials and selection is determined by the following parameters (Gilron *et al.*, 2003):

- **Hydrophilicity:** Low hydrophilicity will reduce wetability of the surface and cause water to simply run down the surface without much evaporation. Highly hydrophilic materials will also reduce evaporation rates due to increased water/surface bonds.

- **Physical structure:** Very smooth surfaces reduce the retention of water on the exposed evaporation surface, thus reducing overall evaporation. Porous materials may become blocked with dust or scaling;

- **Strength:** Materials should be strong enough to withstand strong winds.

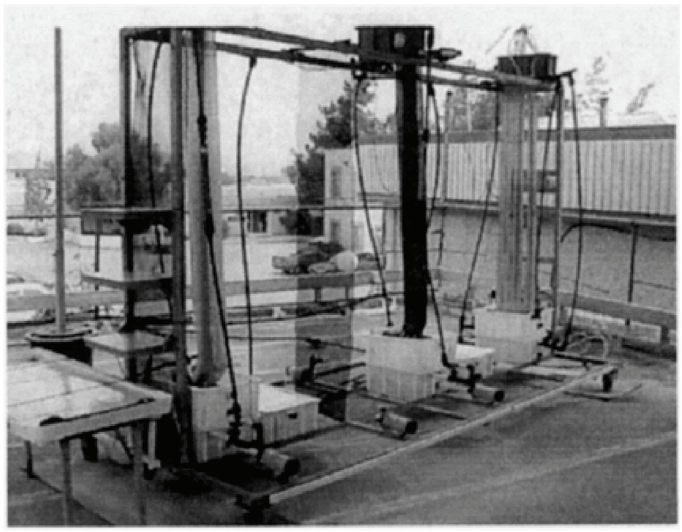


FIGURE 16. WAIV TEST UNIT

Promising results have been obtained to date on small scale applications with hydrophilic materials containing no internal surfaces. Increases in evaporation rates up to 13 times compared to normal open surfaces have been reported (Gilron *et al.*, 2003). Development, however, is still on-going and major concerns include:

- Scaling of sparingly soluble salts and resultant maintenance of evaporation surfaces;

- Fouling of evaporation surfaces by wind borne particulate matter such as dust, grass, *etc.*;

- Mechanical damage due to strong winds;

- Fog harvesting;

- Optimisation of evaporation performance in relation to wind direction and control of humidity internally to the pack of evaporation surfaces.

6.5.2 Dewvaporation

The Dewvaporation process is a patented technology that uses a humidification / dehumidification cycle to purify water. The process operates in a tower with vertical heat transfer areas, at moderate temperatures and atmospheric pressure. The process has no filters or membranes to be replaced, nor any moving parts in its core operating elements (L'Eau, 2006).

The process begins by dribbling brine down the evaporation side of the heat transfer wall. At the same time, air is introduced at the bottom of the tower at approximately 20ºC and is run past the water up the heat transfer wall. As it travels past the water, the temperature is increased by heat transferred through the heat transfer wall. As a result, the water carrying capacity of the air increases and water evaporates from the brine stream into the air stream (L'Eau, 2006).

At the top of the tower, the air is turned around and is sent back down the tower, but before it does, heat is added in the form of steam. This results in an incremental rise in temperature. This slightly warmer air stream then travels back down the tower along the dew formation side, transferring heat through the heat transfer wall until it cools down to approximately 70ºC at the bottom. As the air cools down, its water carrying capacity is reduced, resulting in condensation of the water evaporated on the other side of the heat transfer wall.

The dewvaporation units are made entirely of polypropylene and other non-corrosive engineering plastics, whilst the core processing towers are entirely passive elements. The only moving parts of the process are the external low pressure blower and brine feed pump. The process thus overcomes most of the corrosion and cost concerns associated with traditional mechanical evaporation processes.

The key to the energy-efficiency of the dewvaporation process is the multiple re-use of heat added. By using this heat to maintain a thermal gradient across the heat transfer wall, the latent heats of vaporization released in condensation are recycled to power the evaporation process. Multiple reuse effects of 4 to 8 have been documented, depending on configuration (L'Eau, 2006).

Figure 18 shows a recent installation by L'Eau of DV4000 towers at a customer site in the Southwest United States. Towers are approximately 2.3 m tall, and clustered in groups of four with a combined footprint of 4' x 4'. This pilot installation will process approximately 20 m^3 per day of RO effluent.

The anticipated concentration of the brine will increase from approximately 5,000 mg/l 300,000 mg/l, reducing the size of the waste stream by a factor of about 60. Distilled water is produced as a by-product.

The process is very new with only a single operating unit presently available. Several concerns may therefore be raised:

- Energy efficiency – it is not clear if the overall energy efficiency claimed by technology suppliers will be reached;
- Scaling on heat transfer surfaces may be significant in reducing overall efficiencies;

- Ambient air temperature and humidity may limit effectiveness of the process significantly.

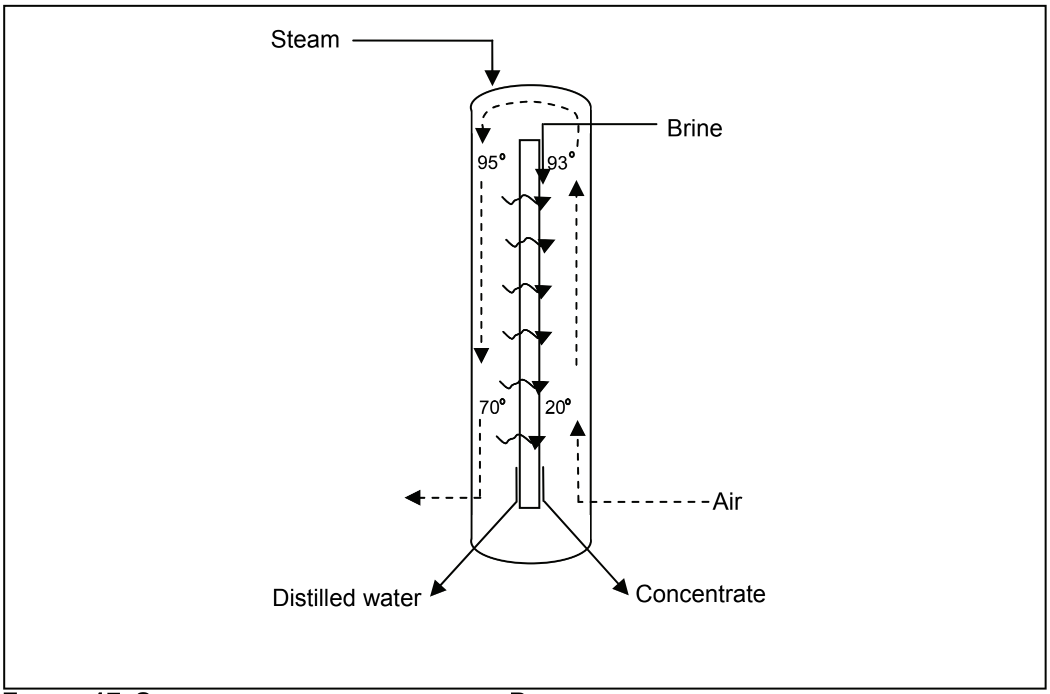


FIGURE 17. SCHEMATIC REPRESENTATION OF DEWVAPORATION PROCESS

FIGURE 18. 20 M^3/D RO CONCENTRATE TREATMENT PLANT BUILD BY L'EAU (L'EAU, 2006)

6.6 Brine utilisation in aquaculture

Globally, aquaculture is a growing industry and markets presently exist for fish grown in semi-saline to saline environments (Ahmed, Desalination 134, 2001; AFFA, 2002). In South Africa, the cultured fish market presently imports as much as 25-30% of local needs – a market which grows at an estimated 15% annually (Stubbs, 2006; Strydom, 2006).

In principal it should be possible to produce fish and similar products from saline brine streams, though rigorous control and monitoring of brine quality is required. Also, all toxic components such as metals, organic contaminants, *etc.* should be removed. Whilst no direct re-use of brine is presently done in South Africa, it was previously suggested by others and is being tested elsewhere in the world. Generally, a process called bio-concentration is used to cultivate different species in increasing salinity (Figure 21).

A similar approach was described by Rose (WRC, 2002) who included treatment and desalination of saline effluents from power stations by biological sulphate and metals removal, followed by RO and subsequent beneficiation of brine in a series of bio-producing activities.

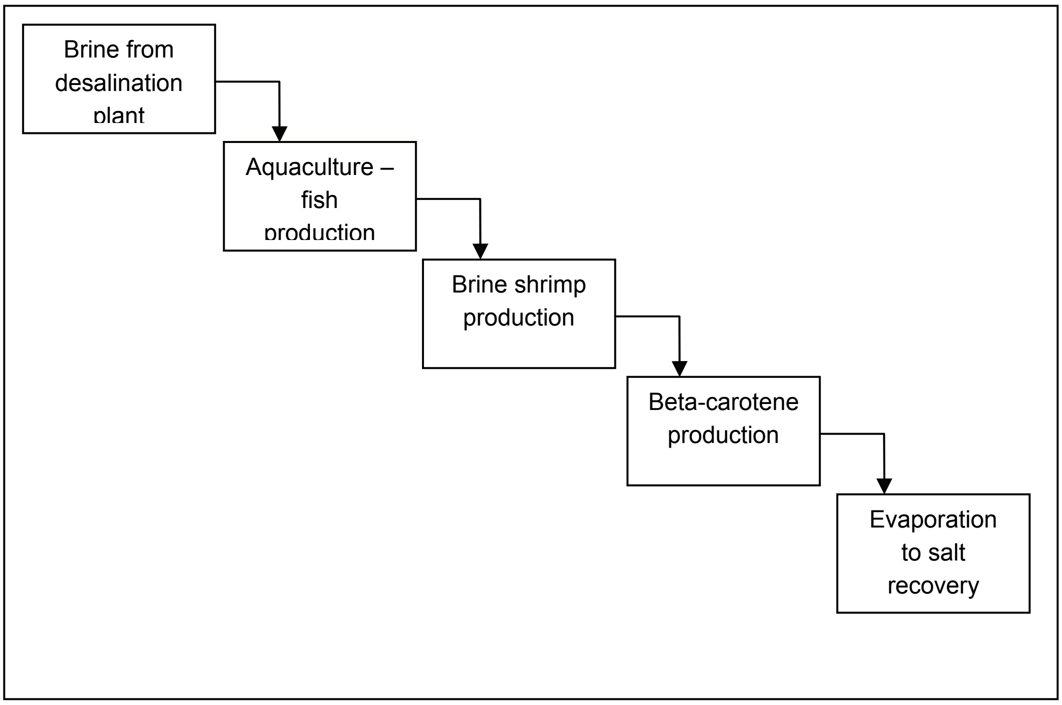


FIGURE 19. BIO-CONCENTRATION AND PRODUCTION OF VARIOUS PROTEIN SOURCES

6.6.1 Fish

Species like Barramundi (*Lates calcarifer)*, Red Snapper (*Pagrus auratus)*, Black Bream (*Acanthopagrux butcheri*), Milk fish (*Chanos chano*), Mullet (*Mugil cephulux*) and Tilapia (*Oreochromis mossambicus*) can grow and prosper in high salinity water. At an experimental site in Tailem Bend, South Australia, different species of marine fish have been cultured for their suitability to be produced using saline water. Initial results have proved successful (AFFA, 2002). This project will be expanded to include oysters and seaweed will soon be tested.

Seaweed forms an integral part of marine aqua-culture and already production of seaweed is being tested on semi-commercial scale by abalone producers in South Africa. This is one of the fastest areas of export growth in the aqua-culture industry in South Africa and already includes some significant production areas in the Southern Cape (Hugo, 2006). Although these facilities are mainly based at the coast, it proves that a local and international market exists for cultured products.

6.6.2 Brine shrimp

Having brine shrimp production downstream from finfish culture has advantages in that the brine shrimp utilise nutrients generated from fish culture, whilst providing food for fish fry (Ahmed, Desalination 134, 2001). A similar approach is being followed in the local abalone industry in that seaweed is produced downstream of abalone grow-out tanks (Hugo, 2006).

Brine shrimp is successfully grown by the Pyramid Salt company in Victoria, Australia in high salinity salt ponds. Brine shrimp is sold as aquarium food for tropical fish. Brine shrimp production is ideal for high salinity evaporation ponds as there are virtually no predators or competitors to the shrimp, which consequently survive as a natural monoculture.

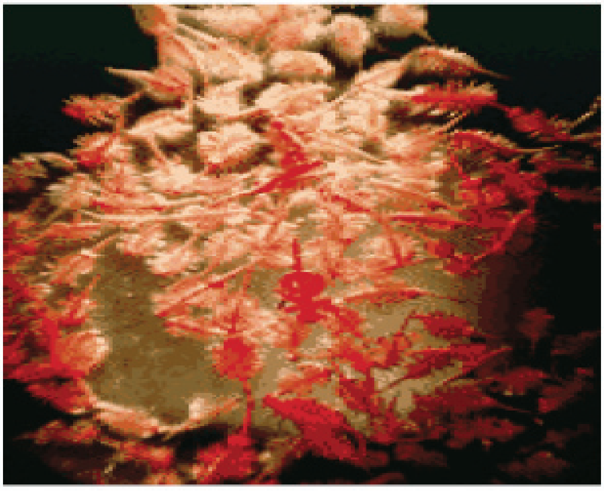


FIGURE 20. BRINE SHRIMP (SVENSSON, 2005)

6.6.3 Algae production

High salinity ponds may also serve as the basis for production of mono-cellular algae such as Dunaliella *salina* (Ahmed, Desalination 134, 2001). These organisms produce *beta*-carotene and production for commercial grades of beta-carotene is possible in highly saline waters with salinity levels in excess of 200 g/l (Svensson, 2005).

6.7 Salinity gradient solar ponds

Salinity gradient solar ponds are yet another possible means of adding value to brine from desalination plants. These ponds combine the collection of solar energy with long-term storage, providing a source of low grade heat.

A typical salinity gradient pond has three regions:

- The first layer at the surface of the pond is called upper convective zone (UCZ) and is comprised of "relatively fresher" water with 1-4% salt by weight. The thickness of this zone is ideally approximately 30 cm as increasing the thickness reduces the ability to store heat.
- The second (middle) layer is called the non-convective zone (NCZ) and is the

insulating zone. The thickness of this layer is between 0.5-1.5 m.

- The third and lower layer is called the lower convective zone (LCZ) and contains near saturated or saturated brine with approximately 26% salt by weight.

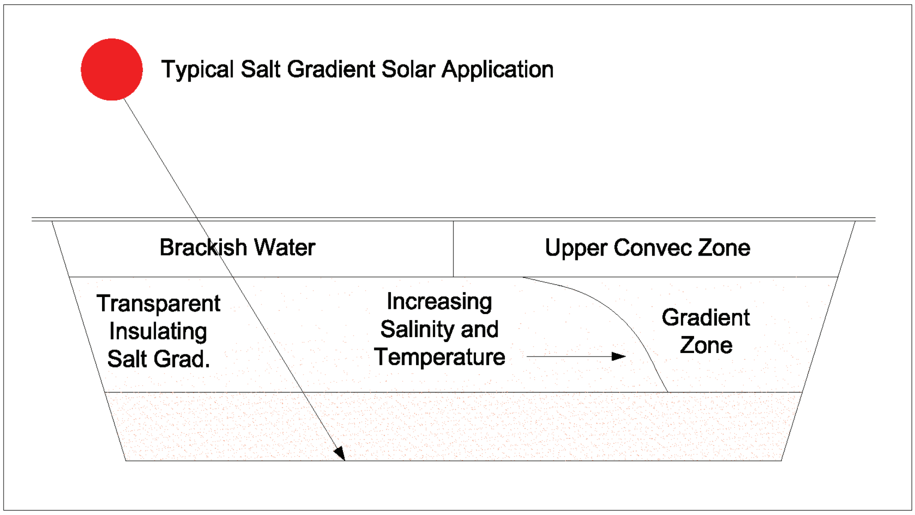


FIGURE 21. DIAGRAM OF THE DIFFERENT ZONES IN A SALINITY GRADIENT SOLAR POND

As density difference effectively prevent convection, sunlight energy that reaches the lower zone (LCZ) can only escape by conduction. The combination of the high heat capacity of water, large volumes of water in the solar pond and the insulating properties of the non-convective layer makes it a device for energy collection and long-term storage. Temperature in excess of 90°C is regularly achieved in the lower zone.

Energy stored in salinity-gradient solar ponds is typically recovered by passing a heat exchange fluid (fresh water) in a heat exchanging pipe through the LCZ. The water in the pipe heats up and the heat is then transferred to land where it is recovered as a low grade heat which could be used for a variety of purposes.

The economic viability of salinity-gradient solar ponds is determined by the demand for low-grade heat, and the price and availability of alternate energy. Solar ponds become attractive as a source of renewable energy where water, salt, solar radiation and flat land are readily available and there is a valuable use for thermal energy.

To be effective energy stores, salinity-gradient solar ponds require (Ahmed, Desalination 134, 2001):

- All year solar exposure;
- Large volumes of brine as well as an adequate source of “fresher” water;
- Cheap, flat land, of low permeability, and high thermal and structural stability;

- To be located away from shallow aquifers;
- Relatively low winds to minimize mixing and deposition of debris; and
- A consistent electricity demand.

The thermal efficiency of salinity-gradient ponds is affected by:

- Brine clarity which relates to energy collection efficiency;
- Thickness of different layers within the solar pond;
- Maintenance of the vertical salt gradient;
- Pond area (1-10 ha);
- Depth to groundwater – shallow groundwater can lead to significant heat loss.

Ideally, power generated from the solar ponds would be fed into the desalination process, or could be used for further processing of salt recovery from brine.

6.7.1 Current installations

- El Paso, USA

Solar-pond-powered desalination has been studied since 1987 at the E1 Paso Solar Pond Project, El Paso, Texas. From 1987 to 1992, the research mainly focused on the technical feasibility of thermal desalination coupled with solar ponds. Since 1999, the research has focused on long-term reliability, improvement of thermodynamic efficiency, and economics.

The El Paso solar pond has a surface area of 3000 m 2 (0.75 acre) and a depth of about 3.25 m. The UCZ, NCZ, and LCZ are approximately 0.7 m, 1.2 m, and 1.35 m, respectively (Lu *et al.*, 2000).

FIGURE 22. SALINITY GRADIENT SOLAR POND AT EL PASO, USA

- Victoria, Australia

A 10 000 m^2 solar pond in Victoria (Australia) produced 200 000 kWh of electricity per year (Svensson, 2005). This means that a 500 m3/d desalination plant with a total energy consumption of 2.5 kWh/m^3 could run 160 days a year solely dependent on the energy supply from a solar pond with this capacity and size.

FIGURE 23. SALINITY GRADIENT SOLAR POND AT VICTORIA, AUSTRALIA

6.8 Disposal to saline environments

6.8.1 Marine disposal

For desalination facilities located close to the coast, it is generally accepted to dispose of the RO brine by discharge to sea – particularly in the case of sea water desalination plants as no foreign salts are introduced. Disposal of brine from plants treating industrial effluents is more complex in that assurances are required that no toxic components are introduced.

For inland desalination plants, disposal to the marine environment is generally not considered a practical option, principally due to complexities, costs and environmental associated with transport thereof.

Whilst this option is generally regarded as not viable for major inland desalination plants in South Africa, this option, however, has not been fully explored and compared with alternative options such as zero-liquid discharge options which may include complex and costly unit operations such as evaporation/crystallisation.

Another option may be to dispose of unwanted salts from evaporation ponds to marine environment. This will reduce transport costs, risks and other complexities.

6.8.2 Salt lakes

An option which has been raised is to dispose of brines to existing inland salt lakes. Unfortunately, Southern Africa does not have an abundance of such lakes available. The major salt lake exists at Sua Pan, Botswana where Botash produces soda ash and salt from naturally occurring alkali-rich brine.

An interesting feature of this location is that despite a hot and semi-arid climate, bird life is prolific in the area. Sua Pan itself is a major flamingo breeding ground, attracting hundreds of thousands of flamingos as well as other species.

FIGURE 24. THE BOTASH PLANT AT THE SUA PAN, BOTSWANA

Care therefore needs to be taken no to introduce toxic compounds in these environments – particularly metals, radioactivity and other compounds such as anti-scalants.

A further consideration – specifically with Sua Pan – is of course the fact that waste material will be transported across international boundaries. As such alternative inland salt lakes of sufficient capacity should be considered.

This option has similar constraints in terms of transport, complexities, environmental risks and quality concerns as with a pipeline to sea.

An alternative is to create a centralised sacrificial area which can be used as regional disposal site of unwanted salts. This concept will have major environmental impacts and risks associated with it and will in all likelihood not be practical. However, from a regional perspective, it has not been evaluated or compared with alternative disposal options such as many dispersed evaporation ponds which has the potential of leaking salt into groundwater over a much wider area. Areas already damaged by industrial activities could be considered for this option. .

6.9 Underground storage of brine

As far as could be determined, there is presently no underground storage of brine in mined out areas or caverns in South Africa apart from a three year trial at the Tutuka Power Station. Taking from experience gained in storing petroleum products in salt caverns and deep well injection, storing brine in mined out areas have been proposed. Considerations similar to those for deep well injection will apply.

However, major concerns for this approach centre on sustainability, risk of groundwater movement and remedial strategies if needed.

6.10 Freeze desalination

The conversion of saline water to fresh water by freezing is a natural phenomenon and can be best illustrated by the formation of icebergs. The concept of freeze desalination for the purpose of potable water production from seawater and other saline solutions dates back to at the early 1950s, with most research activity having taken place between 1955 and early the early 1980s (Buros, 1990).

Previous research focused on producing high quality potable water from saline sources, mainly seawater, in a single step. Salt inclusion in the ice, however, increased salinity of the product water, necessitating several washing steps. These steps introduced inefficiencies into the process which rendered it uneconomical to alternatives such as mechanical evaporation processes. As RO systems and advanced thermal desalination systems became the industry standard, interest in freeze desalination waned.

Today, interest in the technology has been renewed as a brine treatment technology – particularly as it offers significant potential advantages over evaporative processes. Theoretically, the corrosion chemistry of saline solutions is vastly different at low temperatures than at high temperatures. This could mean using less expensive materials of construction for freezing equipment and thus reducing the initial capital investment and maintenance costs. The energy needed to evaporate water (2272 kJ/kg) is 7 times more than to freeze water (335 kJ/kg, which could make the freezing process less energy intensive and reduce the operating cost when compared to mechanical evaporation.

6.10.1 Previous approaches

Previous research into freeze desalination concentrated on reducing energy efficiency by limiting heat exchanging surfaces. In order to achieve this, it meant freezing processes that had direct contact between the refrigerant and the saline water (Spiegler *et al.*, 1980). This approach resulted in three main complications (McKetta, 2002):

- Scale up difficulties due to limitations in primary refrigerant compressors available at the time. The cost of these compressors also significantly increased the overall capital cost, whilst inefficiencies increased energy demand;
- The formation of stable water/refrigerant emulsions, resulting in trace amounts of refrigerant being present in the product water;
- Inefficient separation of ice crystals from saline feed stream, resulting in salt inclusion in the ice and a consequent increase in salinity of the product water. This step is still seen as the critical step which can make the process uneconomical.

Today, the main focus on freeze desalination is in the area of Eutectic Freeze Crystallisation (EFC) – particularly for smaller, specialized applications.

6.10.2 A new approach

Despite the challenges in terms of salt intrusion, the technology holds significant potential benefits in terms of energy efficiency and simple materials of construction, compared to mechanical evaporation processes. One option is to utilise freeze desalination only as a partial desalination step, whilst utilising reverse osmosis as a polishing step.

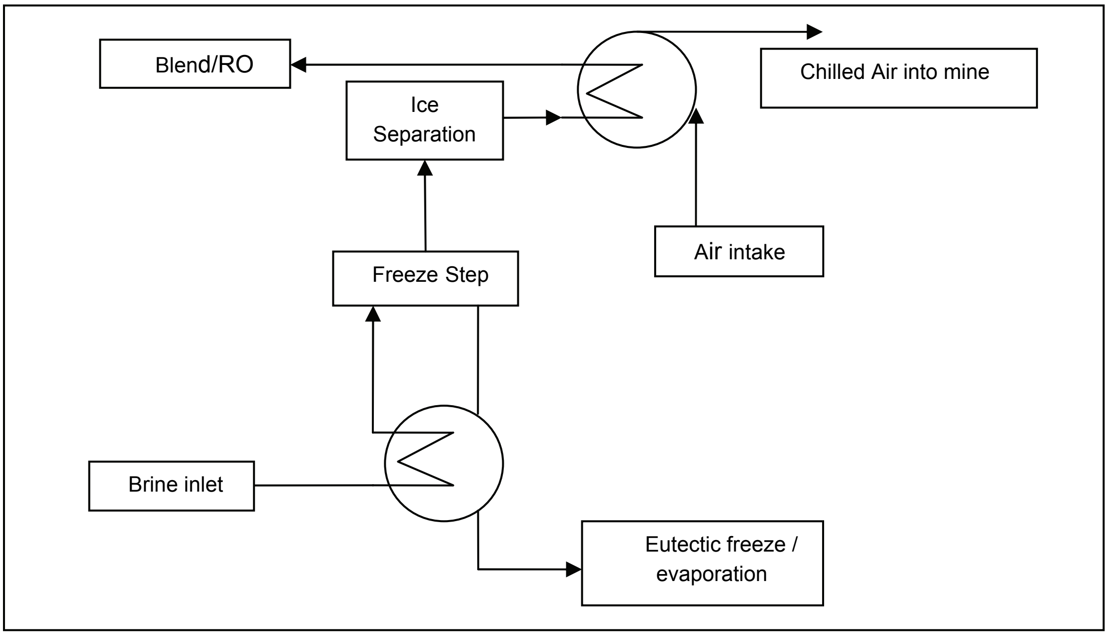


FIGURE 25. CONCEPTUAL PROCESS FOR UTILIZING FREEZE DESALINATION

Such a process concept (developed as part of this investigation) is illustrated in **FIGURE 27**). Here brine from the primary desalination plant is chilled to below the freezing point (but above the eutectic freeze point) and ice removed. The ice will be relatively fresh compared to the incoming brine stream, although still not potable water. After recovering energy from the ice, it is returned to the reverse osmosis unit operation for further treatment. Energy from the ice may conceptually be recovered for a number of chilling operations – such as cooling down air in deep gold mines. The concentrated stream may then be further treated by an EFC process or if the volumes are small enough, by evaporation in a line pond.

6.11 Summary

Many innovations are emerging which could make brine beneficiation/utilisation more economically attractive in future. It is important to note that a "one-size-fit-all" approach is unlikely to be practical and that each situation has to be dealt with separately. The most promising innovations identified, which may be applicable to South Africa are:

- Brine minimization / brine treatment;
- Wind Aided Intensified eVaporation (WAIV);
- Dewvaporation;
- Freeze desalination.

These options will be discussed in more detail in Chapter 10.

CHAPTER 7

7. CURRENT SLUDGE DISPOSAL STRATEGIES

This chapter evaluates various sludge disposal strategies, with the main focus being on sludge produced in the treatment of water arising from the mining industry, or similar type waters. This is motivated in that:

- Acidic water or water that is characterised by elevated sodium, sulphates and metals is not unique to acid mine drainage. Pulp and paper, tannery, municipal and other acidic sludges all face similar issues.

- It is considered that, in terms of water treatment volumes, the mining industry represents the area of greatest growth in the short to long term. Furthermore, the volume of water treated is expected to increase exponentially in the next few years. The volumes of sludge are expected to increase accordingly.

- The nature of the waste produced in the neutralisation and treatment of mine water is problematic in many respects. In most instances the sludge is a "large volume low value" product, and is generated remote from the main industrial areas of South Africa.

The discussion is structured around two primary themes: Firstly, sludge management is discussed in broad terms, with an extended discussion on the history and lessons learnt from sewage sludge disposal in general. Secondly, sludges associated with the neutralisation of acid mine drainage, and/or sludges arising from various pre-treatment steps in the use of membrane technologies are discussed.

Whilst no single database on the amount of sludge produced in South Africa could be found, an order of magnitude estimate of sludge quantities is given in **TABLE 7**

TABLE 7. APPROXIMATE VOLUMES OF SLUDGES PRODUCED IN SOUTH AFRICA.

Activity / Industry	Typical volumes produced	Comment
Sewage sludge	312 000 tons/annum (DEAT, 1997)	EU: 8.3 million tons expected for 2005 (Langenkamp and Marmo, 2000)
Mining industry	250 000-400 000 tons/annum. No information available. Estimates as per Paragraph 3.	Neutralisation of mine water probably the main producer of sludge at present
Paper and pulp industry	234 000 tons in SA, for 2003 @ 50% moisture content (DME, 2004)	Quantity and quality varies according to mill configuration and moisture content.
Electricity generation	Eskom reports on ash and other wastes, but not sludges specifically	
Tanneries	7200 m^3/yr (DEAT, 1997) effluent plant sludges	
Petrochemical industries	Data not obtained to date	
Textile industry	Effluent plant sludge:240 m^3/yr Wool washing sludges 20 700 m^3/yr (DEAT, 1997)	
Timber processing industry	Treatment sludges: 95 m^3/yr (DEAT, 1997) – excludes paper industry	

The management of these sludges generally falls into three broad categories, namely:

- Deposition of sludge or sludge components, varying from the use of land (general landfills or specifically designed waste facilities), the ocean (largely discontinued) or to the air (limited quantities, but for example through incineration)
- Use of the sludge, such as the employment of treated sewage sludge as a fertiliser or a soil conditioner.
- Recycling of sludge through a "productification" strategy, that is, the use of techniques to generate saleable products. Typical "products" from sludge may include: -
  - Generation of energy (electricity, heat, biofuel and oil)
  - The use of nutrients contained in the sludge (phosphate and nitrogen)
  - Extraction of metals or other components of value in the waste

- Inclusion of sludge as a building material additives

- Other uses such as paint pigments, or extraction of other products for use in other manufacturing industries

TABLE 8 below discusses some of the current strategies employed by each of the industries listed in **TABLE 7** for the management of sludges produced by that industry.

TABLE 8. CURRENT STRATEGIES FOR THE DISPOSAL OF SLUDGES USED LOCALLY IN THE VARIOUS INDUSTRIES.

Activity / Industry	Technology utilised in South Africa	Comments
Sewage sludge	• Agriculture • Land disposal (on or off site) • Beneficial use (mine rehab, soil amelioration, etc.) • Thermal treatment • Compost, brick making, pellets	In the EU the split is typically: • 32% agriculture • 13% incineration • 5% ocean • 48% landfill (Hultman et al.)
Mining industry (acid mine drainage)	• Disposal into lined facilities, • Sludge deposited inside clay lined water retention dam during neutralisation. • Co-disposal with other wastes	
Paper and pulp industry	Landfill	Assessment by DME of the commercially exploitable biomass resources in the bagasse, wood & sawmill waste and pulp in South Africa showed that 94 GWh of electricity could be generated from this waste stream (DME, 2004)
Electricity generation	Co-disposal with ash	Current study by Eskom looking at assimilative capacity within the ashing system
Tanneries	Landfill (on or off site) Treatment technologies	
Petrochemical industries	Land filling of some sludges, but recycling of others.	
Textile industry	Landfill (off-site)	
Timber processing industry	Landfill (off-site)	
Metallurgical industries		

7.1 Sewage Sludge Disposal

The current management of sewage sludge in South Africa is covered by a report issued in August 1997 “The Permissible Utilisation and Disposal of Sewage Sludge” (commissioned by the Department of Agriculture, Department of Health, DWAF, the Water Institute of Southern Africa and the WRC). The report (TT261/06) sets out different classifications of sludges, and limits the uses accordingly.

The history of sewage sludge management in general is an interesting case study. Prior to the twentieth century, indoor plumbing was an almost unheard of luxury. In developed areas, common people used outhouses, while the wealthy had a primitive indoor system, namely bedpans to be carried away by servants. Waste was generally buried, and minimal water employed. Ironically, with some improvements required in terms of technology from those early days, this approach to human waste is largely favoured by environmentalists, since the volume of waste is minimised, and the hazardous nature of the waste can be limited to mainly pathogenic organisms.

However, with the industrial revolution, people became urbanised and industrial effluents were also generated. The result was the development of a single effluent system using water as a transport medium. Although the engineering required to develop these systems was in some cases exceptional for the time at which they were constructed, the simple decision to combine waste systems was to have significant environmental impacts. The resulting waste was a diverse mixture of wastes and with increased volumes to be managed due to the addition of water.

Since the waste was initially simply discharged to surface water bodies, the complication associated with mixing waste types was not immediately evident. However, once the consequences of discharge were found to be disastrous in many instances, centralised treatment facilities developed, resulting in the production of sludge.

While the initial management of the sludge was through land filling and composting, it was soon discovered that the presence of chemicals, pesticides, heavy metals, radioactivity and pathogens was impacting on both the environment and human health.

To deal with these two interrelated problems, namely the mixing of wastes and the subsequent generation of a potentially hazardous by-product, two primary strategies have been implemented. Firstly, the use of sewage systems for the disposal of a range of wastes has been curtailed over the last few decades, reducing the hazardous nature of the contaminants entering the sludge system. However, most countries still have entrenched waterborne centralised waste management systems, and most still accept some industrial water.

Secondly, acceptable sludge disposal options have changed. Ocean disposal is no longer allowed, and in many European countries sludge deposits in landfills are being phased out. It is estimated that 35 to 45% of sludge in Europe is still land filled, and a significant quantity is also incinerated. Legislation in Europe is likely to require incineration ash to be managed as a waste which will also result in pressures to implement alternative solutions.

As indicated previously, the WRC has revised the South African guidelines for the utilisation and disposal of wastewater sludge. Options likely to be acceptable but depending on the nature of the sludge and with certain controls and provisions are summarised below.

7.1.1 Probable uses for sewage sludge in South Africa

Sludge can be used in agricultural applications:

- Use of stabilised sludge as a nutrient source and/or soil conditioner at a rate to supply the crop's nitrogen need in areas of food production;
- Production of compost containing sludge that is not sold or distributed to the general public for use;
- The use of sludge as compost in municipal parks used by the public.

Each of these will have certain requirements in terms of treatment technologies and classification.

The options for on- and off-site disposal of sludges include:

- Off-site disposal at a general or hazardous landfill site (depending on classification);
- On-site disposal in a mono disposal landfill or lagoon;
- Disposal to a marine environment (although it is unclear whether this will be permissible in future).

The beneficial uses of sludge can be:

- Use for rehabilitation of mining waste deposits;
- Sludge used in the remediation of contaminated soil;
- Use as a nursery growth medium;
- Once-off high rate application (e.g. during construction of a golf course);
- Covering of landfills;
- Beneficial land application at high loading rates (e.g. cultivation of instant lawn).

Thermal management options include:

- Incineration in dedicated incinerators;
- Incineration in furnace, cement kilns, etc.

The following options are available for the production of saleable products from sludges:

- Manufacturing of pellets (resemble commercial fertilisers);
- Manufacturing bricks, paving, artificial rocks, etc.

7.2 Sludge From Acid Mine Drainage Treatment and Membrane Technology

Neutralisation of acidic mine water as a standalone treatment technology has been widely used to precipitate metals and remove acidity in water released from mining operations. The resulting sludge derived from adding an alkaline reagent is generally a sludge dominated by amorphous ferrihydrite, often with high levels of adsorbed heavy metals.

Historically, neutralisation as a stand-alone treatment has been practiced in South Africa. However, the water would seldom comply with discharge standards due to the fact that water qualities locally are legislated both in terms of metals and salinity (as well as other constituents). The neutralised water is most often reused for purposes such as coal washing plants.

Once the water usage requirements for active mines have been met, the older mines generally are left with a problem in terms of a water surplus. In theory, the possibility exists that the mines can treat the surplus water and return the water to the catchment system. However, the cost of most treatment technologies is such that the proponent is likely to try to offset some of the costs by finding a beneficial use for the water, such as supplying drinking water or industrial water. Typically this would imply the use of a membrane technology to remove the monovalent ions. The membrane technology would in turn involve various pre-treatment steps to remove metals, which will generate sludge.

Current practices utilised in the disposal of the sludges are discussed below (Zinck et al., 2006).

7.2.1 Disposal options

7.2.1.1 Settling ponds

Since sludge disposal generally involves three principle steps, namely solid – liquid separation, sludge dewatering and disposal, the use of a settling pond has the advantage of combining all of these steps. In many wet areas, the pond may remain with a wet cover, thus avoiding issues around dust and metal leaching, but these can become important issues in more arid environments.

Land availability can be limiting in terms of settling pond disposal. In instances where sludge volumes exceed predictions, or where there is insufficient space for the total volume of sludge to be produced, ponds have to be dredged or removed through draining of the pond and excavation. Ackman, (1982) evaluated sludge removal techniques in some detail. The cost to dredge sludge can be significant; a case study for the Kidd Creek Metallurgical Site in Canada spends upwards of $1 million per annum on dredging costs (Scott, 2004).

It should be noted that Zinck (1997) has shown that excess alkalinity in sludge is generally sufficient so as to maintain a moderate pH for decades or even centuries after disposal. This ability is improved by having a water cover.

Conversely, iron hydroxide precipitates evaluated over a period of 4 years indicated that microbial activity can result in pH reductions greater than may be anticipated by pure geochemical modelling, so that care may need to be taken in evaluating long term risks (Kalin et al., 2006).

Some advantages and disadvantages of settling ponds are given in TABLE 9.

TABLE 9. SETTLING PONDS.

Advantages	Disadvantages
• Degree of metal leaching expected to be minimal, especially where water cover remains. • In arid areas, once the material has dried, there is the potential to reclaim the material. However this can take years or even decades for some sludge. • Relatively inexpensive, but can become expensive depending on the liner requirements.	• Require large areas of land which are then “sterilised” for alternative uses • Potential impacts of pond failure significant due to thixotropic nature of sludges • Dust in arid regions • Care required in the design and construction, since these are influenced by the nature of the sludge and the sensitivity of the environment. • Regulatory acceptance uncertain.

It is important to note two considerations in terms of disposal into settling ponds:

- Work on sludge permeability tends to indicate a low permeability in terms of precipitated sludge, so that the contact with future acidic water may be limited, and would certainly be less than the contact used in terms of most leaching tests.

- The applicability of the TCLP or Acid Rain leach test may be questionable for some applications in terms of assessing the toxicity of the material.

7.2.1.2 Co-disposal with tailings or waste rock

Mining sites are often associated with coarse tailings resulting from milling processes. These materials exhibit higher strength characteristics than sludges, so that blending the two results in a material with better engineering properties. Conversely, the lower permeability of sludge has the potential to reduce air and water ingress through waste rock (for example), which is favourable in terms of limiting the production of poor quality leachate. A case study on this disposal approach is presented by Coleman *et al.* (1997) with a follow up in 2004 (Coleman and Butler).

In many cases, particle size of tailings may also be comparable with that of sludge so that in these cases, there may be little benefit in terms of either strength or permeability in mixing sludge and tailings. The logic is then primarily to utilise existing infrastructure and disposal facilities, i.e. a significant cost saving may exist if the sludge and tailings can be co-disposed.

The main concerns in terms of blending sludge with either tailings or waste rock generally relate either the operational practicality, or to the chemical stability of the combined material, particularly where the tailings facility is not built with a high level of liner system.

Some advantages and disadvantages of co-disposal are given in **TABLE 10**.

TABLE 10. CO-DISPOSAL WITH TAILING OR WASTE ROCK.

Advantages	Disadvantages
• Can be very inexpensive since the tailings facility is generally already in existence. • Overall chemistry can be favourable, with some operators indicating precipitation and adsorption chemistry assisting in limiting leaching. • Volume of sludge is generally much less than the tailings (<1:20 ratio in many cases) so that there is no significant impact on the tailings site in terms of capacity.	• Long term stability and buffering capacity still to be established, and may not exist in many instances. • Alternative sludge disposal required post closure when tailings generation ceases, but sludge may still be produced • Potential for oxidation may exist within the tailings facility. There is also a natural leaching process within the facility that may have negative implications.

7.2.1.3 Use as a cover material

The use of wet and dry covers to counter acidic drainage is widely practiced. Trials have been undertaken with some sludges to assess whether they can reduce oxygen ingress, as well as add alkalinity.

Certain sludges such as those from the paper industry or those with organic content appear to be effective for use in capping due to the ability to generate reducing conditions in the water and add alkalinity, but many of the finer sludges appear to have limited benefit, and may result in additional dust issues.

Work by CANMET (2004) indicated relatively limited benefit of capping tailings with sludge, primarily due to cracking and preferential flow paths through the sludge.

Some advantages and disadvantages are given in **TABLE 11**.

TABLE 11. USE AS A COVER MATERIAL.

Advantages	Disadvantages
• Some sludges may be effective as wet or dry caps, but very site specific. • Studies have found some materials that can add alkalinity as well as reducing rainfall ingress to the underlying material.	• Effectiveness influenced by cracking and preferential flow-paths created. • Some materials will add little value in terms of either oxygen or rainfall ingress, and may not add alkalinity. • Wind dispersion on fine particles can result in dust issues

7.2.1.4 Disposal in underground mine workings

In South Africa, the use of tailings to stabilise underground mine workings has been implemented. However, the placement of sludge underground has not (to our knowledge) been permitted anywhere.

Case studies of four sites overseas where sludge with excess alkalinity has been placed into mine workings were found, where the results were promising in terms of the impact on the operational water quality. It is suggested by Zinck that the application could be useful, but possibly limited to specific sites where the level of metal contamination (particularly zinc and cadmium) are low.

An important issue in terms of disposal into mine workings is the system used to determine the hazardous nature of sludge. The toxicity is normally determined by either the Toxicity Characteristic Leaching Procedure (TCLP, US EPA method 1311 – designed to simulate co-disposal with municipal putrescible waste) or the Synthetic Precipitation Leaching Procedure (SPLP, US EPA method 1312, which simulates an acid rain scenario). Neither of these tests are specifically designed for evaluating Acid Rock Drainage (ARD) treatment sludge leachability, where the material could be exposed to the low pH of common mine site disposal environments (McDonald *et al.*). An alternative test (Strong Acid Leach Test, SALT) has been proposed by McDonald for mine disposal environments.

Some advantages and disadvantages of disposal in underground mine workings are given in **TABLE 12**.

TABLE 12. DISPOSAL IN UNDERGROUND MINE WORKINGS.

Advantages	Disadvantages
• Reduced footprint of surface disposal areas • No direct risk for surface water pollution (but still at risk through possible groundwater contamination). • Reduced potential for subsidence in some instances. • Below ground disposal aesthetically more acceptable • Potential utilisation of residual alkalinity in neutralising mine water • Sludge with high Fe content more favourable.	• Sludge with high Cd, Zn or Ni content may represent significant residual risk to mine water or groundwater. • Level of uncertainty will always exist in terms of possible groundwater impact. Issues of residual liability may be problematic to resolve.

A variation on disposal in mine workings is the use of sludge material as a stabiliser or paste backfill (Fiset et al., 2005). Addition of a binder has the potential to limit leaching characteristics, although it must be noted that while cement (for example) can stabilise certain constituents, it can also result in additional compounds being leached. The arguments for and against this approach appear to be similar to those around disposal into mined out areas, with the advantage that the sludge is being used in a "value added" application, albeit with associated costs.

7.2.1.5 Disposal in opencast mine voids

At many opencast mining sites, material balances or the economics around materials handling have resulted in depressions or final voids that remain after mining has ceased. These can range from small areas to large pit lakes.

Disposal into these areas is often attractive due to the possibility of reducing the non-free draining landscapes. In many instances, it is simply the cheapest disposal option due to the close proximity of mined out voids to the water to be managed.

However, mining voids are seldom (if ever) completely isolated from the environment. There are thus similarities compared to placing the material into underground workings, but with the additional disadvantage that the sludge may be above the decant water level and thus exposed to oxidising conditions and leaching through rain water ingress. This is less likely (although also possible) with underground workings.

Some advantages and disadvantages of using opencast voids are given in **TABLE 13**.

TABLE 13. DISPOSAL INTO OPENCAST MINE VOIDS.

Advantages	Disadvantages
• Can be economical if within a reasonable pumping distance. • Other advantages as per disposal into the workings	• Material may not be suitable as landfilling due to lack of shear strength. • May remain in an oxidising and leaching environment. • Risk of groundwater contamination likely to remain.

7.2.1.6 Land filling

The use of landfills for the disposal of wastes designated as hazardous is accepted practice worldwide, albeit that this is an admission that we simply do not have an affordable technology available in many instances to convert waste into either a resource or a benign waste.

This problem often applies to wastes which are either diverse in nature, or for which the likely end product of any technology is a low value type product. For these wastes, placing them into engineered facilities designed appropriately to the nature of the hazard with a system of liners and/or collection / detection systems intended to isolate the waste from surface and groundwater remains an environmentally acceptable solution.

Some advantages and disadvantages of landfilling are given in **TABLE 14**.

TABLE 14. LANDFILLING.

Advantages	Disadvantages
• Material can be isolated from the environment. • Landfill sites are managed by companies specialising in the waste. • Centralised collection of waste allows for better control.	• Landfilling not favoured by many environmentalists. • Distance from mining areas to landfill sites may be prohibitive in terms of transport costs. • Solid – liquid separation of sludge in a landfill can be a problem. • Legislation of landfills is becoming increasingly stringent.

7.2.2 Reprocessing

The historical approach to reprocessing has been primarily to attempt to recover the potential economic value in the sludge associated with (often) a high metal content (typically zinc and copper – Aubé and Zinck, 1999). Approaches used historically include hydrometallurgical options (leaching, etc.) and pyrometallurgical recovery (heating up of the sludges). Approaches are discussed in detail in Zinck (2005).

Historically, the cost of reprocessing has exceeded the economic benefit, and the process has rarely been adopted. However, given that the metal content is a major part of the environmental hazard of most sludges, the comparative disposal cost of sludges after removal of metals could result in these technologies again being considered.

In mine water treatment applications, it would appear logical to selectively target the metals of value in a progressive precipitation/removal process rather than precipitating all the metals in one step.

One technology that has been featured recently is the use of biological H_2S production for the precipitation of heavy metals (Bratty et al., 2006). The use of a standalone reactor producing H_2S on demand appears to have successfully reduced some of the historical problems associated with an onsite sulphide inventory. The BioSulphide® technology claims to be cost effective, and at the time of writing was being operated at two metal mines in Canada and the USA, with a further three in progress. One further plant is used for contaminated groundwater treatment.

7.2.3 Stabilisation / solidification

In terms of disposal options, the use of sludge in paste used as backfill to stabilise mined out workings was indicated. This is just one application of a field of technologies that try to stabilise the sludge so that it becomes a chemically stable solid material with reduced risk of leaching and simplified handling characteristics.

Interesting work in this field has been done by Tseng (1998), Chang et al. (1999), Conner and Hoeffner (1998), Fiset (2003) and various other authors.

Typical technologies that have been considered / used include:

- Sorption;
- Lime-based stabilisation;
- Cement-based stabilisation: Portland cement; combinations of Portland cement and fly ash; Portland cement and slag, lime, fly ash and phosphate binder;
- Thermoplastic techniques;
- Polymeric technologies;
- Encapsulation;
- High temperature techniques: vitrification, thermal bonding, sludge slagging.

Limitations for many of the above processes include,

- Transportation costs. Many sites are remote from prospective areas of application of the inert material;
- Many of the technologies are expensive;
- The high water content of many sludges complicates the treatment of the sludge.

An interesting field is the consideration of the crystalline components formed during neutralisation. McDonald (2006) indicated that the control of oxidation state and Al concentrations can greatly increase the crystallinity and chemical stability of the sludge precipitated. This appears to be an area of further research potential.

7.2.4 Re-use

In terms of sustainable development, the re-use of a waste material either to replace a natural resource, or as a raw material in itself is surely the ultimate goal. Sludges are limited in their reuse application due to their metal content, while there are only limited technologies available to render the material more environmentally acceptable.

Sludge has found application in the following fields:

(a) Building material

The use of waste products in building materials is widespread for many solid wastes where contaminants can be bound into the matrix of a product such as a brick (Levlin, 1998). The high alumina content of some sludges is favourable for aluminous cement (Lubarski et al., 1996).

While for many sludges the volume that can be mixed in to cement (for example) without affecting the final product are limited to around 5%, there are reported instances that some sludges could replace as much as 30% of Portland cement in a blended cement mix (Hwa et al., 2004).

There are limitations, however, both in terms of handling the material (the sludge needs to be dried before use) and cost (most cement kilns are relatively remote compared to coal mining areas in South Africa, resulting in potentially large haulage costs). The consistency of sludge may also be a problem if it is to be used as a blend to cement, since variability in quality would make the material less desirable for re-use.

(b) Agricultural land application

A study by the Minnesota Pollution Control Agency (MCPA) (1999) indicated that low metal content sludges blended with agricultural lime may have application to raise soil pH in agricultural applications. The nutrients of value were considered to be sulphur and boron, but strict limits in terms of metals given by the MCPA. Concerns exist in terms of public health and other social concerns, and the application may be limited.

(c) Treatment of industrial wastewater treatment

An interesting application of the ferrihydrite ($Fe(OH)_3$) component of sludge is the use of the material for metal removal, particularly copper and zinc (Edwards and Benjamin, 1989).

Treatment sludge has also been found to remove carcinogenic dyes and colour from waste water (Netpradit et al., 2003).

(d) Carbon dioxide sequestration

The same mechanism that generates CO_2 in the production of lime can be used to sequester or absorb CO_2. The benefit of this is both the removal of CO_2 and the production of more stable sludges. This process apparently occurs naturally in sludge ponds, but can be developed and optimised. Zinck (2006) indicates that in Canada some 60 000 t CO_2 could be sequestered annually. Presumably the funding of this would be through carbon credits.

(e) Production of paint pigment

Hedin (2002, 2006) has published several papers on the use of passive treatment processes to yield iron oxide sludge that has marketable pigmentary characteristics. The technique currently involves obtaining sludge unaffected by surface water sediments (that may contain alumino-silicate minerals). In order to have a saleable Fe oxide sample, greater than 50% Fe oxides are required. These appear to be generated in alkaline environments (pH 6 to 7) where passive treatment is applied. Active chemical systems appear to result in sludges that are not pure enough for exploitation.

The application appears to be most suited to small to moderate flows where there is a high iron content, where the pH of the mine water is alkaline and where passive treatment systems can be installed to precipitate the iron.

It is uncertain whether anyone has tried to develop systems associated with active neutralisation that are able to achieve purities of the order required to obtain a marketable pigment feedstock. However, crystallisation technologies used at the downstream end of brine management do target Fe oxides as potential value products.

(e) Other

Other applications that have been employed include: -

- Use of spray-dried sludge as a risk dust substitute for explosion control (Simonyi et al., 1977).
- Production of high strength aggregate by drying, pulverizing, pelletising and sintering of sludge (Hwa et al., 2004).

7.3 Summary – Sludge disposal

Our understanding of the current status in South Africa is as follows:

- Several mines neutralise mine water within settling ponds
- Lined lagoons are used for brine as well as sludge from the process;
- Applications have been made to allow the disposal of low metal sludge into a mine waste area, that is, with a certain level of liner, and being co-disposed with coal discard;
- Prior to the construction of a crystalliser plant, one site was able to utilise a tailings facility for brine and sludge, but only on a temporary basis;
- Application was made for a trial disposal underground of brine within an isolated compartment. The status of this and whether it was used for brine or brine and sludge is uncertain;
- Consideration has been given historically to utilising old tailings for both sludge and brine, but a negative response was received from the authorities and landowners at the time, due to issues around groundwater impacts and liability issues.

It would appear that:

- A weakness in the current approach to metal and acidity removal in the treatment process is that the precipitation process generally does not minimise the volume of hazardous material. The toxicity of sludge is frequently controlled by the concentration of metals in the sludge, which may, or may not be, quite a small proportion of the total waste stream;
- A range of uses have been found or tried for sludge from Acid Mine Drainage, but there are limitations in terms of the volumes being generated (large), the location of the material (often remote) and the potential uses (certain select possibilities rather than a general or widespread application suggesting relatively small volumes will be used);
- Selective metal removal using sulphides, or the precipitation of minerals such as jarosite at low pH appear to have the potential to produce lower volumes of sludge, and possibly significantly lower volumes of high hazard sludge;

- On any large mining operation, there are normally significant volumes of waste to be managed. Technologies that result in the potential disposal of significant volumes of sludge back into the mining operation or on to existing waste facilities must be highly desirable;

- To this end, technologies that result in a low hazard sludge such as the formation of more stable crystalline structures that may be able to limit the leachability of metals appears to have significant possibilities, particularly if the metal removal can be selectively controlled. While the focus for sludge management is quite correctly on minimising sludge volumes, possibly a more important focus should be to limit the volume of high hazard sludge, and maximising the volume that can be co-disposed either within the mine, or with the mine waste;

- An important further consideration is whether the techniques used to classify the sludge are appropriate. The correct approach will depend on the final disposal option or use, but consideration may have to be given to other techniques such as SALT (McDonald, in press) rather than the Acid Rain Test, as well as requiring an understanding of the potential impact of bacteriological action.

CHAPTER 8

8. COMPARISON OF SELECTED INNOVATIVE CONCEPTS

This chapter compares selected innovative brine management concepts with present disposal strategies, namely disposal to lined evaporation ponds and mechanical evaporation/crystallisation.

The innovative concepts evaluated here are:

- Wind Aided Intensified eVaporation (WAIV)
- Dewvaporation;
- Freeze desalination;
- Brine treatment.

8.1 Basis for comparison between options

In order to compare different innovative brine management options, a conceptual brine was defined, consisting mostly of sodium chloride, with scaling potential from calcium sulphate. It was decided to keep the conceptual brine composition relatively simple in order to minimize inter ion reaction effects which could mask major differences between various technologies. However, it is recognized that this is a hypothetical case and should be verified by on-site work with real life brines, including other contaminants such as metals, organic compounds, etc. All evaluations were done for a 20 year project life using prices as quoted in first quarter 2007.

TABLE 15: CONCEPTUAL BRINE COMPOSITION

Component	Unit	Value
pH		10
TDS	mg/l	18900
K	mg/l	710
Na	mg/l	6300
Ca	mg/l	450
Cl	mg/l	10360
SO_4	mg/l	1080

All processes options were compared at a feed rate of 1000 m^3/d of brine. This is equivalent to a desalination plant capacity of 10 Ml/d at 90% water recovery and 20 Ml/d at 95% water recovery, which is a reasonable representation of a typical larger scale desalination plant presently in the local industry.

The temperature of the conceptual brine was assumed to be in accordance with **TABLE 16**.

TABLE 16. ANNUAL TEMPERATURE PROFILE OF BRINE

Month	Mean	Max	Min
	deg C	deg C	deg C
October	19	20.9	18
November	19.5	21.4	18.1
December	21.3	21.5	19
January	22	22	21.2
February	21.8	22	20.4
March	21	21.3	20.4
April	18.3	19	17.9
May	15.2	15.5	14.9
June	14.9	15.4	14.5
July	14.9	15.3	14.5
August	15.2	15.6	14.9
September	17.1	18	16.8
Annual	**18.4**	**19.0**	**17.6**

Witbank was selected as an arbitrary site to compare the various technologies, with the meteorological characteristics as given in **TABLE 17** and **TABLE 18**.

TABLE 17: TEMPERATURE DATA FOR WITBANK AREA
(South African Weather Service)

Month	Daily mean	Daily max	Daily min
	deg C	deg C	deg C
October	18.3	24.8	11.7
November	18.9	24.6	13.2
December	19.8	25.1	14.5
January	20.6	26.2	14.9
February	20.5	26	15
March	20.2	26.1	14.2
April	17.5	23.9	11.2
May	14.5	21.3	7.7
June	12.2	19.1	5.2
July	11.4	18.4	4.3
August	14.1	21.5	6.7
September	16.1	23.5	9.2
Annual average	**17.0**	**23.4**	**10.7**

Data from the South African Weather Service indicates that the relative humidity in Witbank varies between 45% and 65% with an average of about 55%.

Wind speeds are generally light to moderate, except during thunderstorms when North-East winds predominate. For 40% of the time, wind speeds are below 1 m/s, whilst wind speeds exceeds 1.5 m/s for 35% of the time. Maximum wind speeds in excess of 3.6 m/s is measured only 1.2% of the time, whilst wind speeds rarely exceed 5.5 m/s. A mean wind speed of 1.8 m/s was used in this report.

TABLE 18: EVAPORATION AND RAINFALL DATA FOR WITBANK

A-PAN EVAPORATION DATA (WRC Report No 298/2.94)				
Month	**Days/ month**	**Evaporation**	**Rain**	**Nett Evaporation**
	ea	**mm**	**mm**	**mm/month**
October	31	139	80	60
November	30	131	115	17
December	31	145	101	44
January	31	142	131	11
February	28	119	88	30
March	31	117	81	36
April	30	90	46	44
May	31	76	13	63
June	30	62	8	54
July	31	67	6	62
August	31	89	7	82
September	30	116	27	89
Annual		**1,292**	**700**	**592**

8.2 Baseline costs

8.2.1 Evaporation ponds

The disposal option assessed here entails placing the brine into a suitably lined holding pond, with an overall salt storage capacity for a project life of 20 years. While storage within a containment facility is not highly desirable in terms of sustainable development, it remains a preferred disposal method for low value or highly mixed waste.

Bearing in mind that with evaporation of the water, the remaining brine will increase in salinity, a standard double liner system as shown in **FIGURE 26** was used for the brine pond. It was assumed that a reasonably large site will be available where a pond can be excavated, walls formed with the material removed, and the liner system then put in place.

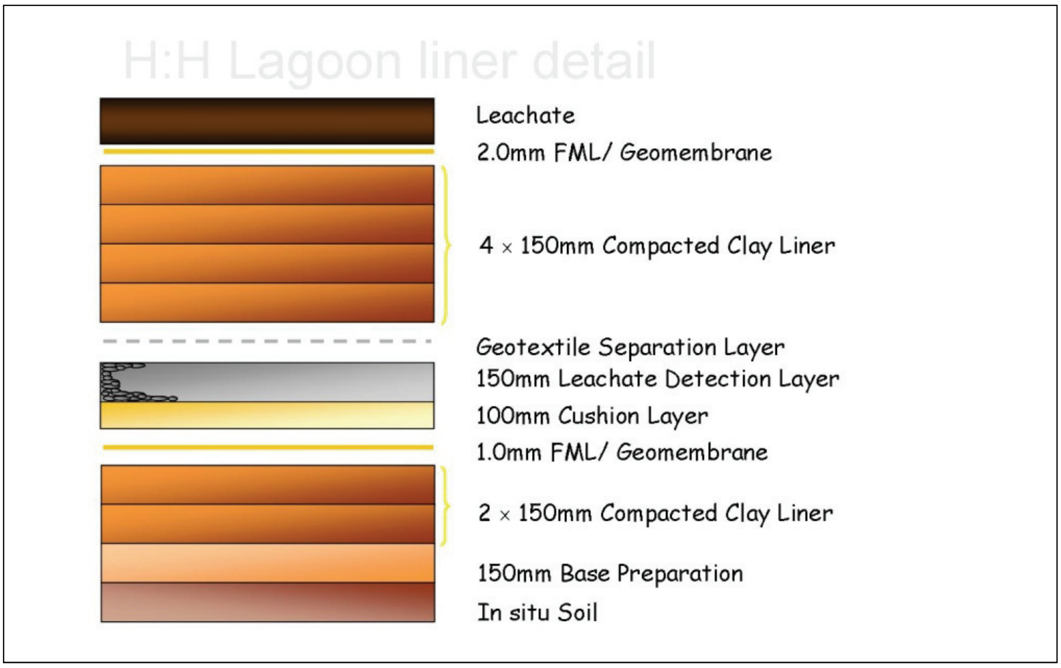


FIGURE 26. CONCEPTUAL LINER SYSTEM

Note that this liner is the H:H lagoon liner which may be conservative in some applications. Our understanding is that similar liners are being planned for new water treatment sites.

Two systems of storage were then modelled, firstly assuming evaporation from the water surface only, and secondly allowing for water to be drained into the pond off the sides of the dam, thus obtaining evaporation from the exposed sides as well.

From **TABLE 18** a precipitation rate of 700 mm/a and evaporation rate of 1200 mm/a were used in modelling the evaporation pond.

Data from evaporation rates studies undertaken on the Dead Sea water was used to factor in the effect of salinity on clean water evaporation rates. The reduction associated with increasing salinity was of the order of 20% to 30%. A value of 30% was used in the calculations. Note that although the overall salinity is quite a bit lower than seawater, this will increase with time due to the evapo-concentration effect. On the side slopes, it is probably reasonable to use the pan evaporation rates, which are 30% greater than those for the dam.

A conceptual dam was then modelled, having 1:4 side slopes. Monthly time steps were used to avoid excessive errors that can occur when evaporation is taken as occurring from the surface area after the inflow of water without evaporation, when in reality evaporation occurs on a daily basis, thus preventing the higher water level being reached within a particular time step.

Assuming that the optimal cut to fill will result in a depth of dam somewhere around 5 to 15 m, and that excessive cut could be problematic due to a shallow water table within a few metres of surface, a dam of depth around 15 m was modelled. The results are given in **FIGURE 27**.

For this particular dam size, a life of 20 years can be obtained, but with a lined surface area calculated at 38,2 ha. The computed costs are expected to be in the range of R150 million to R230 million, for an all in liner cost of the range of R400 to R600/m^2. **This excludes the cost of land.**

The current strategy adopted at several sites to improve cash flow is to implement brine disposal in phases. In this strategy, implementation of the first brine ponds will be made, and options are developed to reduce brine volume during the operational life of the project.

The cost of land will depend on the location of the site and if it is already owned by the owner of the desalination facility. In the Witbank area, undeveloped agricultural land prices varies between R1800/ha and R5000/ha. Using a value of R5000/ha, the cost of land will add a further R191 000 to the project cost, thus a relatively small percentage of the overall cost. Clearly, in build-up or industrial areas, this cost will be significantly higher, and could be as high as R250 000/ha, in which case the cost of land could be as high as R95 million – clearly an incorrect land application.

In terms of dividing the dam up into several ponds, the cost difference is not that significant. Several smaller ponds are theoretically less efficient in terms of area of liner required for a particular storage volume, but may have additional evaporation off the sides.

In terms of these costs, the costs for monitoring boreholes are negligible. On the assumption that around 8 to 10 boreholes may be required, the cost for these would be around R0,3 million. Annual sampling costs would be typically R60 000/annum, or some R1.2 million over a 20 yr period. The total cost of the project at present value over 20 years is thus approximately R151-R231 million.

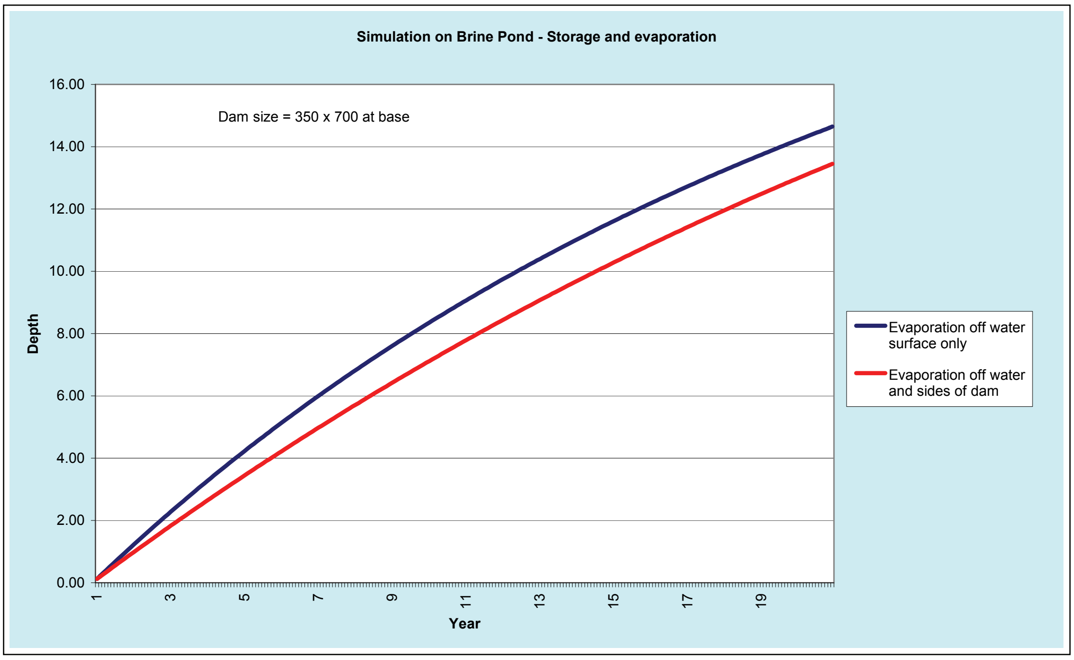


FIGURE 27. CONCEPTUAL DAM DEPTH AND AREA

The liner is not expected to require any ongoing maintenance. However, several aspects may require attention:

- Liner lifespan is normally in excess of 100 years, but at an operating temperature of typically 20ºC. The salinity of the water could result in increased temperature of the water, potentially affecting the life span of the liners.

- Liners are vulnerable to damage by fly rock (if constructed next to a mine), theft and vandalism.

8.2.2 Mechanical evaporation

For the evaluation of mechanical evaporation, a forced circulation evaporator, operating in slurry mode, followed by a crystalliser was evaluated. This option allows recovery of a by-product or alternatively precipitation of a mixed salt stream.

Conceptually, the process flow is given in **FIGURE 28**. For the purpose of this document, the pre-treatment section and reverse osmosis system was ignored, but it was assumed that the resulting brine from the reverse osmosis system will approximate that of the hypothetical brine, which exhibits the following important characteristics in terms of evaporator design:

- Chloride is present at high concentration, thus sophisticated materials of construction will be required to minimize corrosion. This situation frequently occurs with industrial brines in South Africa;

- The brine will become scaling as water is evaporated, again mimicking real life brines. As a result the evaporator will have to be operated in the slurry mode, probably as a forced circulation type evaporator.

In order to optimise energy costs, the evaporator unit was designed as a MVR unit, manufactured from SS316 and Duplex steel. This option increases the capital cost of the system but reduces energy requirements significantly and should be the general approach for actual applications.

In the evaporator, pure water is evaporated, for downstream recovery and re-use. Concentrate from the evaporator is routed to the crystalliser, where additional vapour is recovered. Solid crystals are recovered as potential by-products whilst a small purge stream leaves the system for final disposal elsewhere. Typically, such a purge stream may be routed to a small lined evaporation pond, or eliminated completely, depending on the process chemistry.

Materials of construction will largely be determined by the brine feed to the evaporator/crystalliser. In this instance, the presence of chlorides and the scaling nature of the feed require the use of specialised material. General process pumps are typically manufactured from SS316, whilst slurry pumps and axial flow slurry pumps must be constructed from Monel or higher grade materials. It is anticipated that the evaporator and crystalliser units will have to be constructed from Monel and that all major heat exchangers will consist of mixtures of SS316, titanium, 254SMO and SS904L.

The system should be fully automated and be operated continuously with appropriate buffer tanks upstream and downstream of the system. Provision has to be made for a control room and a four shift operating system.

Cost estimates and proposal from equipment vendors suggest a total cost of R180 million to R220 million for a complete turn installation, depending on other peripheral infrastructure on site. Of course, a significant portion of infrastructure will be shared by the upstream desalination system, thus it is probably fair to state that actual best case costs, directly associated with the brine evaporator/crystalliser, will be closer to R180 million, excluding VAT.

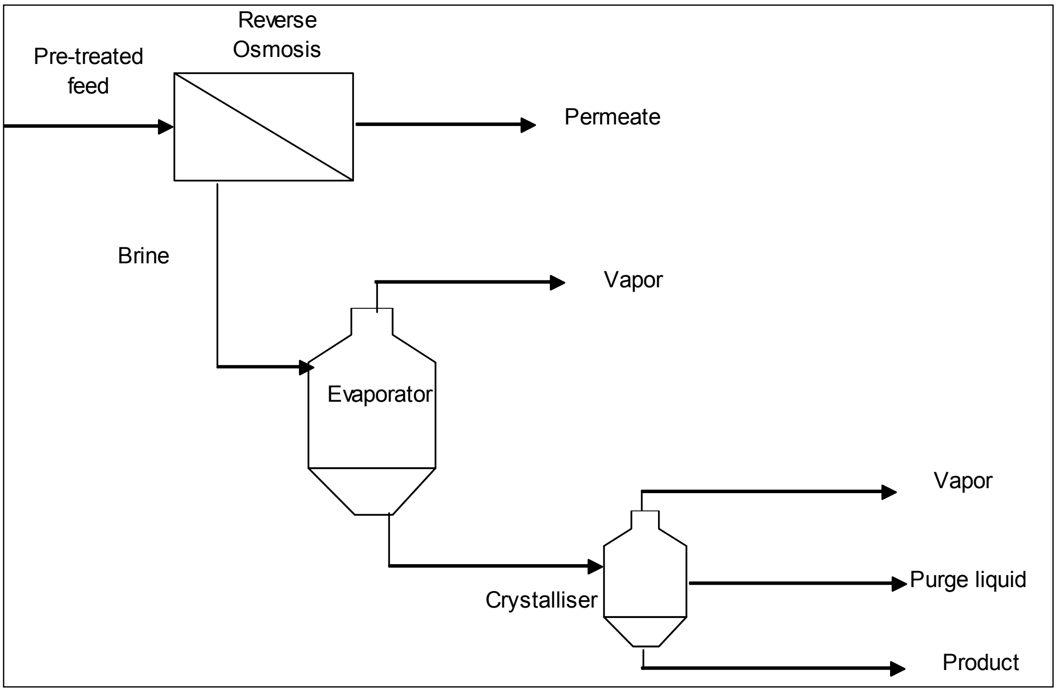


FIGURE 28. CONCEPTUAL FLOW DIAGRAMME OF EVAPORATION SYSTEM

It was assumed that sufficient plant utilities such as compressed air, steam and electricity are available. Should this not be the case, significant additional capital costs will be incurred.

Operating costs are estimated to be in the region of R35-R40/kl evaporated water (**TABLE 19**). It should be noted that a significant provision for maintenance was made, considering the poor operating history of these plants.

Over a projected life-time of 20 years, the operating cost equals approximately R267 milion. Including the capital cost of R180 million, the overall project cost over the life of the project comes to approximately R447 million. This is significantly more than that of the evaporation pond option. However, it should be noted that the total footprint of the evaporator/crystalliser option is likely to be less than 1500 m^2, compared to the 38 ha of the evaporation pond system. Given the space constraints in built-up areas, the evaporation/crystallisation option may be the only practical solution.

Table 19: Estimated operating cost – evaporator/crystalliser

Description	*Dosage*	*Unit*	*Consume*	*Unit*	*Unit price*	*Cost (R/a)*
Cleaning chemicals						
HCl			21507	l/a	6.7	143,771
Total						*143,771*
Electricity						
Electrcal consumption EC		kW	1194	c/kWhr	20	1,882,699
Total						*1,882,699*
Steam						
EC plant (10 bar (g))		t/a	13912.94	R/t	80	1,113,035
Total						*1,113,035*
Manpower						
Description				*Total*	*Cost*	*Cost (R/a)*
Plant foreman				4	300,000	1,200,000
Panel controllers				4	260,000	1,040,000
Skilled operators				4	200,000	800,000
Total						*3,040,000*
Unit cost of product						
Description					*Cost (R/a)*	*Unit cost (R/m^3)*
Annual volume		365000	m3/a			
Cleaning chemicals					143,771	0.39
Electricity					1,882,699	5.16
Steam					1,113,035	3.05
Manpower					3,040,000	8.33
General maintenance (EC)					7,200,000	19.73
Total					**13,379,505**	***36.66***
Input data						
Description	Unit	Qty				
Annual operating time	hrs	7884				
Capital cost (EC)	R	180,000,000				
Maintenance factor (EC)	%	4.0				

8.3 Wind Aided Intensified eVaporation (WAIV)

8.3.1 Description

Previous work have shown that whilst evaporation ponds are appropriate for brine disposal in smaller applications located in remote, arid areas, the main drawbacks of evaporation ponds are:

- Large land area required;
- Decreasing efficiency with pond area;
- Increased hazard of ground and aquifer contamination with increased pond area;
- Expense of double lining and associated monitoring.

Mickley (2001) concurs with the above comments and found that between 1993 and 2001, the use of evaporation ponds reduced by some 50% for brackish water and industrial water desalination.

Evaporation rate due to wind from a body of water has been correlated to the vapour pressure of the air and of the evaporating water body, and to wind speed (equation 8.1):

$$E = N.u.(e_w - e_a) \qquad (8.1)$$

Where:

E	Evaporation (mm/d)
N	Evaporation efficiency coefficient
u	Wind speed (mm/d)
e_w	Vapour pressure of water at surface temperature
e_a	Vapour pressure of air at surface temperature

It has been shown by Brutsaert (1982) that as pond area increases, evaporation efficiency drops significantly as given by the following correlation of the wind coefficient, *N* (equation 8.2):

$$N = 3.367.10^{-9}.A^{-0.05} \qquad (8.2)$$

Where:

A Area of water evaporation body.

This correlation was shown to hold for water bodies of 4000 m^2 to 120 km^2. Brutsaert also found that evaporation efficiency is lowest at ground level where lower wind speeds prevail as opposed to higher areas where the wind has increased velocity. Equations (8.1) and (8.2) clearly show that mass transfer efficiency drops with increasing extension of evaporation ponds downwind.

Contrary to standard open evaporation ponds, the WAIV concept exploits wind energy to evaporate water from wetted surfaces that are packed in high density per foot-print. By deploying such surfaces in arrays with large lateral dimensions, significant height (>3 m) and minimal depths (4-5 m), wind energy can be used successfully while it remains below its moisture saturation point. Thus a maximum driving force ($e_w – e_a$) (eq. 8.1) is maintained. (Gilron *et a*l., 2003).

The WAIV process involves circulation of brine over vertically suspended “wetable surfaces,” designed to increase the effective evaporative surface area.

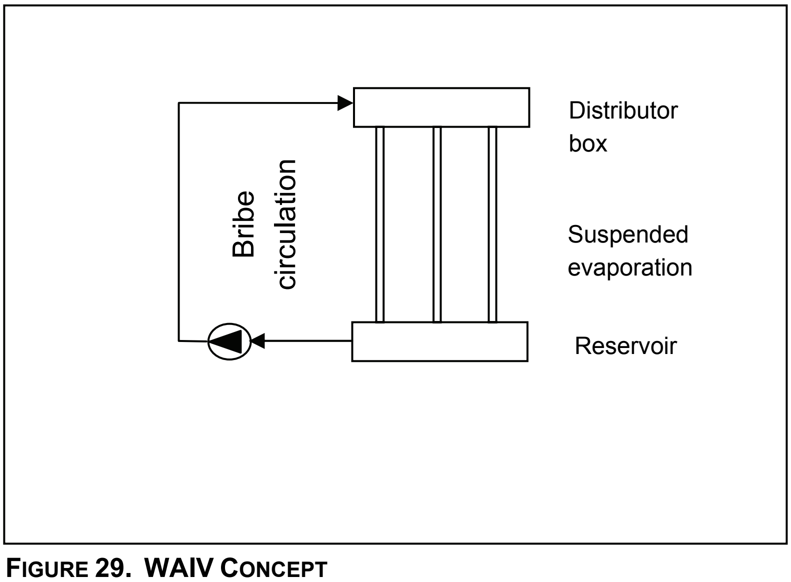


FIGURE 29. WAIV CONCEPT

The surfaces are suspended as shown in **FIGURE 29** and were wetted by circulation of water from the top.

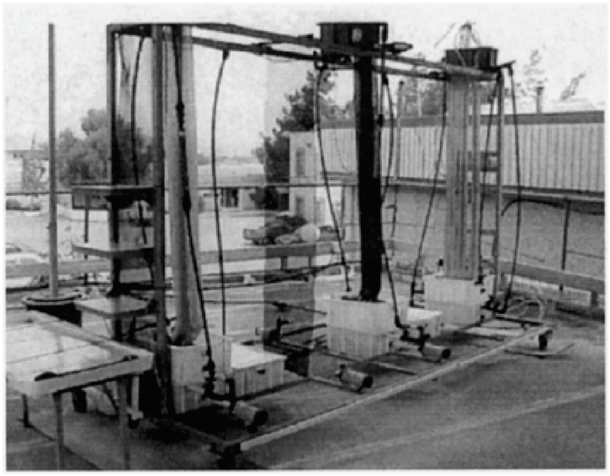


FIGURE 30. SMALL SCALE WAIV TEST UNIT

Using small scale "roof-top" experiments, researchers at Ben Gurion University in Israel evaluated the concept of brine evaporation from vertically suspended surfaces (**FIGURE 30** and **FIGURE 31**).

FIGURE 31. CRYSTAL FORMATION ON WAIV SURFACES

In developing the WAIV concept the researchers considered a number of parameters:

- **Hydrophilicity:** An optimum has to be found in the hydrophilic nature of the surface, that it is hydrophilic enough to allow spreading of the brine, but not so hydrophilic as to reduce the effective vapour pressure;

- **Scaling:** It should be possible to remove scale from evaporation surfaces without long term damage;
- **Porosity:** An extremely smooth surface may not allow sufficient water retention for meaningful evaporation to take place, whilst highly porous surfaces may become blocked by dust or scaling;
- **Packing density:** Packing should be high enough to get good enhancement of evaporation capacity per footprint without necessary blocking of the wind;
- **Mechanical strength:** Evaporation surfaces have to be light, yet strong to prevent wind damage;
- **UV-resistance:** Materials should be UV stabilised;
- **Cost:** Surfaces should be significantly cheaper than pond liner to facilitate a reasonable saving.

To date, the Ben Gurion University researchers have evaluated a number of alternative surfaces, with the most promising results being obtained from "woven netting". This material has proven particularly successful in longer term trials with regard to build-up of dust and scale. In one particular "roof-top" experiment, scale was deliberately allowed to form on the surface (**FIGURE 31**). Using a clean water flush, most salt could be removed from the surface, with no significant long term deterioration in evaporation performance.

During "roof-top" experiments, packing densities of 20 m^2 evaporation area/m^2 footprint were used. It was found that evaporation of tap water was at least ten times that of evaporation from a standard A-pan of the same size as the footprint of the WAIV unit.

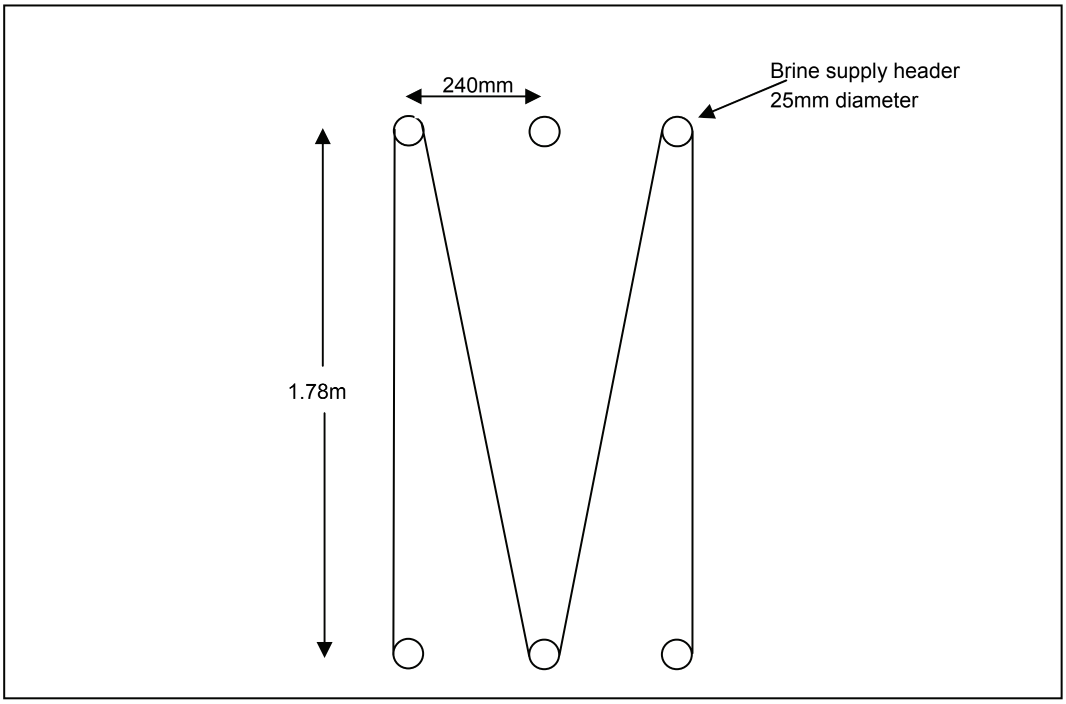


FIGURE 32. DESIGN OF WAIV SYSTEM – BEN GURION UNIVERSITY "ROOF-TOP" TESTS

Following small scale tests, a demonstration unit was installed on an existing mine water desalination brine in Eilat, Israel. This unit was designed to evaporate approximately 5-8 kl/d of desalination brine with a starting TDS of 20 000 mg/l (**FIGURE 33**). A similar unit was installed on dead-sea brines with TDS values in excess of 45 000 mg/l.

Packing densities achieved in these units were 34 m^2/m^2. Evaporation rate per square meter wetted WAIV surface approaches that of a normal A-pan. Total evaporation rate per footprint area is between 32 and 34 times that of a normal A-pan used as control in this experiment.

FIGURE 33. DEMONSTRATION SCALE UNIT FOR DISPOSAL OF 5-8 KL/D MINE WATER BRINE

The demonstration plant is in operation since 2005 with no apparent deterioration of surfaces or evaporation efficiency. However, the concept is still in early development stage and the following concerns remain – particularly relating to local conditions:

- Scaling of sparingly soluble salts and resultant maintenance of evaporation surfaces;
- Fouling of evaporation surfaces by wind borne particulate matter such as dust, grass and seeds;
- Mechanical damage due to strong winds;
- Fog harvesting resulting in a net increase in brine volume;
- Freezing of surfaces during extreme cold winter months;
- Theft;
- Replacement frequency of WAIV sheets;
- Corrosion of support structure and recirculation pumps;
- Scaling in recirculation pipes;
- Applicability of system to larger application.

8.3.2 Conceptual design – 1 Ml/d unit

Conceptually, brine flows into a holding pond which is covered by vertical WAIV strips where it is concentrated by a factor of 10. The concentrated brine is then routed to a final evaporation pond which serves as the final concentrate evaporation pond and storage volume for precipitated salts (**FIGURE 34**). Both the holding pond and final concentrate evaporation pond are double lined ponds.

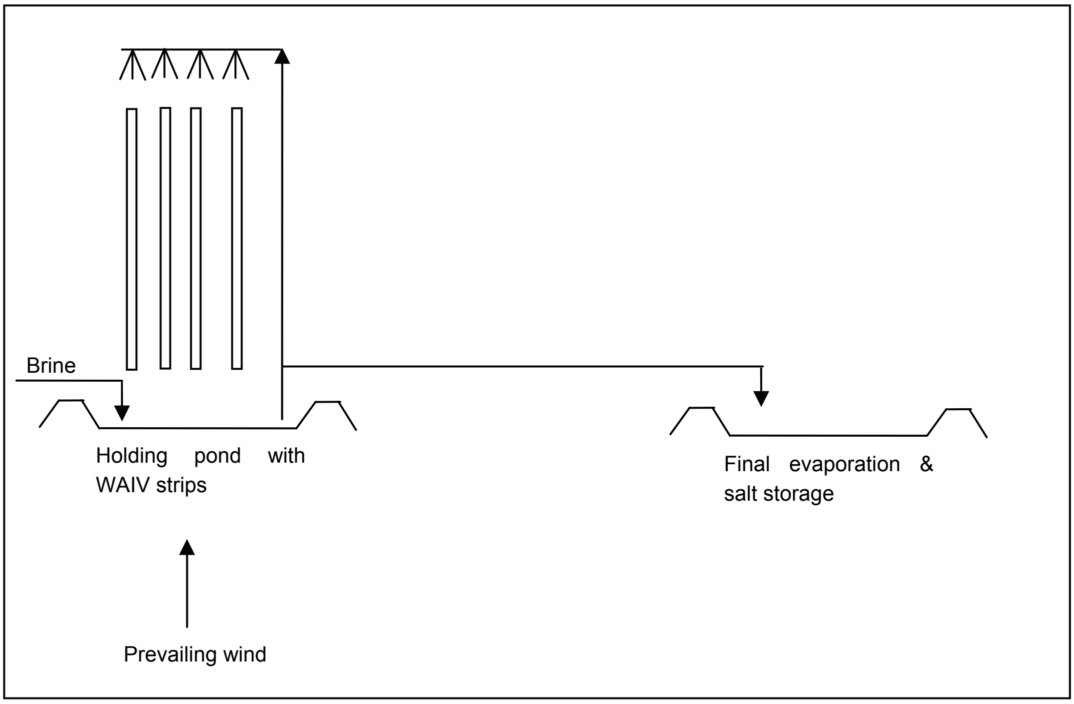


FIGURE 34. CONCEPTUAL WAIV SYSTEM

For the purpose of this conceptual design, 40% shade netting is used as the WAIV strips, suspended over the pond using a support frame made of fibreglass. WAIV strips should be aligned with the predominating wind direction. All piping and pipe fittings could be manufactured from an engineering plastic such as u-PVC. This arrangement eliminates to a large extend the requirement for expensive materials of construction such as what would typically be required for brine evaporators. The only part which requires the use of duplex stainless steel is the pumping system and even here it may be possible to consider the use of peristaltic or plastic pumps such as is used for the pumping of chemical brines and acids.

Agricultural shade netting is available in strips of 3 m wide and manufacturers recommend that for vertical surfaces, the maximum surface area between support poles should not exceed 50-60 m^2. Assuming a maximum height of 5.5 m (two strips), the maximum recommended distance between supports should not exceed 3.5 m and the total distance of 9 m. This is roughly double the depth recommended by Ben Gurion University researchers, and some drop in evaporation efficiency compared to an open pan may be observed. For the purposes of this evaluation, a 10-20% drop in efficiency has been assumed, based on discussions with researchers at Ben Gurion University.

Using a spacing of 0.5 m between vertical strips, a packing density of 36 m^2 evaporation area per m^2 footprint is achieved which is of the same order as that achieved in the demonstration facility (**FIGURE 33**). From meteorological data and an evaporation efficiency of 80% compared to A-Pan data, an evaporation rate of 2.83 mm/d from WAIV surfaces can be calculated. Thus, a total WAIV evaporation surface area of almost 353135 m^2 is required, resulting in an overall footprint of 1.0 ha (**TABLE 20**).

For a maximum depth of 9 m, the required lateral width exposed to prevailing wind is 1.09 km. This very wide, but shallow system is probably not practical and a number of WAIV units, each 200 m long is probably more appropriate.

TABLE 20: MAJOR DESIGN PARAMETERS FOR 1 ML/D WAIV SYSTEM

Brine inlet TDS	mg/l	18900
Brine evaporation capacity	m3/day	1000
Evaporation efficiency	%	80
Evaporation rate	mm/d	2.83
Area	m2	353135
Packing density	m2/m	36
Footprint	m2	9809
	ha	1.0
Width of WAIV units	m	9
Length of WAIV system required	m	1090
Selected WAIV unit length	m	200
Number of WAIV units	ea	5

Thus, 5 WAIV units are envisaged, each being 200 wide and 9 m deep, positioned 100 m apart in the down-wind direction.

The distance of 100 m is purely arbitrary at this stage and the lay-out may be optimised to fit available site. Each WAIV system will have its own lined pond underneath it, inter-connected with other ponds. These ponds can be as shallow as possible. From brine inflow volume, evaporation data and footprint requirements for the WAIV units, a minimum depth of 2.8 m can be calculated.

It is envisaged that the brine will enter the first WAIV unit of each train and will be progressively concentrated by sequential units as it progresses from one train to the next. When it reaches the fifth unit, it will be concentrated by a factor of 10 times. At this point it is pumped to the final evaporation pond for final evaporation and salt storage.

To prevent scaling on pipe surfaces, it is anticipated to allow salt crystals to be circulated in the main distribution loops, thus using previous experience from the SPARRO processes.

As with the 100 m distance between WAIV units, the volume concentration factor of 10 times is somewhat arbitrary. The main purpose of this, however, is to illustrate that the brine will not be evaporated to final dryness in the WAIV units, but that a final pond is required for evaporation to dryness and salt storage. A total surface area of 4.3 ha is required for this pond. To make provision for salt storage, and assuming no salt removal during 20 yrs of project life, the required pond depth is 2.0 m.

8.3.3 Operating costs

Anticipated operating costs are summarised in

Electrical requirements are mainly associated with brine recycling. This number is somewhat uncertain at present as the recycling rate is not fixed. It is anticipated that the recycling rate will be between 2 and 6 times the daily evaporation rate to ensure properly wetted surfaces.

Data from netting suppliers and operational experience in Israel suggest a minimum life of 5-7 years for the netting. Provision has been made for full replacement of the netting and wire support system once every 5 years.

A single operator is required for daily checking and maintenance of the system. Depending on the complexity and size of the final installation, this operator may be shared with other duties on site.

The maintenance cost listed in **TABLE 21**.

TABLE 21 is mainly related to piping and general corrosion prevention. This cost is uncertain as no supporting data could be obtained from Ben Gurion University at this stage.

TABLE 21: ANTICIPATED OPERATING COST FOR 1 ML/D WAIV SYSTEM

Plant capacity	1000	m3/day		
Operating hrs	8760	hrs/annum		
Netting life	5	yrs		
Operators	1			
Description	**Unit**	**Consumption**	**Cost/unit**	**Annual cost**
Electricity	kwh/kl	0.22	0.24	19,272
Netting	m2/annum	138725	6	832,348
Wire system	m/annum	48000	1.2	57,600
Maintenance	R/annum			500,000
Operator	ea	1	100000	100,000
Total				**1,509,220**
Specific cost			**R/m3**	**4.13**

8.3.4 Capital cost

Capital costs are estimated at R100 million, including contingencies and professional fees, but excluding cost of land and VAT (**TABLE 22**). Adding the operating cost over the 20 year lifetime of the project, the net present value of the project comes to R99 million.

The cost of land should be the same for that of a standard lined pond. Using R5000/ha, the cost of land comes to roughly R20 000.

More than 50% of the capital cost of the project can be attributed to pond lining whilst the actual WAIV system accounts for less than 10% of the overall capital cost. This is an interesting result, particularly in cases where there is an existing evaporation pond and evaporation capacity has to be increased. In these instances, the WAIV concept may provide a very attractive expansion option by installing the system as a suspended unit across the evaporation dam.

TABLE 22: CAPITAL COST ESTIMATE – 1 ML/D WAIV SYSTEM

Description	Unit	Quantity	Unit cost R/unit	Cost R, excl VAT	Total R, Excl VAT
Ponds					**23 344 514**
Inlet pond	m2	3298	500	1 649 147	
WAIV pond	m2	9809	500	Integrated with inlet pond	
Final pond	m2	43391	500	21 695 367	
WAIV unit					**32 825 087**
Netting	m2	353135	8	2 825 077	
Polyprop piping					
150mm	m	200	300.00	60 000	
80mm	m	100	218.00	21 800	
50mm	m	500	44.02	22 010	
25mm	m	2000	11.60	23 200	
Provision for pipe fittings				50 000	
Provision for valves				50 000	
Provision for pipe supports				50 000	
Support structure					
Frame	ea	30000	960	28 800 000	
Twine	m	120000	1.2	144 000	
Pumps					
420 m3/hr, 2bar(g),Plastic	ea	5	55000	275 000	
Labour					
Manual labour	ea/2months	10	8000	80 000	
Foreman	ea/2months	2	12000	24 000	
Supervisor	ea/2months	1	40000	40 000	
Digger loader	hr	240	250	60 000	
Peripheral costs					**1 590 000**
Electrical				300 000	
Pump house & control room	m2	200	200	40 000	
Fencing	m	2500	500	1 250 000	
Sub-total					**57 759 602**
P&G's				15%	8 663 940
Contingency				20%	11 551 920
Sub-total					**77 975 462**
Professional fees				12%	9 357 055
Total					**87 332 518**
Add operating cost over 20yrs at present value					11 966 592
Nett present value of project					**99 299 110**

8.4 DEWVAPORATION

8.4.1 Description

The basic dewvaporation technology is a simple and elegant concept based on nature's process of making pure rain water from seawater. As illustrated by **FIGURE 35**, dewvaporation towers can be viewed as two chambers, one for evaporation and the other for dew formation with an internal heat exchanger.

The process begins by dribbling brine down the evaporation side of the heat transfer wall. At the same time, a carrier gas (air at ambient conditions, or dried air) is introduced at the bottom of the tower. The temperature of the carrier gas will typically be around 15-25ºC. The gas is run past the water up the heat transfer wall. As it travels past the water, the temperature is increased by heat transferred through the heat transfer wall. As a result, the water carrying capacity of the air increases and water evaporates from the brine stream into the air stream.

At the top of the tower, the air is turned around and is sent back down the tower, but before it does, heat is added in the form of steam. This results in an incremental rise in temperature. This slightly warmer air stream then travels back down the tower along the dew formation side, transferring heat through the heat transfer wall until it cools down to approximately 60-70ºC at the bottom. As the air cools down, its water carrying capacity is reduced, resulting in condensation of the water evaporated on the other side of the heat transfer wall.

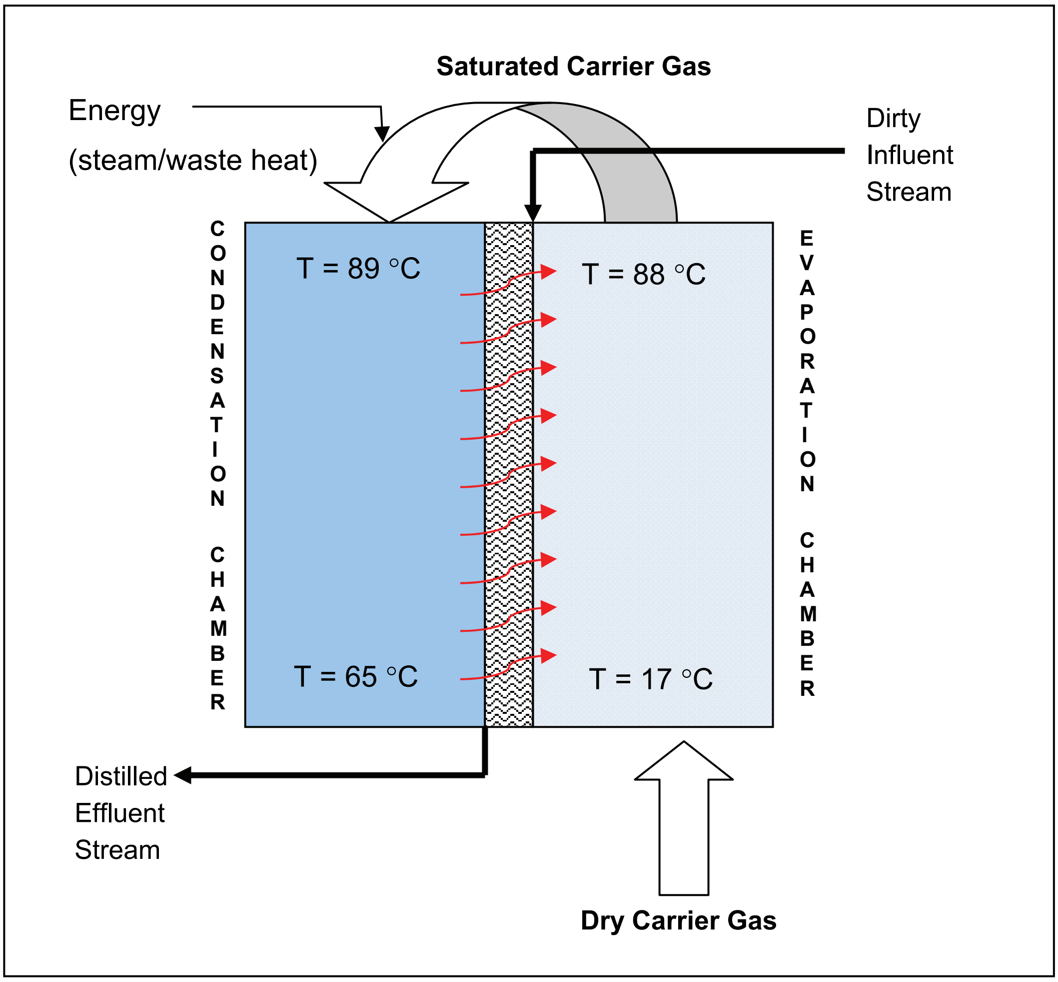


FIGURE 35. DEWVAPORATION PROCESS

The use of plastics minimizes or eliminates many of the maintenance issues related to corrosion of metal systems. The moving parts in the system are few, and consist of proven, robust, off-the-shelf components, such as low pressure water pumps and air blowers. The system operates at ambient pressures and modest temperatures, and as such, should have few mechanical failures in plumbing and related systems.

Evaporation occurs as a result of humidification of the carrier gas from the surface of the bulk fluid, with no boiling at the heat transfer surface as in traditional evaporation equipment. Thus, whilst precipitation is still possible as a result of super-saturation, the developers of the technology claims reduced scaling of the heat transfer surface.

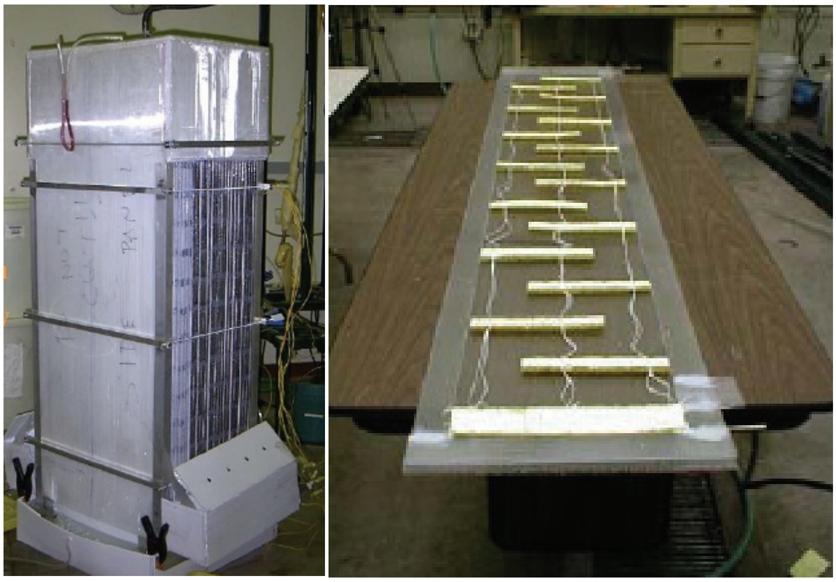


FIGURE 36. TYPICAL DEWVAPORATION MODULE (LEFT) AND HEAT TRANSFER WALL (RIGHT)

Presently the design of the dewvaporation module consists of a series of rectangular chambers, separated by a thin heat transfer wall (**FIGURE 36**). Work to date suggests short-circuiting of air through the unit, resulting in reduced process efficiencies. To overcome this, air flow baffles have to be installed in the evaporation chamber.

Presently, the module design has a heat transfer density of approximately 72 m^2/m^2. The present design has been tested in several on-site pilot scale operations and evaporation rates of approximately 16 m^3/d can be achieved in a footprint of 24 m^2 (including space for walkways, *etc.*).

The major advantages of dewvaporation technology include:

- Recovery of high quality water;
- Operation near ambient pressure at low temperature;
  - Conceptually could use waste heat or low pressure steam to operate;
  - Conceptually could be constructed from engineering plastics;
  - Reduced corrosion problems;
  - Potential for significantly lower capital cost.

The main concerns about the technology include:

- Reduced scaling of the heat transfer surface remains to be proven;
- Typical engineering plastics are hydrophobic, thus resulting in reduced film formation with subsequent reduced heat transfer efficiency;
- Short-circuiting of air flow, resulting in increased process inefficiencies. Whilst this may be overcome by the use of flow spacers, this increases

construction complexity and cost. Furthermore, scaling in flow paths will be difficult to remove.

8.4.2 Conceptual design – 1 Ml/d unit

The conceptual design of the dewvaporation plant is based on pilot plant data gathered by Altela (2007). Figure 37 below shows the process flow diagram developed for such a conceptual dewvaporation plant. The process consists of several units in series, with brine proceeding sequentially from Stages 1 to 5. Each stage may consist of any number of dewvaporation units, with each stage containing a sufficient number of units for the feed volume in that stage. Air is introduced to all units from the top and recovered water collected in a common manifold at the bottom.

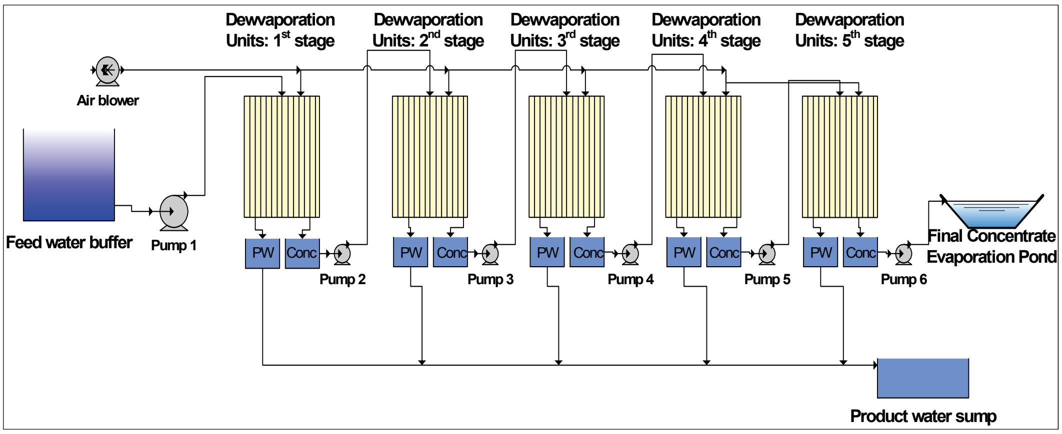


Figure 37. Process flow diagram for dewvaporation water treatment plant

TABLE 23 shows the major design parameters that were used along with the pilot plant data to design a 1 Ml/d dewvaporation plant.

Table 23. Design basis for dewvaporation plant

Brine inlet TDS	mg/l	18900
Brine evaporation capacity	m3/day	900
Ambient air temperature	°C	17
Ambient air humidity	%	55
Evaporation capacity	g water/kg air	405
Packing density	m2/m2	72
Footprint	m2	340
Width of a Dewvaporation unit	m	1
Length of Dewvaporation unit	m	10
Height of a Dewvaporation unit	m	2
Number of units	ea	34

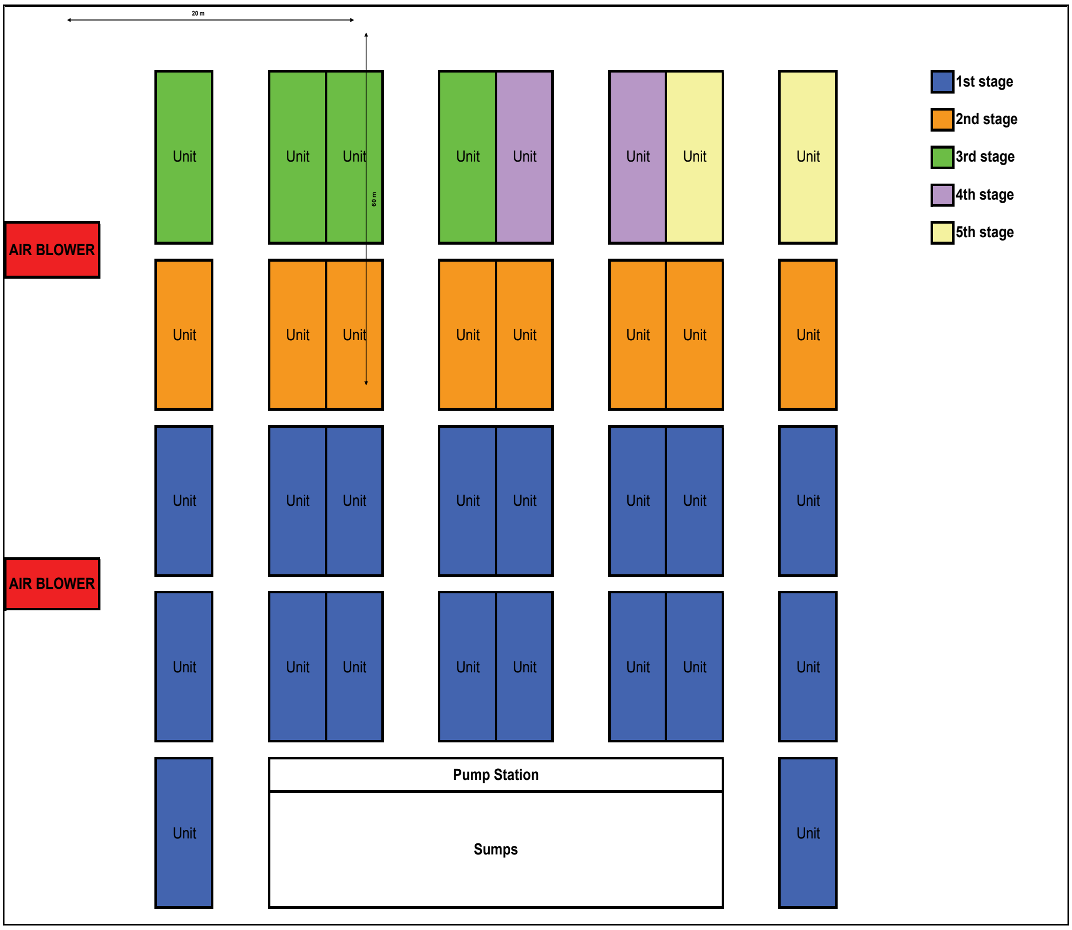


FIGURE 38. PLANT LAY-OUT – CONCEPTUAL DEWVAPORATION PLANT

FIGURE 38 shows the lay-out of the conceptual 1 Ml/d plant, which resembles a series of blocks, with each stage represented by a different colour. It is proposed that the plant will have a central pumping station adjacent to various process sumps for feed, product and final waste. Dual air blower stations are situated adjacent to the units and probably on the outside of the building housing the dewvaporation units. A total footprint of approximately 1200-1500 m^2 is anticipated.

8.5 Operating cost

TABLE 24. OPERATING COST SUMMARY

Plant capacity	1000	m3/day		
Operating hrs	8760	hrs/annum		
Operators	8			
Description	**Unit**	**Consumption**	**Cost/unit**	**Annual cost**
Electricity	kwh/kl	0.28	0.24	24,933
Natural Gas	MJ/kl	117.50	0.05	2,058,611
Maintenance	R/annum			826,655
Operator	ea		100000	800,000
Total				**3,710,198**
Specific cost			R/m^3	**10.16**

8.6 Capital cost

In order to estimate the capital cost for the design, 1 mm polypropylene sheets were used as heat transfer area and 5 mm thickness for spacers. The unit configuration followed the traditional plate & frame heat exchanger design (**FIGURE 39**).

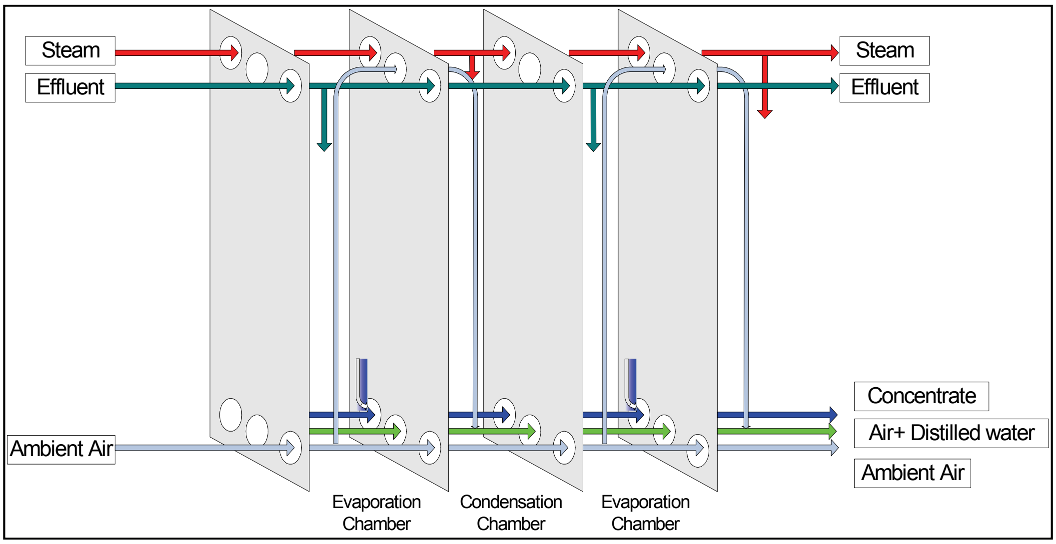


FIGURE 39. SHEET CONFIGURATION FOR A DEWVAPORATION UNIT

The capital cost estimate is summarised in Table 25. Due to limited information available, a 50% contingency was added to the capital cost estimate.

TABLE 25. CAPITAL COST SUMMARY: DEWVAPORATION

Description	Unit	Quantity	Unit cost R/unit	Cost R, excl VAT	Total R, Excl VAT
Dewvaporation units					**6,424,876**
Polypropylene sheets (1 mm)		5807	54.4	315,878	
Polypropylene spacers (5 mm)				521,199	
Seals				1,015,977	
Backing plates		68	9118	620,024	
Machining of plates				295,769	
Tie rods		136	7560	1,028,160	
Support frame				2,550,000	
Manufacturing assembly labour				77,870	
Tanks					**5,538,000**
Sumps	m^3			400,000	
Final Concentrate evap pond	m^2	10276	500	5,138,000	
Pumps					**500,000**
Pump 1 (120 m3/hr @ 1.5 bar (g))		2	55,000	110,000	
Pump 2 (51 m3/hr @ 1.5 bar(g))		2	28,000	56,000	
Pump 3 (24.9 m3/hr @ 1.5 bar(g))		2	28,000	56,000	
Pump 4 (16.5 m3/hr @ 1.5 bar (g))		2	28,000	56,000	
Pump 5 (13.2 m3/hr @ 1.5 bar (g))		2	28,000	56,000	
Pump 6 (12 m3/hr @ 1.5 bar (g))		2	28,000	56,000	
Pump 7 (114 m3/hr @ 1.5 bar (g))		2	55,000	110,000	
Air blowers					**333,000**
Blower (50 000 m3/hr @ 4 kPa)		3	111000	333,000	
Polyprop piping+ducting					**4,502,368**
Air ducting	m			402,732	
150mm	m	140	50.92	7,128	
80mm	m	135	27.19	3,671	
50mm	m	100	13.48	1,348	
25mm	m	400	6.22	2,489	
Provision for pipe fittings				750,000	
Provision for valves				935,000	
Provision for pipe supports				550,000	
Installation and fitting of piping				1,850,000	
Peripheral costs					**6,400,000**
Electrical+instrumentation				1,600,000	
Civil construction	m2	1200	4000	4,800,000	
Sub-total					**23,698,244**
P&G's				15%	3,554,737
Contingency				50%	11,849,122
Sub-total					**39,102,103**
Professional fees				12%	4,692,252
Total					**43,794,355**
Add operating cost over 20yrs at present value					84,391,003
Nett present value of project					**128,185,358**

8.7 Freeze desalination

The conversion of saline water to fresh water by freezing is based on the striking difference between liquid water and ice in terms of salt solubility. On one hand, water is an excellent solvent for many salts, capable to dissolve molar quantities of common inorganic salts such as sodium chloride, calcium sulphate, *etc*. On the other hand, salts are almost insoluble in ice, with solubility in the micro-molar range at best (Petrenko, 1999).

A review of the literature on freeze desalination indicates that there was a great surge of interest in freeze desalination during a 19 year period of support by the Department of Interior, Office of Saline Water (OSW) from 1955-1974. The major focus of the research efforts was directed at the desalination of sea water, to produce potable water as an alternative to evaporative processes. During this period 11 diverse demonstration plants were constructed and operated on sea water under the direction of the OSW at its Wrightsville Beach test facility in North Carolina (McCormack & Anderson, 1995). Two basic freezing techniques were studied during this time:

- Indirect Freezing
- Direct Freezing, with sub-classes being:
  - Vapour compression (VFVC)
  - Vapour adsorption (VFVA)
  - Secondary refrigerant absorption(SRF)

Two publications, one by Barduhn in 1983 and the other by Wiegandt in 1990, summarize the status of freeze desalination as it developed at the time. These two documents show that there was little, if any, progress made between 1982-1990 and few publications since 1990 was found. (McCormack & Anderson, 1995). As far as could be determined, one of the main reasons for this lack of research is the structural changes which took place at OSW during the late 1960s and early 1970s. At the time, technologies such as membranes and thermal desalination techniques such as multi stage flash evaporation, were much more advanced and already in semi-commercialised or commercialised. When the OSW finally closed, no government of private funding was available to proceed with further technology development.

Today, with increased energy costs and a focus on CO_2 emissions from energy intensive processes, interest in low temperature desalination techniques is rising. An important reason is the fact that the energy requirement to freeze water is approximately 6.5 times less than the energy requirement to evaporate water. In addition, corrosion and scaling problems so typical of high temperature desalination applications is markedly reduced at low temperatures (Spiegler, 1962). In particular, techniques such as eutectic freeze desalination and desalination through clathrates appears to be receiving increasing attention.

8.7.1 Ice crystal formation

If sea water or contaminated water is reduced in temperature to a value very close to that of the freezing point, microscopic ice crystals begin to form within the solution. The structure of the ice crystal has great regularity and symmetry and cannot accommodate other atoms or molecules such as salt without very severe local strain (Chalmers (1959, Snyder, 1966)).

The size and growth of ice crystals are very important when working towards an efficient ice/brine separation step. Microscopic examination indicates that these initial crystals they are very small (<100 um) and flat. As a consequence it has a large surface-to-weight ratio and such minute crystals tend to retain a comparatively large volume of brine (Snyder,1969). From this it is obvious that if the ice crystals could be formed as very large pure crystals, the separation of the fresh ice from the resulting brine, and subsequent washing operations would be relatively simple. Barduhn (1982) determined that crystals with an average size of less than 150 um are not easily freed from adhering brine and that crystals of a minimum size in the range 200-300 um, is preferred.

8.7.2 Indirect freezing

The indirect refrigeration methods is described first because it was the first method proposed for practical application and has all the elements necessary for understanding the fundamentals of the freezing process. A schematic diagram is given in **FIGURE 40**.

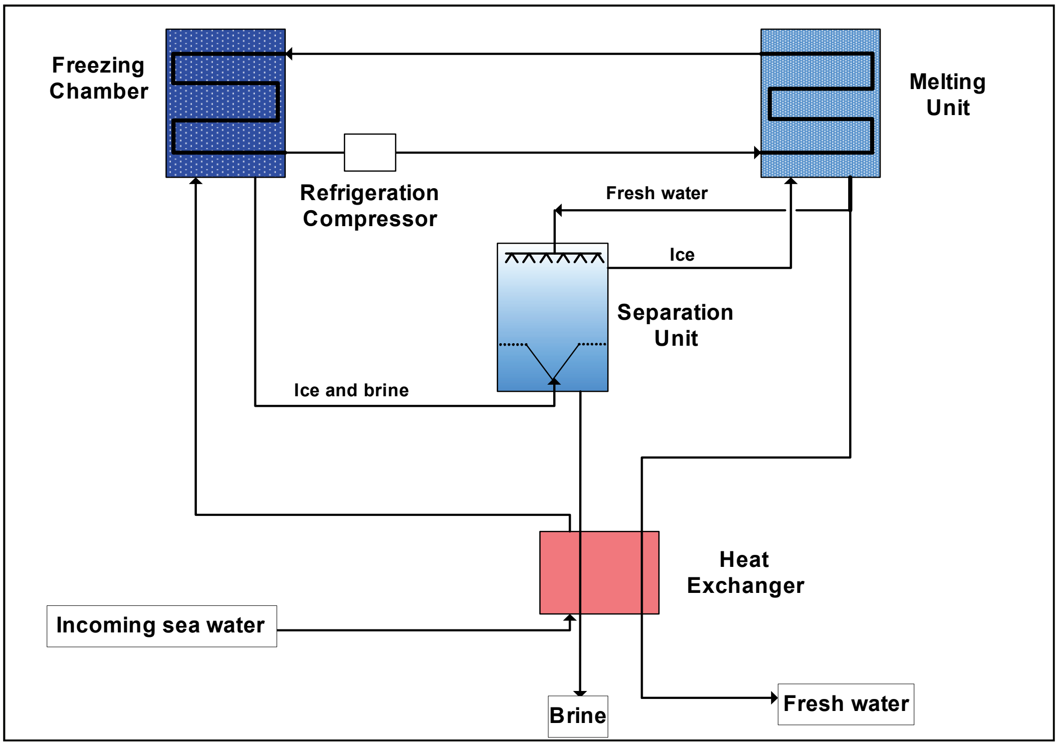


FIGURE 40: BASIC FLOW DIAGRAM OF THE INDIRECT REFRIGERANT METHOD

The incoming sea water is cooled in the primary heat exchanger and then routed to a freezing chamber, which is cooled by means of an external refrigerant. In the freezing chamber, ice crystals tend to form on the heat exchange surfaces, thus the freezing unit is fitted with a scraping mechanism to control the freezing rate and recover ice crystals. The ice/brine slurry then flows to the separation unit, where separation is achieved based on density differences. The brine is returned to the saline source and the ice is transferred to a melting unit, where cooling energy is recovered by cooling of the external refrigerant. As the ice melts, fresh water is recovered from the melting unit as product water, part of which is by-passed to the separation unit, where it is used for washing the ice crystals.

The first efforts in desalination by freeze separation used conventional ice making machines for the production of ice from saline water. Several ice making machines were tested and it was concluded that they were not suitable for desalination purposes. The primary reason was high cost due to the fact that the heat removed had to pass through a solid surface as well as two liquid films (Hendrickson and Moulton, 1956).

To cool the feed solution, it is necessary to remove heat from the bulk of the solution. Using indirect freezing, heat is removed through a solid heat transfer surface and ice crystals tend to nucleate almost uniformly over the entire surface. The ice crystals will continue to grow until they contact each other and eventually form polycrystalline ice. This type of formation leads to salt entrapment in the ice and, because of the formation of ice on the heat exchange area, also inhibits heat transfer.

8.7.3 Vacuum freeze vapour compression

VFVC is a direct freeze desalination process. As most research has taken place in this area, this process will be discussed in more detail.

To overcome the problems identified with indirect freezing, a method of freezing that would permit direct heat exchange between the water and refrigerant is desirable. Heat can then be removed from the bulk liquid by evaporation of a refrigerant in direct contact with the liquid so that the ice crystals will nucleate and grow independently of one another and form a slurry within the remaining unfrozen brine. The refrigerant may be the water itself or a refrigerant immiscible with water. In the case of VFVC, water is used as the refrigerant using a process illustrated in Figure 41.

As the entire process operates at high vacuum, any non-condensable gasses entering the system is removed in a deaerator to reduce the overall volume of gas to be moved. From here, the de-aerated feed passes through two counter flow, small approach, heat exchangers to cool the feed to near freezing temperature. These heat exchangers are also used to recover as much as possible of the cooling energy from the resulting product and brine streams.

As the heat exchangers will not be 100% efficient and other equipment add heat into the system, this heat "leakage" into the system must be removed to maintain a thermal balance. This is the function of the pre freezer (**Figure 42**).

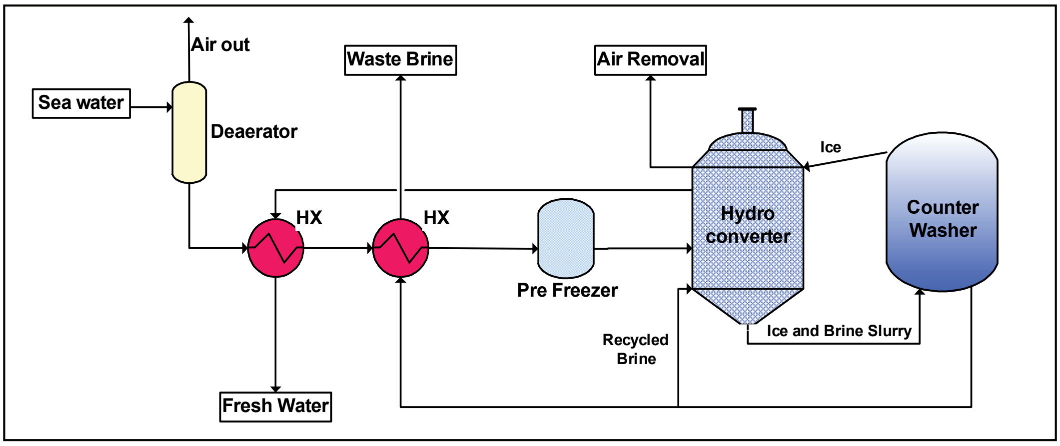


Figure 41. Flow diagram of the VFVC process

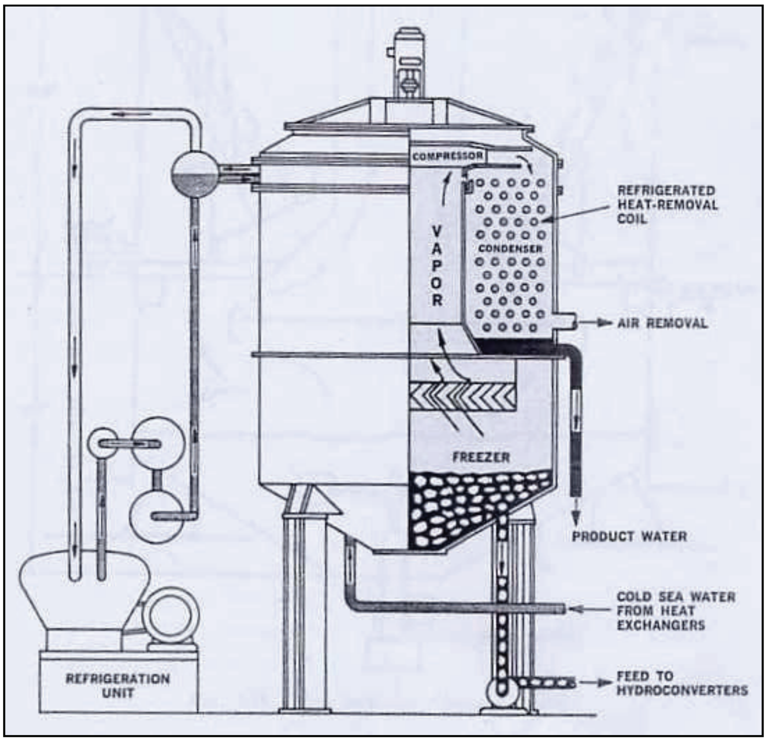


FIGURE 42. PRE-FREEZER

Basically, the pre-freezer cools the feed water by removing a quantity of vapour with a compressor and condenses the vapour on a coil condenser, which is cooled by mechanical refrigeration. The refrigeration coil is maintained at 3 °C which prevents any freezing of ice on the coils. This method has several advantages:

- Removal of heat before the feed enters the main freezer, so that none of the sensible heat has to be removed main freezer and maximum capacity can be obtained;
- The feed to the main freezer contains nuclei ice crystals on which freezing can occur and ice crystals of a maximum size can be obtained. This further minimizes freezing on solid surfaces;
- The heat is removed at a relatively high temperature level, so that the refrigeration cycle has a high coefficient of performance.

From the pre-freezer, the pre-cooled feed enters the hydro-converter, which is the main freezing vessel. It consists of 3 major components: freezer, compressor, and melter as shown in **FIGURE 43**.

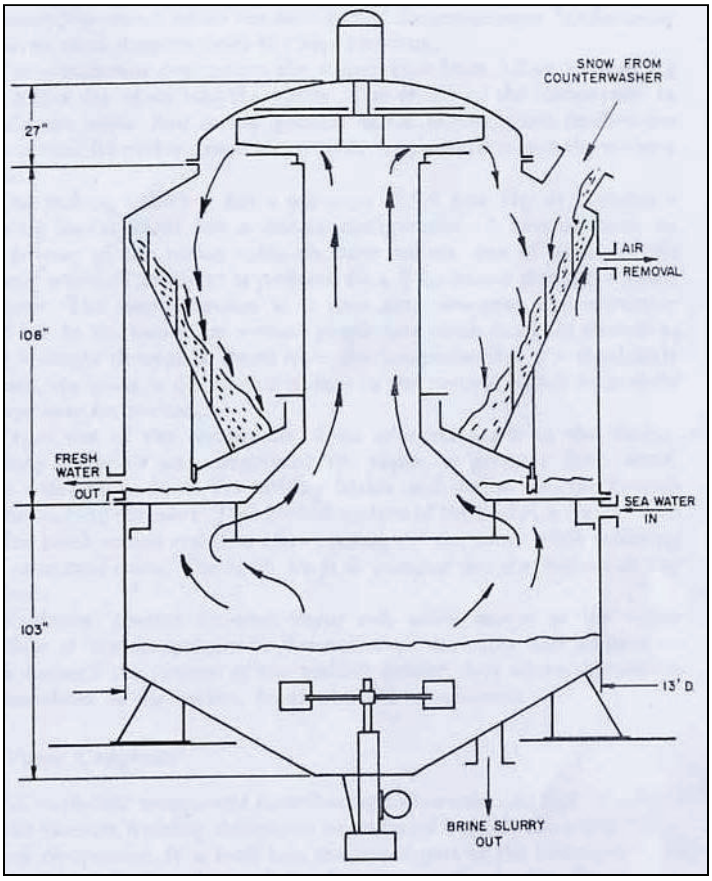


FIGURE 43. THE HYDROCONVERTER

The entire lower section consists of the freezing chamber, where an ice/brine slurry is formed through falling film vacuum freezing. The pressure in the freezer is kept at 3.2 mmHg absolute. The water is fed at -2.5ºC that is constructed such that a thin layer of water distributed on the wall.

An agitator at the bottom of the freezer ensures that there is a homogeneous mixture of ice and brine. This increases the heat transfer rate and prevents ice accumulation and clogging of the outlet pipe. The slurry in the freezer is pumped out through an outlet in the bottom of the vessel to the counter washer.

In order to maintain a vacuum in the freezing chamber, the water vapour formed by evaporation must be continuously be pumped out. In principle, it would be possible to bring the vapour pressure up to atmosphere and discharge it and then let the ice melt by itself. However, the amount of power to compress the dilute vapour from 3.2 mmHg to atmospheric will be very large. To save energy and capital, the vapour is not pumped into the atmosphere, but into the melter where the pressure is about 1 mmHg higher than in the freezing chamber.

Since the pressure difference between intake and output sides of the compressor is only between 1 and 2 mmHg, the power consumption is much lower than if the vapour had to be pumped into the air. Moreover, this arrangement recovers evaporated water vapour when contacted with ice.

The melting chamber has a pressure of 4-5 mmHg absolute and contains a rotating basket which has a conical configuration. As the basket rotates the ice from the counter washer is distributed evenly to present a large area for melting. Vapour out of the compressor flows over the ice crystals in the basket, melting the snow and condensing the vapour, to produce fresh water. The fresh water is pumped out of the bottom of the melter.

Finally, the ice has to be separated from the brine and washed to remove residual salts. Three methods have been used to separate ice from brine in freeze desalination processes, namely, centrifugation, compression and counter-current washing. Centrifugation was attempted first and proved to require excessive amounts of energy and was relatively ineffective in producing high quality water. With compression, pressures from 70 to 140 bar could reduce the salinity of the melted ice to 500 ppm and yield a quantity of water equivalent to 90% of the ice (Hendrickson et al., 1956). This method was not further investigated due to the large amounts of energy needed for separation (Howe, 1974). The greatest success in separating the ice from the brine has been achieved by the use of counter current wash columns (see **FIGURE 44**).

In operation, the ice brine slurry from the freezing chamber is pumped continuously into the bottom of the wash column. The ice crystals rise due to buoyancy and form a porous ice pack which extends from the top of the column to a about 100 cm below the brine outlet. About 5% of the product water is used as wash water, washing off the brine from the crystals as it flows downward from the top of the column to join the waste brine at the brine outlet. The device for the removal of the ice to the melter has generally been a scraper blade, rotating over the top of the wash column, shaving off the clean ice through a chute into the melter (Howe, 1974).

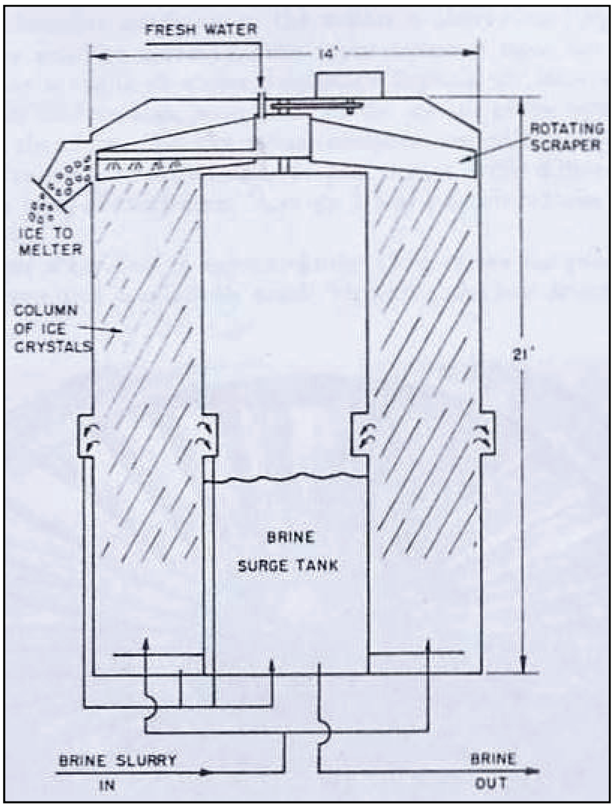


FIGURE 44. COUNTER CURRENT WASH COLUMN

COLT INDUSTRIES and the Israeli Government jointly developed the VFVC process around 1960. Four VFVC units were constructed simultaneously in Eilat with a total capacity of 1 Ml/d. This was the first and only freeze desalination plant installed for water supply and was operated for several years. As the water demand in Eilat grew, a new 4 Ml/d distillation plant was built and the VFVC plant decommissioned. Figure 45 shows a model of the 4 Unit plant.

Colt Industries also built a pilot plant at the OSW research test facility in Wrightsville Beach. The plant was commissioned in 1968 and operated very successfully at near the design rate of 380 m^3/d. The product water contained 400 mg/l salt from a raw feed of 37000 mg/l. Overall power consumption was 12 kWh/m^3 and the plant logged 2000 continuous hours of automated operation.

A further 55 m^3/d truck mounted unit for brackish water desalination operated in Roswell, New Mexico. The feed water had a TDS of 15 800 mg/l and a $CaSO_4$ content of 3000 mg/l. The plant reported yields as high as 80% and operation was good with no evidence of scaling or corrosion over its operating life of 3 years.

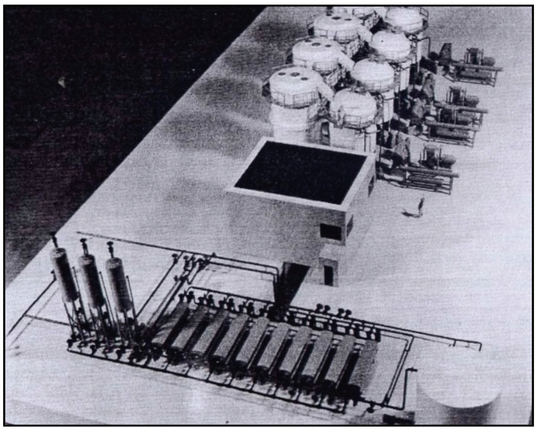


FIGURE 45. SCALE MODEL OF THE 4 MODULE PLANT

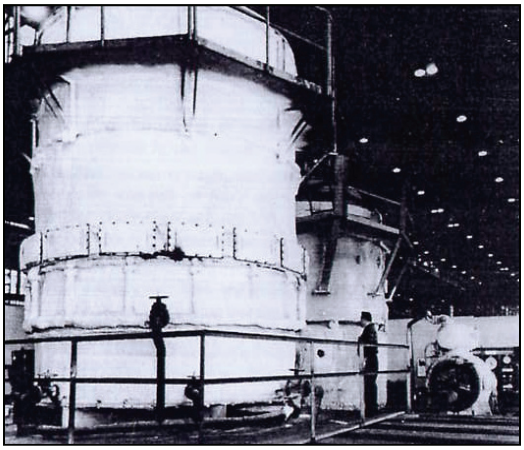


FIGURE 46: PICTURE OF FREEZE DESALINATION TANKS

One important aspect for reducing the energy consumption of VFVC was the compressor design. The compressor had a difficult task of handling a very large volume of low molecular weight vapours at pressure from 3 to 5 mmHg. The first models were only 35% efficient, but this was improved to 59% in 1968 and to 65% later.

8.7.3.1 Opportunities

This method is the only freeze desalination method to have been implemented on a large scale and, from the literature, one of the few to have been tested on water other than sea water. The fact that operation on high $CaSO_4$ waters did not adversely affect operation, suggests that VFVC may be applied to industrial brines with a high Ca and SO_4 content (typical of AMD).

8.7.4 Vacuum freeze vapour absorption

This freeze desalination process was devised to overcome the early design restrictions of the compressor in the VFVC process. The process is essentially the same as VFVC except that the water vapour is absorbed rather than compressed.

The water vapour formed in the freezing step passes through the absorber where it is condensed by absorption in a spray of the concentrated absorbent such as lithium bromide. The water is recovered through vaporisation/cooling and the lithium bromide returned to the process.

In the middle 1950s the Carrier Corporation worked on vapour absorption and a 60 m3/d pilot plant was built at the OSW test facility in Wrightsville Beach in 1959. This was the only research done of importance on the absorption process (Barduhn, 1982).

Although it had been demonstrated that the plant could produce fresh water, the high capital and operating cost, largely due to the high cost of the absorption refrigeration machine, proved so great that no commercial application has resulted to date (Howe, 1974).

8.7.5 Secondary refrigerant freezing

This is another variation of the VFVC process that makes use of direct evaporation and condensation of the refrigerant in contact with water to freeze the water. The refrigerant used in this process must be insoluble in water such as butane.

In this process the liquid refrigerant is dispersed in the freezing chamber by internal jet sprays. It is immediately vaporized, removing heat from the water, which causes the water to freeze into an ice-brine slurry. The refrigerant vapour leaving the freezing chamber is routed to a compressor and then to a melting unit. A heat exchange takes place between the vapour and ice resulting in a mixture of water and refrigerant. The water and refrigerant are then separated by density difference.

The use of refrigerants other than water has been studied extensively under the sponsorship of the OSW. The first SRF plant was built by Cornell and Blaw-Knox in St Petersburg, Florida. The SRF process used butane as a refrigerant and the facility reached a 200 m3/d production rate of fresh water from sea water. This plant was the pioneer for interest in the SRF process for desalting sea water.

Struthers-Wells under Svanoe was awarded contracts by the OSW in the early 1960s to build both 55 m3/d and 750 m3/day plants at Wrightsville Beach.

A potential problem with this approach is low concentrations of residual butane in the product water, especially if it is to be applied for potable purposes.

8.7.6 Conceptual design – 1 Ml/d unit

As most development on freeze desalination has taken place in the period 1955 and 1974, only very limited information on capital and operating cost is available. Some information could be obtained from research articles on COLT INDUSTRIES' installed plants, and these were converted to present costs and compared to alternative thermal desalination units.

In comparing these costs, the major assumptions were:

- Base cost in 1966: 1.5 million US$
- Capacity: 1 Ml/d
- Inflation over the period 1966-2006: 4.5%
- Rand/US$ exchange rate: 7.5

Using these assumptions, the present day cost of a 1 Ml/d VFVC unit by COLT INDUSTRIES should cost in the region of R54 million. In 1966, the observed energy cost for VFVC units in operation was 10.5-12 kWhr/m^3. Units were shown to operate for extended periods without scaling or significant corrosion. Unfortunately, not much information is presently available on the materials of construction of the units.

By comparison, a present day design for an evaporator (excluding crystalliser) which concentrates 1 Ml/d of brine as per Table 15 will cost approximately R120 million and will use approximately 12-17 kWhr/m^3 if it was designed as a forced circulation MVR unit. It is known that these units require significant maintenance cost and downtime and sophisticated materials of construction is generally required to combat corrosion.

The above cost conversion is unsatisfactory and probably optimistically low in favour of freeze desalination. To gain an improved understanding of costs, modern indirect micro-ice machines were used in the conceptual development of a 1 Ml/d plant. As part of this investigation, ice quality produced from commercially available ice machines were tested for salt removal. Depending on draining time and fresh water volumes for washing, salt removal rates of 80-99% were recorded.

For the purposes of developing the conceptual design, a salt removal efficiency of 85-90% in freeze desalination was assumed from a starting brine as per **TABLE 15**.

TABLE 26 summarises the salient modelling results for a 1 Ml/d freeze desalination systems, with a feed TDS of 18900 mg/l and a salt removal of 87%. It follows that at 80% water recovery, the quality of the resulting product can be expected to be approximately 4056 mg/l, whilst at 90% water recovery, it increases to 4736 mg/l. At 90% water recovery, a reverse osmosis unit with brackish water design characteristics could be used to polish the feed, resulting product to potable quality, if required.

TABLE 26: MODELLING OF FREEZE DESALINATION PRODUCT & BRINE QUALITY

Recovery	Product withdrawn	Cumulative product	Concentrate left over	Product cut	Salt removed in cut	Cumulative salt removed in product	Salt remaining in concentrate	Brine	Product
	kl/d	kl/d	kl/d	mg/l	kg/day	kg/day	kg/day	mg/l	mg/l
0	0	0	1000				18900	**18900**	
10	100	100	900	**2457**	246	246	18654	**20727**	**2457**
20	100	200	800	**2695**	269	515	18385	**22981**	**2576**
30	100	300	700	**2988**	299	814	18086	**25837**	**2713**
40	100	400	600	**3359**	336	1150	17750	**29584**	**2874**
50	100	500	500	**3846**	385	1534	17366	**34731**	**3069**
60	100	600	400	**4515**	452	1986	16914	**42285**	**3310**
70	100	700	300	**5497**	550	2536	16364	**54548**	**3622**
80	100	800	200	**7091**	709	3245	15655	**78276**	**4056**
90	100	900	100	**10176**	1018	4262	14638	**146377**	**4736**
95	50	950	50	**19029**	951	5214	13686	**273725**	**5488**
97.5	25	975	25	**35584**	890	6103	12797	**511865**	**6260**

Using these results and proposals from vendors of commercial ice making machines for the fishing industry, a modular design approach was adopted for a 1 Ml/d plant. A typical ice making machine is shown in **FIGURE 47**. Such a unit can produce 50 t ice per day, thus 20 modules will be required.

FIGURE 47 : TYPICAL ICE MAKING MACHINE USED IN FISHING INDUSTRY (PHOTOS COURTESY OF PAM REFRIGERATION)

An integrated process for treating brine in a freeze desalination system is shown in **FIGURE 48**. 1 Ml/d of brine at a TDS of 18900 mg/l enters the freeze desalination system. A reverse osmosis unit polishes the product to potable water standards, with the brine from the RO unit being returned to the freeze desalination unit. Concentrate from the freeze unit is routed to a WAIV system for final concentration before the final slurry salt slurry is disposed of in a final pond.

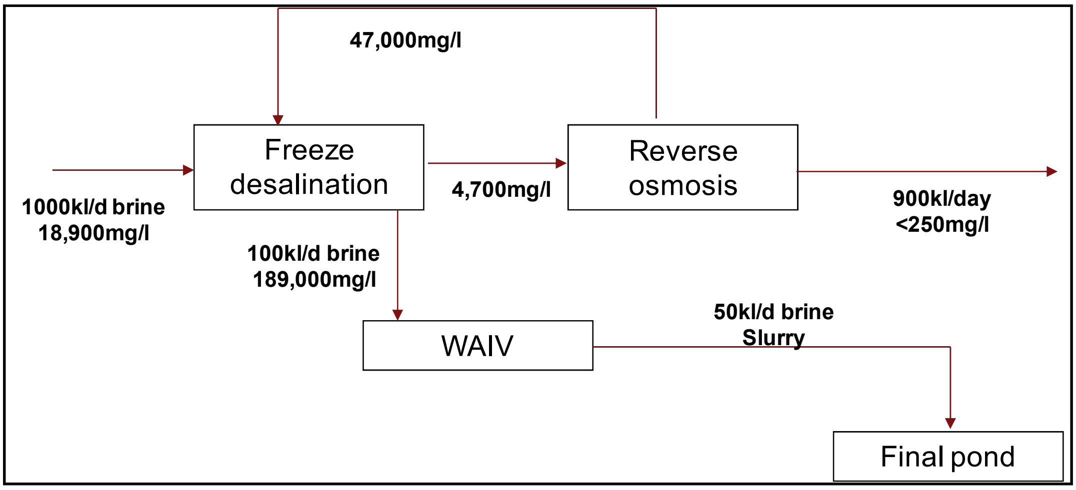


FIGURE 48. CONCEPTUAL INTEGRATED FREEZE DESALINATION SYSTEM

TABLE 27: CAPITAL COST ESTIMATE – 1 ML/D FREEZE DESALINATION UNIT

Description	Unit	Qty	Unit cost	Cost
Freezing units complete, 50t capacity each, micro-ice scraped surface	ea	20	1,400,000	28,000,000
Reactor - 50m3, complete with harvester, GRP	ea	1	1,250,000	1,250,000
Knock-out pot, 30m3, GRP	ea	1	140,000	140,000
Melting pot, 20m3, GRP	ea	1	97,000	97,000
Ammonia cylinder, 20t	ea	2	655,000	1,310,000
Compressor, 660kW	ea	2	2,475,000	4,950,000
Air coolers	ea	2	350,000	700,000
Provision of process heat exchangers, Ti plates	ea	2	335,000	670,000
Filter press, semi-automated	ea	1	500,000	500,000
Ammonia pumps	ea	2	67,000	134,000
Air extraction fan	ea	1	880,000	880,000
Product circulation pump	ea	2	86,000	172,000
Plant sub-total				**38,803,000**
Electrical		18%		6,984,540
Instrumentation & control		14%		5,432,420
Plant building	m2	2000	3,000	6,000,000
General site civils		8%		3,104,240
Piping & insulation		20%		7,760,600
Sub-total				**68,084,800**
Contingency		50%		34,042,400
Contractor P&G's		15%		10,212,720
Sub-total				**112,339,920**
Professional fees		18%		20,221,186
Total - Freeze desalination unit				**132,561,106**
Add-on				
RO unit - 1 Ml/day polishing RO skid, integrated with main RO plant				3,465,101
Add-on integration of RO unit into plant				500,000
WAIV unit for 100kl/day, including final salt pond				11,293,795
Total				**147,820,002**

TABLE 27 summarizes the capital cost for this system. It follows that the main equipment for the freeze desalination part amounts to approximately R38 million. On top of this, some R30 million is required for electrical, piping, building and other requirements to give a sub-total of R60 million. Considering the significant uncertainty with the technology at present, a 50% contingency has been included and 15% contractors fees. Including professional fees at 18%, the total capital estimate for equipment associated with the freeze desalination plant comes to R132.6 million.

To this value, a total of R3.5 million has to be added for a 1 Ml/d brackish water desalination plant, and some R0.5 million to integrate this unit with the main desalination plant.

TABLE 28. 100 KL/D WAIV UNIT

Description	Unit	Quantity	Unit cost R/unit	Cost R, excl VAT	Total R, Excl VAT
Ponds					**6,253,765**
Inlet pond	m2	2232	500	1,115,815	
WAIV pond	m2	2447	500	Integrated with inlet pond	
Final pond	m2	10276	500	5,137,950	
WAIV unit					**1,180,676**
Netting	m2	88079	6	528,475	
Polyprop piping					
150mm	m	30	50.92	1,528	
80mm	m	100	27.19	2,719	
50mm	m	300	13.48	4,043	
25mm	m	500	6.22	3,111	
Provision for pipe fittings				100,000	
Provision for valves				35,000	
Provision for pipe supports				50,000	
Support structure					
Poles	ea	500	256	128,000	
Wire	m	24000	1.2	28,800	
Pumps					
30m3/hr, 2bar(g), Duplex steel	ea	1	132000	132,000	
Labour					
Manual labour	ea/months	5	8000	40,000	
Foreman	ea/months	1	12000	12,000	
Supervisor	ea/months	1	20000	20,000	
Digger loader	hr	240	250	60,000	
Peripheral costs					**35,000**
Electrical				35,000	
Sub-total					**7,469,441**
P&G's				15%	1,120,416
Contingency				20%	1,493,888
Sub-total					**10,083,746**
Professional fees				12%	1,210,050
Total					**11,293,795**

Finally, 100 kl/d of brine from the freeze unit has to be disposed of. This can be done in a number of ways, but for the purpose of this document, a further concept design on a small WAIV unit was performed (**TABLE 28**). The system was designed in a similar fashion as previously, including a salt storage dam for a project life of 20 years. The cost of this WAIV unit comes to R11.3 million.

This brings the total capital cost of the integrated freeze desalination system to R147.8 million.

Operating cost for the integrated freeze desalination unit is given in **TABLE 29**. The overall cost of the unit comes to R12.45/m^3 brine and includes estimates for the reverse osmosis unit and WAIV system.

TABLE 29: OPERATING COST ESTIMATE – 1 ML/D FREEZE DESALINATION SYSTEM

Description	Unit	Unit Rate	Qty	Annual cost
Electricity	kWh	0.2	5478000	1,095,600
Maintenance @ 3.5%				2,382,968
Operators	ea	120000	4	480,000
Total				3,958,568
Specific cost				10.85
Add				
RO operating cost				415,816
WAIV operating cost				168,207
Total operating cost				4,542,591
Total specific operating cost				**12.45**

The total operating cost of the proposed integrated design over a 20 year life thus amounts to R90.9 million, bringing the total project cost to R238.7 million.

An important consideration of this integrated design approach is the overall energy requirements, particularly as an additional reverse osmosis unit is included in the design. **TABLE 30** lists the estimated energy consumption of each unit operation. As expected, the bulk of the energy is consumed by the freeze desalination units, consuming almost 91% of the total energy. The total energy of 17 kWh/m^3 is significantly higher than that quoted by COLT INDUSTRIES for direct freezing. This is not surprising, considering the modular design of the system as well as indirect nature of the freezing mechanism. Clearly, there is room for improvement in this area.

TABLE 30: SUMMARY OF ENERGY CONSUMPTION

Description	kWh/m^3
Freeze desalination unit	17.6
RO plant	1.6
WAIV system	0.2
Total energy	**19.4**

8.8 Staged RO design and brine softening

8.8.1 Introduction

The concept of brine softening and recycling has been discussed for some time and a significant amount of work has been done on concepts such as SPARRO and ASTROP. In principle, the concept relies on precipitating hardness salts in the brine stream, using a dedicated de-saturation/precipitation reactor. The reactor is typically a seeded reactor design.

Significant risks are associated with the process, in particular scaling in pipelines and membranes and carry-over of sludge. A further challenge is to overcome the effect of anti-scalants in order to control the precipitation step in the seeded reactor.

Various reaction schemes have been proposed in the past, depending on the chemical make-up of the raw water as well as final targeted water quality. One such flow scheme is described below (**FIGURE 49**) as applied in calcium rich mine waters:

Stage 1: $CaSO_4$ precipitation

In this stage the SO_4 is removed by precipitation with lime. Lime and the RO brine is mixed and dosed to the $CaSO_4$ clarifier. The raw mine water is fed to the clarifier where the following reaction takes place:

$SO_4^{2-} + Ca(OH)_2 = \underline{CaSO_4} + 2OH^-$

Note that gypsum precipitation will only occur down to saturation levels. Further softening can only be achieved by means of addition of carbonates, typically in the form of sodium carbonate.

Stage 2: Aeration and Iron precipitation

In this stage air is sparged to assist in the formation of $Fe(OH)_2$. This is then sent to a clarifier where the precipitated iron settles out of solution.

$Fe^{3+} + Ca(OH)_2 = \underline{Fe(OH)_2} + Ca^{2+}$

Stage 3: Reverse osmosis

The clarified water passes through sand and cartridge filtration to remove any suspended solids before entering the RO unit. Biocide, acid and anti scalant are also added to optimize the efficiency of the RO unit. After RO the concentrate is recycled back to the slurry tank reactor and the permeate is the final product water.

Stage 4: Sludge disposal

The sludge from the $CaSO_4$ clarifier is recycled back to the slurry reactor tank, while the rest goes to the sludge sump. The sludge from the iron clarifier is sent to an iron sludge tank where the bottoms are recycled back to the $CaSO_4$ clarifier and the aerator while the overflow goes to the sludge sump.

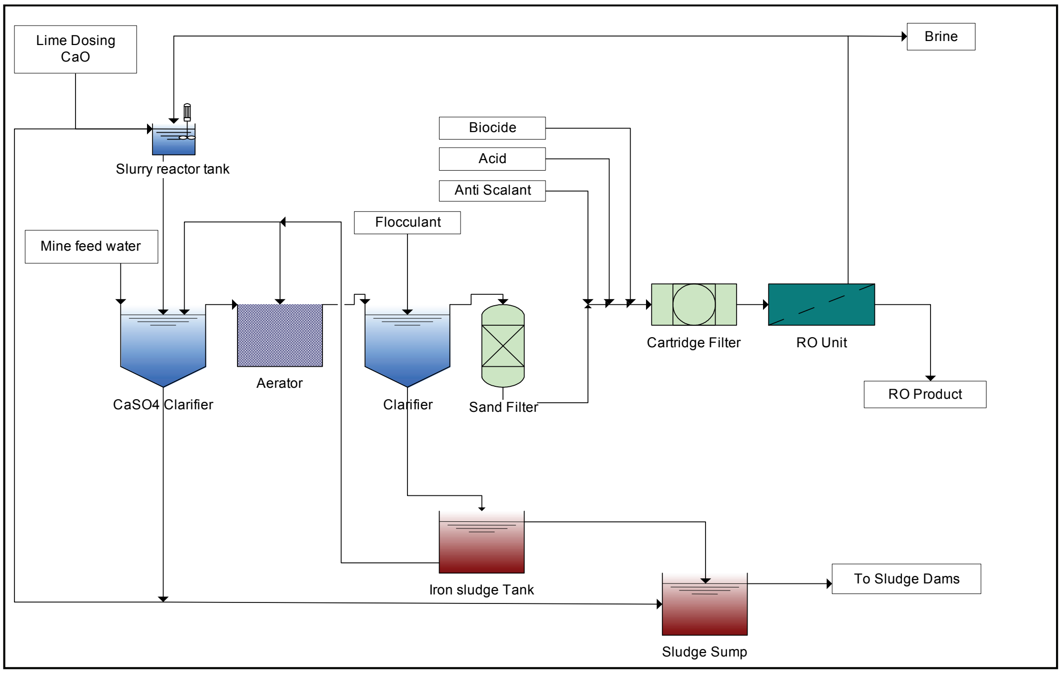


FIGURE 49: BRINE SOFTENING/RECYCLE CONCEPT

The important factors in the design of brine softening systems followed by reverse osmosis, other than hardness salts, is the following:

- **TDS:** Overall TDS will ultimately limit the water recovery rates which can be achieved with membrane desalination processes. Considering the brine in **TABLE 15** with a TDS of 18900 mg/l, and consisting mainly of sodium chloride, osmotic pressure limitations will probably limit ultra-high water recovery rates. However, after softening, and employing a staged desalination design, brine volumes may nonetheless be reduced significantly;

- **Bio-fouling:** Bio-fouling, whilst absent in most mine water applications, could be a significant challenge in desalination systems when applied on cooling water systems, several industrial effluents and secondary domestic effluent. In these instances, brine softening and recycle to the desalination plant may cause a logarithmic increase in bio-foulants and thus impair operation of the plant. Improved pre-treatment to prevent such occurrences is required;

- **Silica:** This compound is often present in cooling systems operating on sources such as the VAAL system. Care should be taken to prevent silica fouling on membrane systems, particularly as performance of silica removal in softening systems may be variable.

- **Nanofiltration:** Recently the use of nanofiltration as an alternative to reverse osmosis systems has been advocated as an option to reduce overall brine volumes. In principle, nanofiltration (NF) will remove less monovalent salts such as sodium and chloride, thus allowing these salts to pass through to the permeate and thus be “exported” off-site as part of the product water. This technique has been employed successfully in several applications in Europe as reported in earlier. However, care should be taken to ensure that required product quality is maintained in case feed water composition changes. In such cases, required operating pressures will exceed available pump pressure and product quality may not be achieved. This approach is thus limited to specific applications;

- **Anti-scalants:** The effect of anti-scalants in ultra-high recovery applications is generally not well understood. Whilst it is clear that certain anti-scalant formulations is easier to “overwhelm” through shear over-concentration by scaling salts, long term effects and scaling in pipe-lines remains to be proven;

- **Oil & grease:** Oil and grease is generally present in effluents from steel works and other heavy industries. Brine recycling and high recovery rates will result in exponential and irreversible membrane damage if oil is not completely removed from the feed water;

- **Composition:** Overall and detailed chemical analysis is arguably the single most important factor determining the applicability of brine recycling and ultra-high water recovery. The higher the water recovery aimed for, the greater the process risk.

8.8.2 Staged RO design

It is interesting to note that the brine from **TABLE 15** can be further concentrated without significant risk of $CaSO_4$ scaling. Thus, by employing a simple two stage reverse osmosis design, a 75% reduction in brine volume should be possible. This is illustrated below by assuming a raw feed stream TDS of 18900 mg/l and 90% water recovery in the first stage RO (**FIGURE 50**).

In the first stage RO system, the operating pressure is approximately 14 bar (g) and overall water recovery is about 90%. The resultant brine contains approximately 18900 mg/l TDS. Traditionally, this brine was routed to the brine disposal system. Using a second RO unit, operating at 55bar(g) and 75% water recovery, only 252 m^3/d of brine at a TDS of 74160 mg/l is produced. The two RO units are designed and operated independently, but with the same infrastructure and operational overheads.

The most salient factors of the design are indicated below (**TABLE 31**). It is noteworthy that the amount of brine reduces from 1000 m^3/d to about 252 m^3/d, whilst capital costs increases only by R5 million (note peripheral infrastructure costs such as supply pipelines and product reticulation is excluded in this calculation).

TABLE 31: COMPARISON BETWEEN SINGLE AND TWO STAGE RO SYSTEMS

Description	Unit	Single stage	Two stage
Feed	m3/day	10000	10000
Feed TDS	mg/l	1890	1890
Product water	m3/day	9000	9766
Product TDS	mg/l	28	53
Brine	Ml/day	1000	252
Brine TDS	mg/l	18900	74160
Energy absorbed	kW	250	340
Capital cost RO portion	Rmillion	40	45
Operating cost	R/m3	R2.00-R3.00	R3.00-R3.50

Operating cost increases as a result of increased energy consumption, although manpower and other overheads cost are not expected to increase.

Considering the costs of disposing of a 1000 m^3/d of brine as calculated above, it is clear that the cost of brine disposal should be significantly reduced by implementing such a design option.

At 74 160 mg/l brine TDS, it is unlikely that any further water recovery could be achieved by employing brine softening. Should the selected water composition be different, it should be possible to prove in a similar fashion that the benefits of brine volume reduction outweigh the additional capital and operating costs.

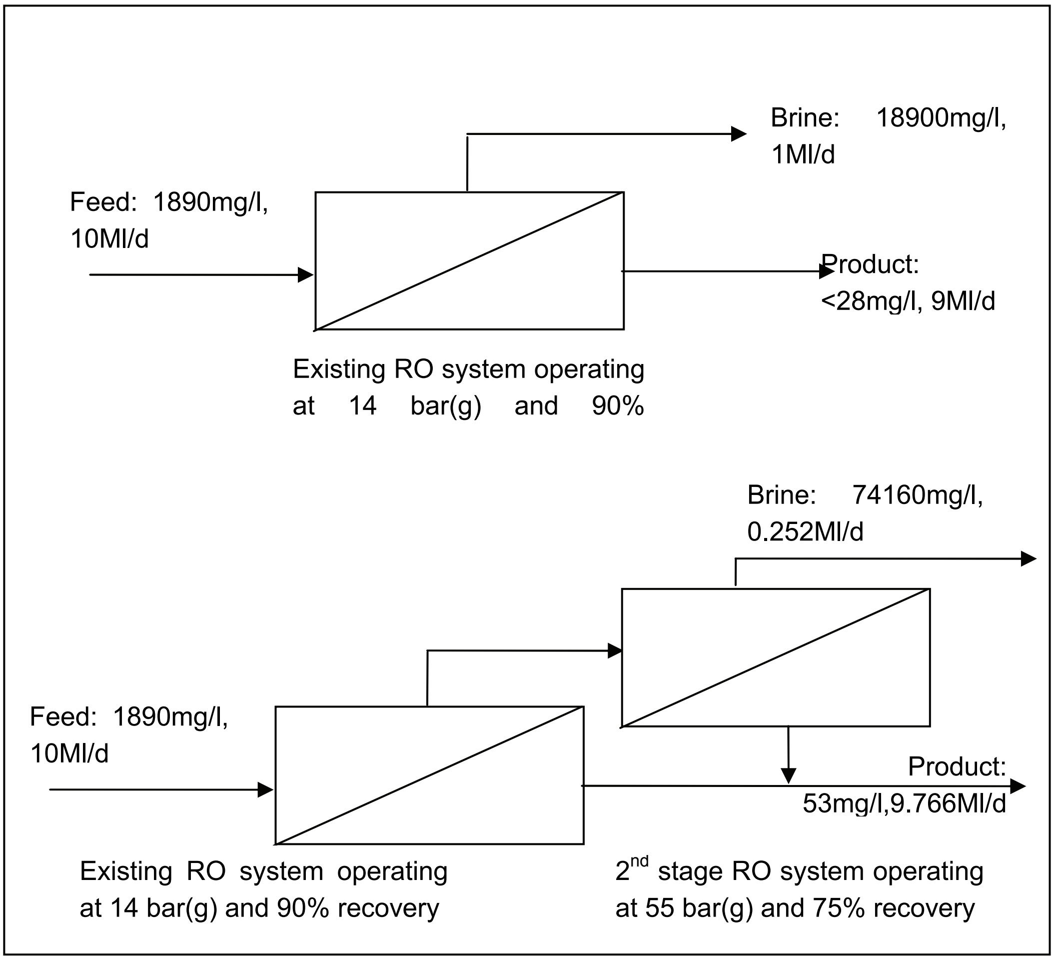


FIGURE 50: CONCEPTUAL TWO STAGE RO SYSTEM

8.8.3 Brine softening

Brine stream chemistry may be manipulated through either advanced pre-treatment options or alternatively softening or precipitation of salts/by-products from the brine stream. However, attempting to select any one particular brine stream to do this will be futile, as the preferred chemistry is determined by site conditions, detailed chemical make-up and market conditions.

8.9 By-product recovery

By-product recovery is always an option and frequently promoted by various technology vendors. However, global experience has shown that by-product recovery from waste water is rarely economically viable and should never be used to justify the financial viability of a project. Rather, it is suggested that by-product recovery could potentially be practised to reduce long term liability with regards to salt disposal.

In particular, when considering the financial feasibility of a project which recovers by-products, care should be taken not to only consider the projected cash flows (NPV or IRR basis) BUT also to consider the risks associated with the cash flows. For example, it is clear that the risk profile of a project that only produces potable water will differ materially from the risk profile of a project that produces potable water and certain speciality chemicals. This difference in risk profile does not only stem from increased production risks, but more importantly from the increased marketing risks.

It would therefore be incorrect to conclude that the project that also produces speciality chemicals is more feasible simply because it has a higher NPV at the same discount rate. In this instance, the discount rates used to calculate the NPV's of the two projects should differ materially to reflect the increased risks. This increased marketing risk is frequently ignored by proponents of by-product recovery schemes.

To evaluate the possibilities for by-product recovery, a preliminary review of the potential market of potential by-products was performed. For this review, import data was obtained from the Department of Trade & Industry (DTI) as well as major local chemical suppliers and consumers. The review should not be viewed as a detailed, exhaustive market study, which is clearly outside the scope of this study, but rather as a basis to identify major opportunities and risks for further technology development.

8.9.1 Imported raw materials

Ideally, by-products recovered should be able to replace imported products, as this represents a relatively low market risk, whilst minimizing the impact of a price war between various local sources. **TABLE 32** lists imported products which could potentially be recovered from industrial brines resulting from mine water treatment, cooling tower blow down, *etc.* This list excludes valuable materials present in effluents specific to any particular industry.

It is clear that the biggest import replacement opportunities are for sulphur (R681 million), potassium nitrate (R20.6 million), sodium sulphate (R16.3 million), ferric oxide (R13.7 million) and magnesium sulphate (R8.3 million). No data could be obtained for calcium carbonate from DTI, although a significant market exists locally.

TABLE 32: VARIOUS IMPORTED RAW MATERIALS: DTI JAN-DEC 2006

Product	Quantity Imported	Value of imported product	Unit value of imported product
	t	R'000	R/t
Gypsum	3,703	2,408	650
Chlorine	38	0.3	8.8
Magnesium hydroxide	2,001	968	484
Ferric oxide	81,970	13,701	167
Calcium chloride	6,219	3,525	567
Calcium carbonate	-	-	-
Magnesium chloride	1,266	535	423
Magnesium sulphate	6,006	8,269	1377
Potassium chloride	1,576	77	49
Mono ammonium phospate fertiliser	526	103	196
Sodium chloride	4,592	4,936	1075
Sulphur	295,453	681,000	2305
Sodium sulphate	7,671	16,310	2126
Potassium nitrate	79,737	20,603	258
Sodium nitrate	4,913	2,632	536
Total imported	**R/a**	**755,067**	

Considering a typical mine water or cooling tower blow down, then **TABLE 33** indicates the equivalent daily volume of water which could be treated to replace 100% of the imported quantities. From this table, it is clear that the biggest opportunities lie with the potential recovery of sulphur (1407 equivalent Ml/d), iron (1008 equivalent Ml/d) and potassium (5775 equivalent Ml/d). Most other ions afford significantly less volumes, thus a significant risk exist that a single or perhaps a few installations will saturated the local market. Such an imbalanced supply/demand situation is likely to reduce prices, thus reducing project viability.

TABLE 33: EQUIVALENT VOLUMES OF WATER TREATED

Product	Quantity Imported	Chemical formula	Mr	kmole imported	Amount of specific ion imported (t/a)						
	t				Na	S	Cl	Mg	Ca	Fe	K
Gypsum	3,703	$CaSO_4$	136	27,227		871			1,089		
Chlorine	38	Cl_2	70	538			38				
Magnesium hydroxide	2,001	$Mg(OH)_3$	75	26,685				640			
Ferric oxide	81,970	Fe_2O_3	160	512,314						56,355	
Calcium chloride	6,219	$CaCl_2$	100	62,193			4,353		2,488		
Calcium carbonate		$CaCO_3$	100								
Magnesium chloride	1,266	$MgCl_3$	129	9,815			1,031	236			
Magnesium sulphate	6,006	$MgSO_4$	120	50,051		1,602		1,201		24,591	
Potassium chloride	1,576	KCl	74	21,295							830
Mono ammonium phospate fertiliser	526										
Sodium chloride	4,592	NaCl	58	79,178	1,821		2,771				
Sulphur	295,453	S	32	9,232,907		295,453					
Sodium sulphate	7,671	Na_2SO_4	142	54,024	2,485	1,729					
Potassium nitrate	79,737	KNO_3	101	789,474							30,789
Sodium nitrate	4,913	$NaNO_3$	85	57,801	1,329						
Total ion imported				**t/a**	**5,636**	**299,655**	**8,193**	**2,077**	**3,577**	**80,946**	**31,620**
Typical ion concentration in water to be treated				mg/l	210	583	180	120	450	220	15
Equivalent mine water flow				Ml/day	74	1,407	125	47	22	1,008	5,775

Considering both the monetary value and equivalent volumes of water which could be treated to replace 100% of imported products, it follows that the main opportunities lie with the potential recovery of sulphur, iron and potassium salts. Potassium is generally available only in very low concentration in mine water effluents, cooling tower blow down and the bulk of industrial effluents, thus presents a relatively low challenge in the overall brine disposal situation. Whilst it can be recovered through ion exchange technologies, previous work indicated that this option is generally not cost effective.

8.9.2 Identification of high potential by-products

Some additional comments on selected by-products are provided below in order to summarise major opportunities and risks.

8.9.2.1 Iron oxide

Approximately 85% of iron oxide is used in the building industry with the remainder used in the paint- and other industries. Ferric oxide with purity below 99% can typically not be used in the chemical industry and is only suitable for sale to the steel industry.

Discussions with steel producers suggest that they will probably not be interested in handling the relatively small quantities that would be produced by a single desalination plant, thus an alternative marketing channel would have to be considered. One option would be to pool iron oxide sludge generated from various treatment facilities in order to market a larger quantity to steel producers. This might have to be done by specialist waste recycling companies.

Steel producers would require the iron oxide in a pellet form as this must fit in with their existing materials handling facilities. The price of the iron oxide delivered to steel producers would be directly linked to the ruling iron price as well as its iron content (ca 60% of tonnage for dry Fe_2O_3);

It is estimated that the market demand for ferric oxide with purity above 99% varies between 6000 and 9000 t/a, mainly in the manufacturing of primer / protective paints. The product will have to be fully dried and suitably packaged to meet the requirements of the client. Strict quality control measures and testing would have to be provided for.

Both demand and price depends on, and varies significantly with purity as well as the specific nature of the impurities. Due to sensitivity to specific impurities that differ from consumer to consumer, it is virtually impossible to quote a price unless a suitable sample is tested and analysed by the specific consumer.

Considering the varying quality of any effluent water to be treated, it is unlikely that the high quality demands from the chemical and paint industry will be consistently met, resulting in significant marketing risks. As such, this market is not considered to be suitable for iron by-product recovery.

8.9.3 Sodium sulphate

Sodium sulphate is marketable in two forms, namely sodium sulphate decahydrate (Glauber salt) or anhydrous sodium sulphate (dried out Glauber salt). Anhydrous sodium sulphate accounts for more than 60% of the total sodium sulphate market of approximately 75000 t. Existing processes in detergent and pulp industries are geared to use sodium sulphate in fairly complex processes, making it unlikely to be substituted in the near future.

However, there are numerous local suppliers that view sodium sulphate as a fatal by-product of their manufacturing process and are consequently willing to dispose of it at minimal cost to the customer. Many producers often supply low-grade sodium sulphate free of charge. This situation is reflected by the fact that more than 90% of the demand is supplied from local sources (only 7600 t imported in 2006).

The quality of this by-product will determine the market price and quantity sold. The estimated price for sodium sulphate is between R700-R2 300 per ton (depending on the quality and size of purchase).

The technology for producing sodium sulphate from desalination processes have been proven on large scale in South Africa and involves the application of sodium carbonate in the softening process, followed by evaporation and crystallisation of the resultant salt. Equipment required for these processes require high capital investment and are generally expensive to operate. Considering the relatively low value of imported sodium sulphate (R16.3 million in 2006), this does not appear to be a very attractive option.

8.9.4 Calcium carbonate

High-grade precipitated calcium carbonate (PCC) is used in the paper and plastic, pharmaceuticals, food processing industries and analytical research laboratories. High-grade PCC is used in high quality applications, where the higher cost can be offset by higher performance.

Low-grade PCC is commercially equivalent to lime (calcium carbonate). There is an extremely large market for calcium carbonate with demand predominantly from agriculture (fertilizer, soil neutralizer), metallurgical and the cement industries. There appear to be few obstacles for entry into this sector.

Local consumption of high-grade PCC is estimated at 37 000 tons per annum and consumption of low-quality PCC is estimated at 600 000 tons per annum. The price for high-grade PCC is between R1 200 and R1 300 per ton.

In water treatment, calcium carbonate is typically formed during the lime softening process through the reaction of sodium carbonate with sulphate salts of calcium and magnesium. In this instance, the challenge is the disposal of the associated sodium salts.

Where temporary hardness is removed through lime addition, this situation is eliminated and calcium carbonate marketing may be a real opportunity.

8.9.5 Magnesium hydroxide

In South Africa, approximately 95% of magnesium hydroxide is used in the steel industry and the remainder in the glass and cement industries. It is estimated that the total market is 85000-5000 t/a. Of this, only 2000 t was imported during 2006, indicating sufficient local sources. Significant marketing efforts are therefore anticipated in order to dispose of magnesium salts to the local industry.

The international price for magnesium hydroxide is approximately $400 per ton. Fused magnesium is sold at R2 500 per ton. The price for dead-burned magnesium is about R950 per ton (from the Chinese market). All other magnesium grades are priced around R1 500 per ton.

8.10 Summary

TABLE 34 compares the WAIV, dewvaporation and freeze desalination systems with conventional base cases. All three innovative systems compare favourably with traditional brine disposal options, specifically if the overall project life cycle cost is considered over 20 yrs.

TABLE 34: SUMMARY OF INNOVATIVE CONCEPTS EVALUATED

Technology	Capital cost estimate	Operating cost estimate over 20yr project life	Total cost over 20yr project life	Comments
	Rm	Rm	Rm	
Base case - evaporation pond	150-230	1.2	151-230	38.2ha double lined surface area required. This may not be practical on such a scale. The evaluation, however, provides a basis for comparision.
Mechanical evaporation and crystallisation	180	267	447	Costs excludes a final salt store. Also, no provision for disposal of purge stream for crystalliser has been allowed in the cost estimates. These aspects will increase capital costs.
WAIV	100	30.5	130.5	1.9ha of double lined surgace area is required. Whilst this is signficantly smaller than the base case evaporation pond, a 9.2ha final salt store has to be provided. Also, individual WAIV units have to be spaced which increases the overall surface area
Freeze desalination	147.8	90.9	238.7	The costs allows for anintegrated freeze desalination and is based on relatively inefficient indirect ice making equipment, polish RO unit and a final WAIV evaporation pond for final brine disposal.
Dewvaporation	44	84	128	Of all options, Dewvaporation presently holds the largest uncertainty. As such the attractive cost may be overly optimistic.

The WAIV system offers a saving in capital cost of around R20-R100 million over 20 years when compared to the base case evaporation pond. This is despite the higher projected operating costs. The WAIV system appears to be attractive to small to medium systems, whilst application to larger systems remains to be investigated further. In particular the following should be investigated:

- Application of the WAIV system to large brine flows, with specific reference to spacing requirements in order to reduce overall footprint;
- Application to existing brine disposal ponds which require capacity expansion and the possibility of integrating the WAIV system with these ponds, using existing lined surface areas;

Freeze desalination compares favourably with traditional brine evaporation/crystallisation. The evaluation was performed using relatively conservative assumptions of only 85-90% salt removal and indirect freezing systems.

Dewvaporation systems compares favourably with traditional evaporation ponds and have the additional benefit of using waste heat as energy source as well as recovery of high quality water. Water recovery is a particular benefit of this technology over WAIV where water is lost to atmospheric evaporation.

It was further possible to demonstrate the potential benefits of staged RO system design on industrial applications to reduce brine volumes. The additional capital and operating costs are relatively small when compared to the potential savings which can be achieved in disposal of reduced brine volumes. The same applies to brine softening/precipitation. However, these designs are highly dependent on the specific chemistry of the raw feed and resultant brine. Furthermore, manipulation of feed or brine chemistry is probably more dependent on market factors than on technology restrictions. As such, a preliminary review of market opportunities for by-product recovery was performed.

The preliminary market survey suggests that sulphur and calcium carbonate affords the largest potential for by-product recovery. As such, it is suggested that research efforts in this area should be supported.

CHAPTER 9

9. PROOF OF CONCEPT TESTING

Four promising technologies were identified for further investigation:

- Wind Aided Intensified eVaporation (WAIV);
- Dewvaporation;
- Freeze desalination;
- Brine softening and re-treatment.

As brine softening and re-treatment was already demonstrated in concepts such as SPARRO and full scale applications is increasing being contemplated, it was deemed that the concept was already proven and that no proof of concept testing was required. However, brine softening and re-treatment is considered as one of the main opportunities to reduce brine volumes and it is expected as technology and markets develop, that additional by-product recovery will become more viable in due time.

The chapter thus reports on proof of concept testing on the remaining three promising techniques. In all instances, the primary strategy for testing may be summarised as follows:

- To establish an improved understanding of the theory and concept of each process option, whilst at the same time identify major design considerations and process concerns;
- To demonstrate workability of the concept on a small scale;
- To establish a preliminary baseline performance model which may be used to plan future development work.

9.1 WAIV

9.1.1 Introduction

As the WAIV concept is primarily based on meteorological conditions, the South African Weather Service in Pretoria and Agricultural Research Council in Stellenbosch were consulted on the best approach, resulting in several important decisions:

- The test unit should be placed directly adjacent or as close as possible to an existing, fully automated weather station. In this way, metrological data may be directly related to the performance of the test unit;
- The Penman equation should be used for determining standard evaporation rates and wetted surface efficiency, rather than the traditional A-Pan values;
- Ideally, the test should be repeated in at least three locations, with the following conditions:

- Dry, windy conditions;
- Humid, relatively wind still conditions;
- Somewhere in between.

- Correlation from these data sets should provide a sound basis for design of WAIV units. However, care should be taken in considering topographical conditions which may significantly influence wind speed, relative humidity and temperature.

The Penman equation for determining evaporation rates is currently the standard method used by South African Weather Service and has replaced the A-pan method when officially reporting evaporation rates. This equation was developed by Howard Penman in 1948 and is still considered to be the most representative model available to describe evaporation rates from open surface water bodies. As it is derived from directly measurable atmospheric conditions, it overcomes many of the shortcomings and errors associated with A-pan results.

Penman's equation relates daily mean temperature, wind speed, relative humidity and solar radiation to predict evaporation and may be written as:

$$E_{mass} = \frac{m R_n + \rho_a c_p (\delta e) g_a}{\lambda_v (m + \gamma)} \qquad (9.1)$$

Where:

E_{mass} = Evaporation (kg/m^2.s)

m = Slope of the saturation vapour pressure curve (Pa/K)

R_n = Net irradiance (W/m^2)

ρ_a = density of air (kg/m^3)

c_p = heat capacity of air (J/kg/K)

g_a = wind speed (m/s)

δe = Vapour pressure deficit (Pa)

λ_v = latent heat of vaporization (J/kg)

γ = Psychometric constant (Pa/K)

From this equation above, two main functional terms may be identified, *viz.* an energy term and an aerodynamic term. Radiation, temperature and humidity are used to calculate the energy term of the equation and wind speed is used to calculate the aerodynamic term. At low wind speed (less than 1 m/s) the energy term of the equation becomes the predominant factor, whilst at high wind speeds (>1 m/s) the aerodynamic factor is the predominant factor determining evaporation rates. Long term comparative data suggests that Pennman's equation correlates about 90-110% with traditional A-pan data.

A major uncertainty of the present work is the correlation between Pennman's equation and WAIV performance. Experience from Ben Gurion University suggests that WAIV surfaces are at least 88-94% as effective as that of a standard A-pan in desert conditions. However, this correlation needs to be verified for local conditions.

All data required to calculate the Penman evaporation can be directly measured at a weather station, except relative humidity, which may be determined from a psychrometric chart. As illustrated in Figure 51, the relative humidity at a dry bulb temperature (T_{DB}) of 20 ˚C and a wet bulb temperature (T_{WB}) of 15 ˚C is 60%.

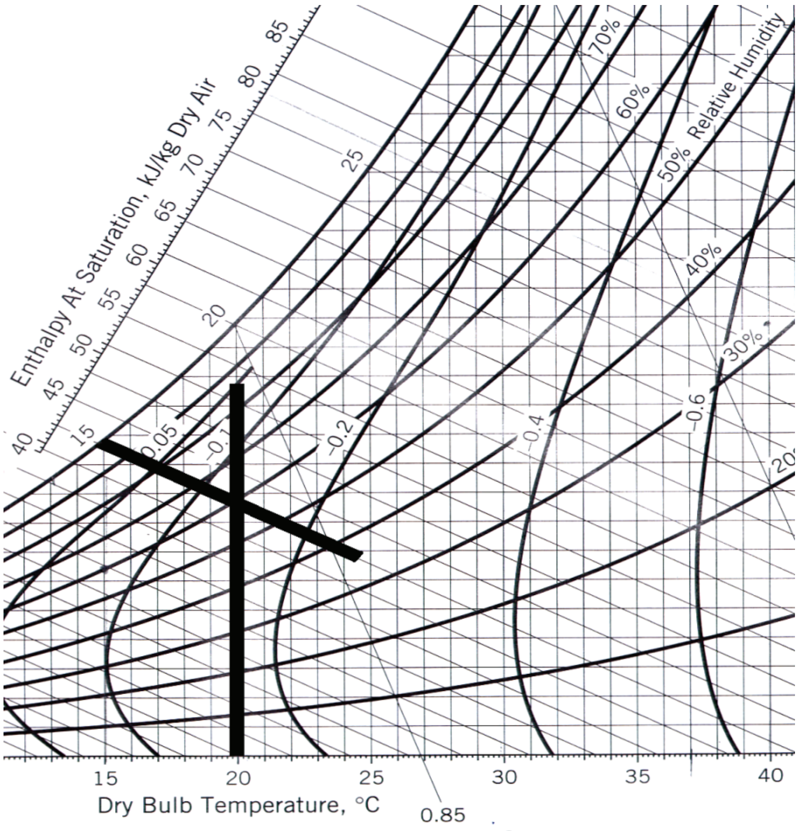


FIGURE 51. DETERMINING THE RH OF AIR AT A GIVEN T_{WB} AND T_{DB}

9.1.2 Practical design considerations

9.1.2.1 Major dimensions

For practical and cost reasons, it was decided to design a unit with a footprint of approximately 1.24 m^2 and a maximum height above ground of 3 m. This allows simple transport of the unit between different sites and facilitates simple installation and set-up.

9.1.2.2 Materials of construction

Due to the highly corrosive nature of typical brines several materials of construction for the main supporting frame were evaluated, including

- Plastic composites;
- Aluminium;
- Stainless steel;
- Wood;
- Galvanised steel.

For the purpose of mobility, cost and ease of construction, it was decided to manufacture the main support frame of mild steel, coated with a zinc rich paint. It is anticipated that corrosion will be become evident during the test period, but this was considered an acceptable trade-off against other considerations. Instead, to evaluate compatibility of alternative construction materials, provision was made in the frame for insertions of different materials to be tested.

Poly-ethylene piping was used for circulating pipes and distribution systems, whilst a SS316 circulation pump was selected.

9.1.2.3 Choice of material for "wettable surface"

To date, the Ben Gurion University researchers have evaluated a number of alternative surfaces, with the most promising results being obtained from "non-woven netting". This material has proven particularly successful in longer term trials with regard to build-up of dust and scale. No further information could be obtained regarding specific wetted material.

A range of materials were evaluated and 50% agricultural shade netting appeared to be the closest material readily available in South Africa to "non-woven netting". Other factors in favour of this material are:

- Relative chemical inertness;
- Available design information for protection against wind damage;
- Known performance of material in low and high temperature regions of South Africa;
- Acceptable UV stability;
- Relatively good understanding of the impact of wind-blown matter such as dust, grass seeds, plastic bags, *etc*.
- Large scale production facilities of agricultural netting in South Africa;
- Relatively inexpensive;
- Different shade grading and colours available which may potentially add other benefits;
- Relatively low attractiveness towards theft as proven by "longevity" of existing

agricultural installations.

9.1.2.4 Packing formation

Three possible modes of packing were evaluated:

- <u>Parallel Packing</u>

  Parallel packing offers the highest possible packing density. There are principally two options for parallel packing (Figure 52). For Option A, the netting is supported both at the top and bottom, using a "wrap-around" configuration, compared to Option B, where only the top of the netting is supported.

  The main benefit of Option B is reduced materials of construction, thus reduced corrosion problems and costs. However, the major concerns with this support are physical damage to the netting in high wind situations, as well as sticking of surfaces to each other.

  Despite increased construction requirements, Option A offers the additional benefit of stretching the netting which will reduce lateral movement in storm conditions. It is thought that this will reduce wind drift losses of brine from evaporation surfaces as "flapping" of netting will be largely eliminated.

  Irrespective of which option is selected, parallel packing suffers from limited flow path width between the netting sheets, where the maximum distance will be the same as the diameter of the supporting top/bottom structure (50 mm in this instance). This will restrict air movement between sheets, resulting in increased humidity and reduced evaporation efficiency.

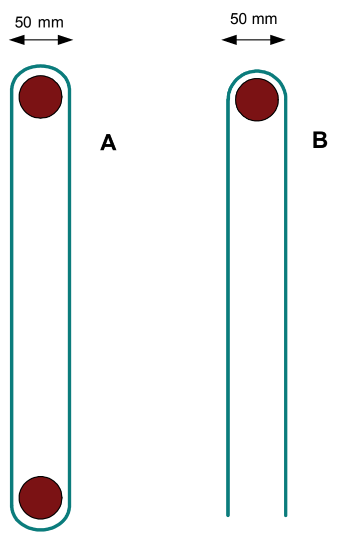


FIGURE 52. DIFFERENT MODES OF PARALLEL PACKING WHEN EMPLOYING WAIV

- <u>Rectangular Packing</u>

  Rectangular packing (Figure 53) eliminates the air movement concerns of parallel packing and offers the further advantage of flexible spacing without changing the dimensions of the top/bottom support structure.

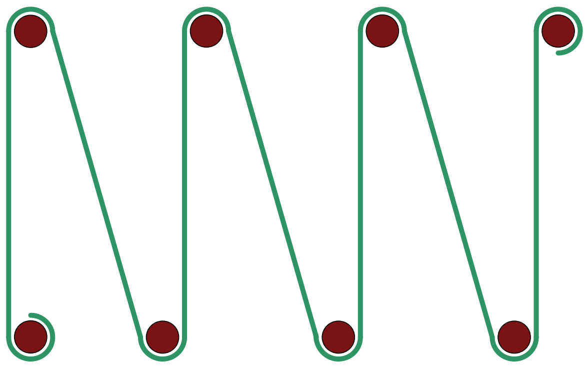


FIGURE 53. RECTANGULAR PACKING FOR THE WAIVCONCEPT

Furthermore, this option allows for the use of a single length of netting to be used during construction, reducing construction labour requirements significantly. There is no apparent difference between this packing configuration and parallel packing in collecting rain or fog.

A possible concern with this configuration is the collection of precipitate in the bottom of the netting structure. However, this is no different than for parallel packing, and instead, this configuration allows for increased access for maintenance.

- Triangular Packing

Triangular packing (Figure 54) is similar to rectangular packing, but provides an increased exposure to direct sunlight from above to the WAIV surfaces. Although this configuration provides the lowest possible packing density, it provides an improved configuration for air flow around surface areas.

Triangular packing was selected as the packing of choice for the pilot plant.

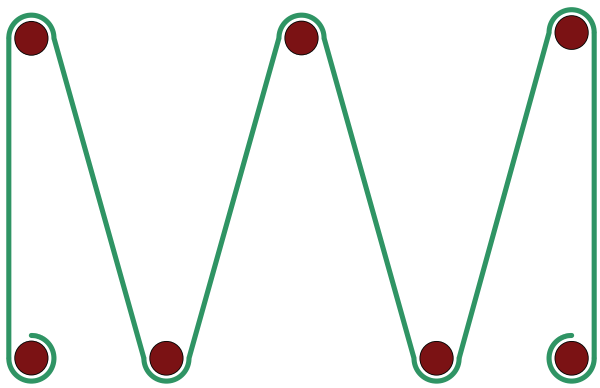


FIGURE 54. TRIANGULAR PACKING

9.1.2.5 Packing density

The unit was designed to evaluate two packing densities of approximately 20 and 40 m^2/m^2. This is achieved by changing the pitch at which the packing is inserted into the basic frame.

Presently, the unit is operating at 19.5 m^2/m^2 packing density with dimensions shown in Figure 55.

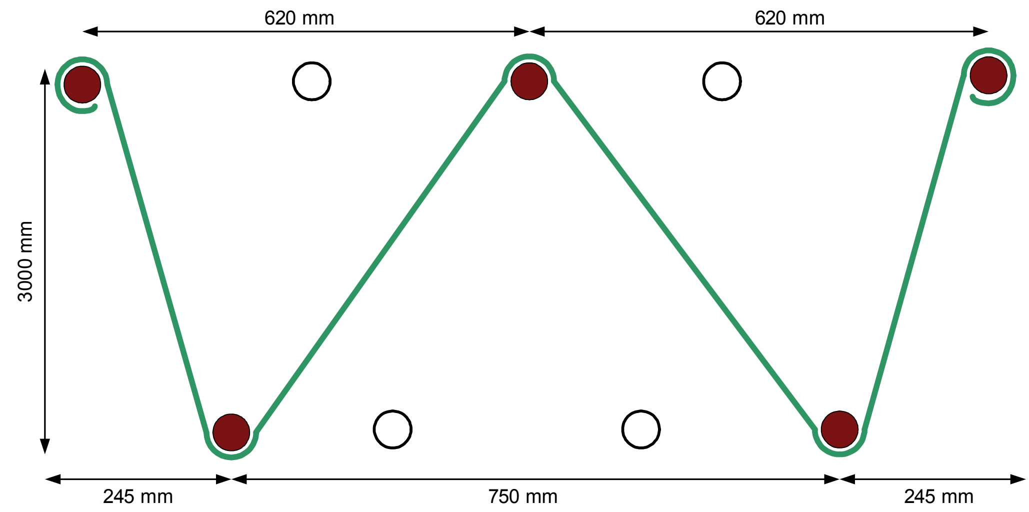


FIGURE 55. DIMENSIONS OF WAIV SYSTEM AT A PACKING DENSITY OF 24 M^2/M^2.

The packing can be increased to 38.8 m^2/m^2 by adding extra supports, netting and piping to the unit. The holes for the extra supports are already drilled in the steel structure. The dimensions of the packing this unit is shown in Figure 56.

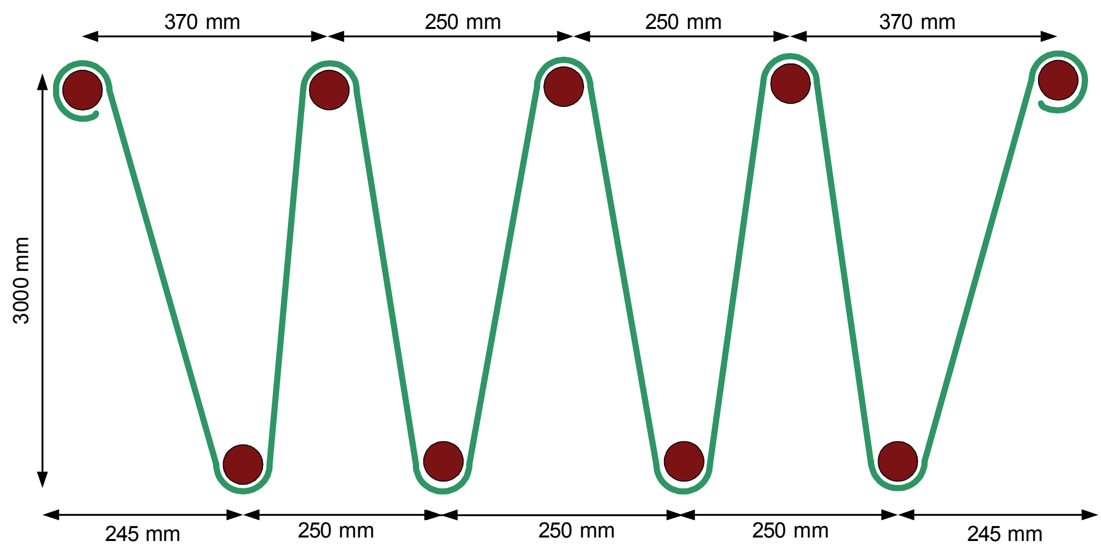


FIGURE 56. DIMENSIONS OF A WAIV SYSTEM AT A PACKING DENSITY OF 48 M^2/M^2

9.1.2.6 Distribution system

For the current packing density of 19.5 m^2/m^2 the distribution system consists of a manifold of 3 off 1" Class 3 polypropylene piping sections (Figure 57):

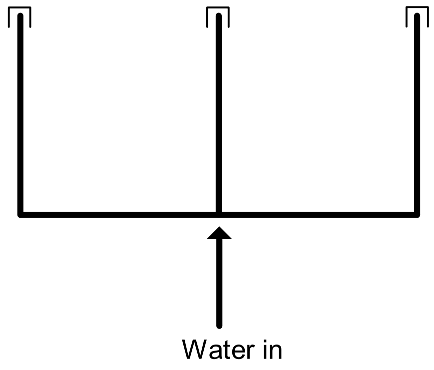


FIGURE 57. BRINE DISTRIBUTION SYSTEM.

The holes in the distribution header were 5 mm in diameter, 200 mm apart at off-set conditions (Figure 58).

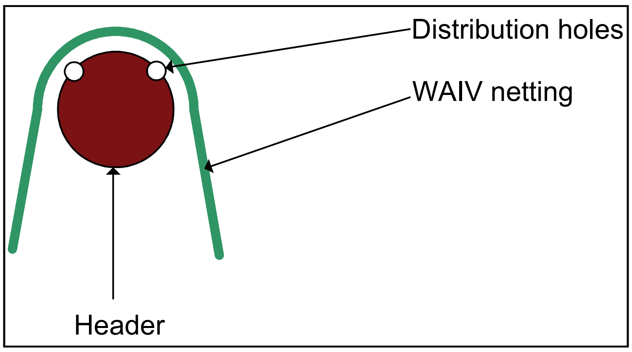


FIGURE 58. CROSS SECTION OF DISTRIBUTION SYSTEM.

9.1.2.7 Circulation rate

An oversized pump was installed to evaluate the impact of flow rate on performance of the system as well as to facilitate flushing of circulating pipe-lines and distribution headers.

The duty of the pump is shown on Figure 59, line 202:

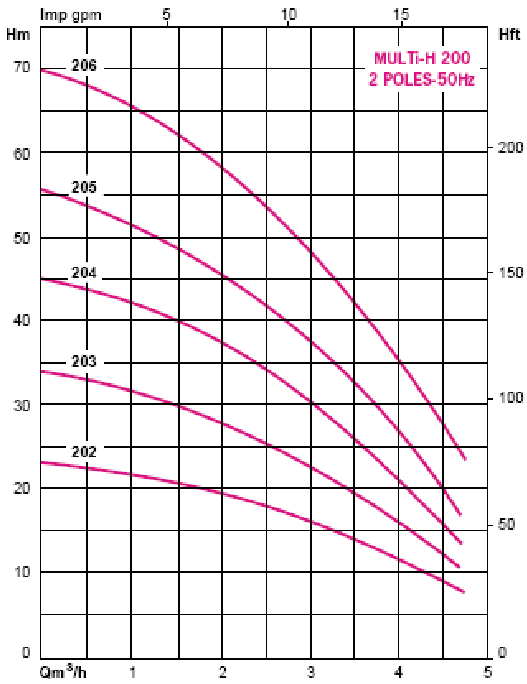


FIGURE 59. PUMP CURVE (LINE 202)

It is possible to test circulation rates between 0.5 and 3 m^3/hr, which is expected to be more than sufficient to provide fully wetted surface areas. Circulation rate is visually adjusted to allow proper wetting of the surface, whilst minimizing spray formation.

9.1.3 Pilot plant positioning

Permission was obtained from Helderfontein Research Facility in Stellenbosch to position the WAIV unit adjacent to the existing automated weather station. (Figure 60).

FIGURE 60. HELDERFONTEIN WEATHER STATION IN STELLENBOSCH

The prevailing wind direction at Helderfontein is South Easterly in summer and North Westerly in winter, thus the unit was aligned such that prevailing winds pass in between netting material. As such, an air flow <u>across</u> the WAIV surfaces, rather than <u>through</u> the surfaces can be expected.

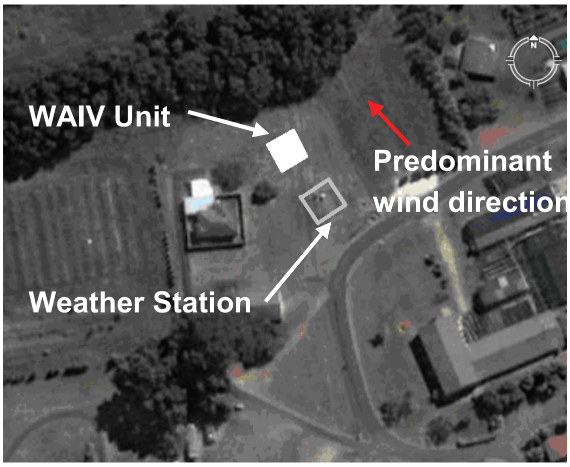


FIGURE 61. POSITION OF WAIV UNIT

9.1.4 Weather Data Analysis

The following parameters are recorded daily by the weather station:

- Wet bulb temperature (˚C)
- Dry bulb temperature (˚C)
- Rainfall (mm)
- Radiation (MJ/m^2)
- Wind speed (m/s)
- Wind direction

FIGURE 62 to **FIGURE 65** summarises the metrological data during the first month of operation of the WAIV unit. During this period, typical mid-late summer conditions prevailed, with low rainfall, regular winds and sunny days with temperatures varying around 20-30ºC. From this, the calculated Penman evaporation rate varied between 2 mm/d and 6 mm/d (**FIGURE 62**).

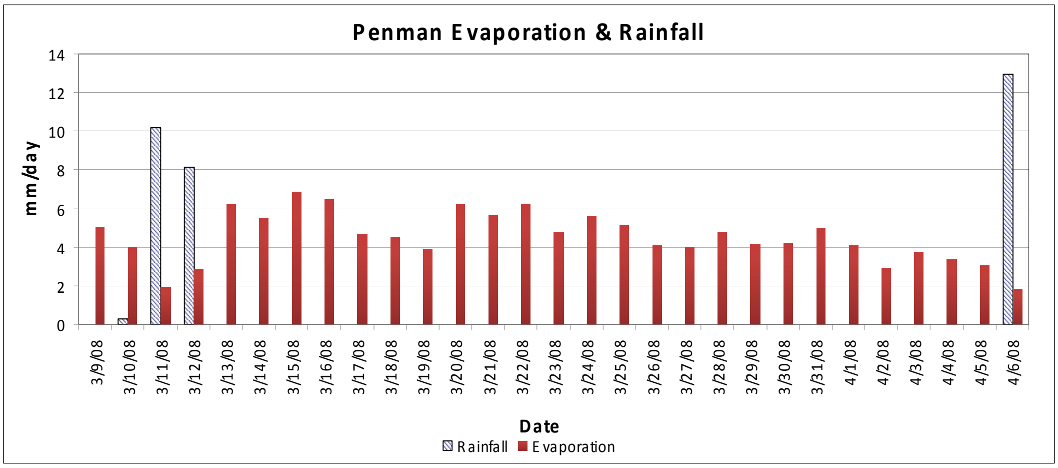


FIGURE 62. PENNMAN EVAPORATION VS. RAINFALL.

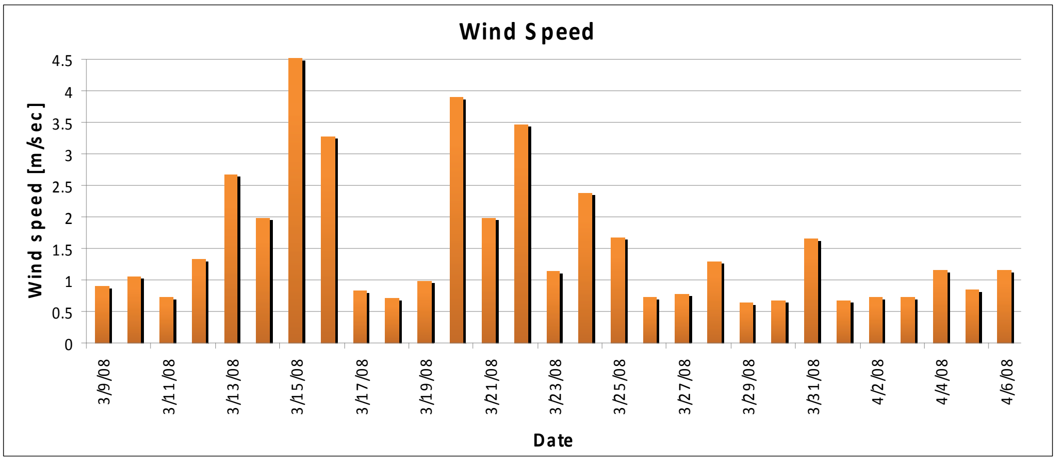


FIGURE 63. WIND SPEEDS DURING TRAIL PERIOD.

Average wind speed during the initial test period varied between 0.7 m/s and 4.5 m/s. It is important to note that this is average is calculated over **24 hrs** and the instantaneous maximum wind speed will in fact be much higher. On 15 March 2008, maximum instantaneous wind speeds of up to 22 m/s (80 km/h) were recorded.

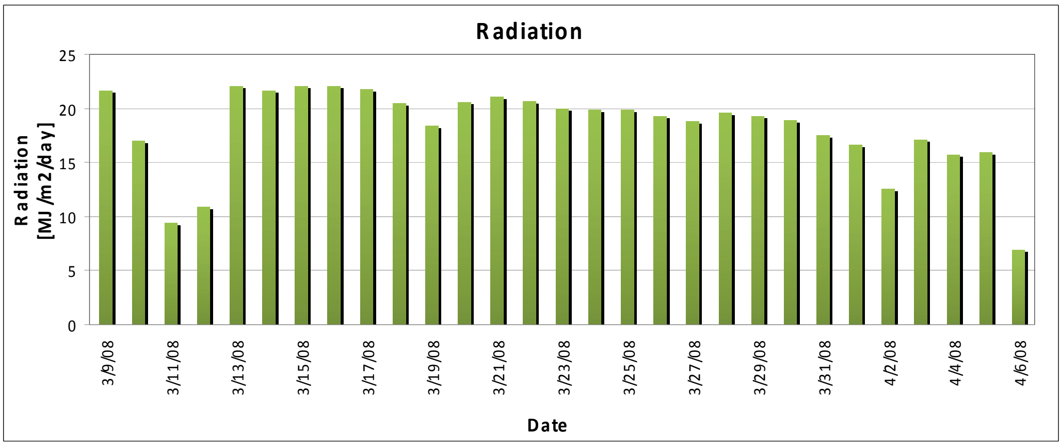


FIGURE 64. RADIATION DURING TRAIL PERIOD.

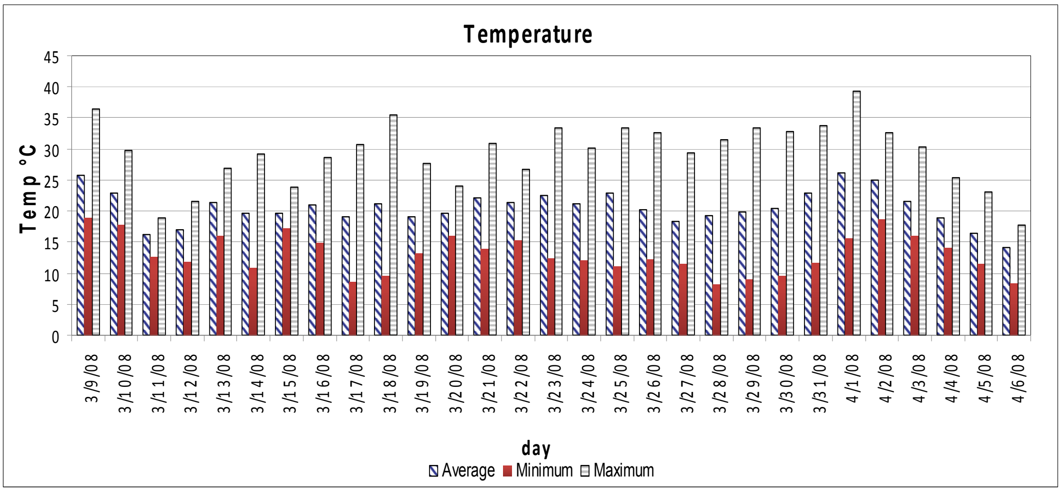


FIGURE 65. TEMPERATURE DATA DURING TRAIL PERIOD.

9.1.5 Setup of Pilot Plant Unit

Figure 66 shows the initial WAIV unit installed in Stellenbosch. The unit is positioned over a lined sump of 1.2 m x 1.2 m and 0.5 m deep.

FIGURE 66. INITIAL WAIV PILOT PLANT.

As a control set-up, separate sump with the same dimensions as the WAIV sump was constructed and lined with black liner (Figure 67). In addition, a white plastic container was also filled with water to check daily evaporation rates and evaluate the possible effect of the colour of the lining on evaporation.

FIGURE 67. THE A-PAN AND WHITE CONTAINER

9.1.6 Results from Pilot Study to Date

9.1.6.1 Evaporation efficiency

For initial testing and commissioning, the pilot plant was operated on potable water. During this period evaporation from the WAIV unit was monitored daily by measuring the level in the lined sump under the unit twice daily. Figure 68 compares the actual WAIV evaporation rate with the calculated Penman rate.

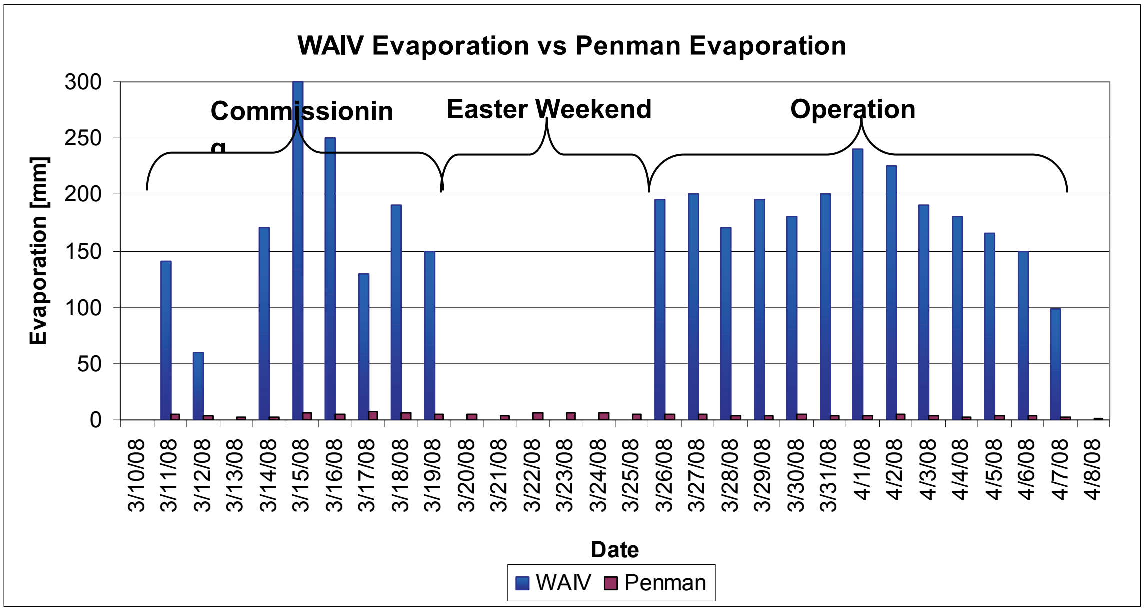


FIGURE 68. WAIV *VS.* PENMAN EVAPORATION

From the initial data, it is clear that the WAIV unit significantly outperformed the natural evaporation rate as calculated by Penman's equation. WAIV evaporation typically varied between 150 mm and 200 mm/d, compared to 3-6 mm/d for Penman and the two control ponds. The WAIV sump was refilled daily with potable water, whilst no level adjustment was done for the two control pans.

During the commissioning period, operation of the WAIV unit was unstable due to practical commissioning issues. However, after the Easter break, operation was significantly more stable. Towards the end of the initial testing period, the daily evaporation rate dropped from about 240 mm/d on the 1st of April 2008 to 100 mm/d on 7 April 2008. During the same period, the Penman evaporation rate dropped from 6.5 mm/d to 2.8 mm/d.

Figure 69 shows that WAIV efficiency was consistently above 100% and even as high as 250%. This is significantly higher than the efficiencies reported by Ben Gurion for desert conditions. Unfortunately, not enough data is presently available to provide a robust interpretation of this result, although the following comments are offered as possible explanations:

- During high wind conditions, a wind drift plume on the downwind side of the unit was observed. The physical dimension of this plume (wet patch) was approximately 1.5 m long by 1 m wide. It is expected that the plume developed form spray originating mainly at the distribution header. Thus, increased efficiencies may simply be as a result of physical water losses.

- Average wind speed during the testing period could be higher than in desert conditions. As noted previously, above 1 m/s, the aerodynamic term in the Penman equation becomes the dominant factor driving evaporation, rather than the energy term (temperature and relative humidity). This, however, was not verified with Ben Gurion University.

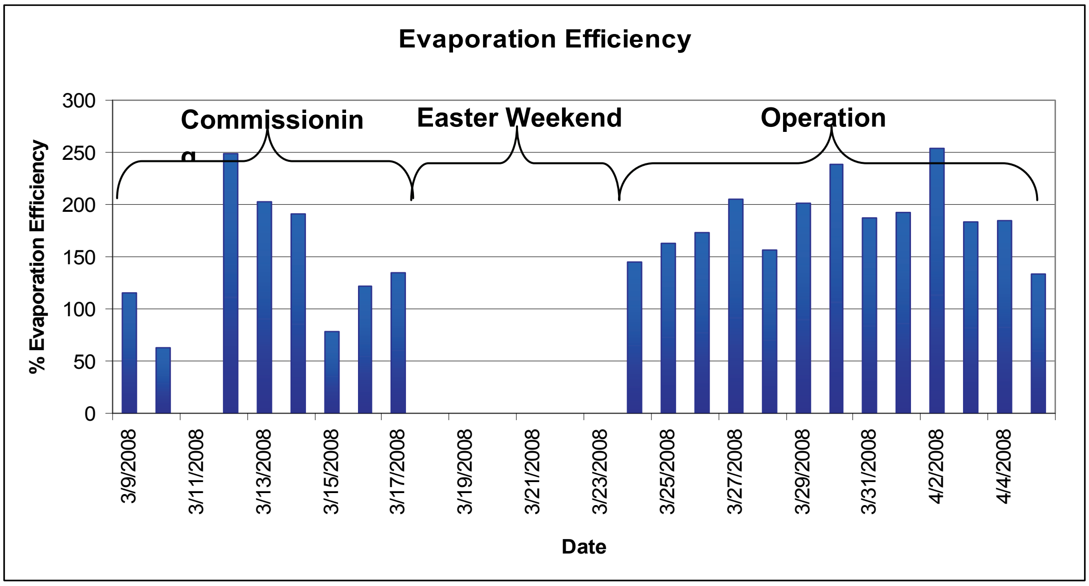


FIGURE 69. EVAPORATION EFFICIENCY OF WAIV WITH POTABLE WATER

9.1.6.2 *Physical damage*

During high wind conditions, no physical damage was observed to the surface netting.

No significant clogging of evaporation surfaces with dust, grass seeds or other solids could be observed.

As only fresh potable water was used for the initial period, not salt build-up was observed on surface netting and in pipelines.

9.1.6.3 Corrosion

As potable water was used, no corrosion was observed.

9.1.6.4 Modifications to WAIV unit

To eliminate physical water losses due to wind drift a number of modifications were made to the unit. These include:

- Relining of the sump with a 3 m wide apron, sloping back into the sump. This will collect and return any wind drift losses to the sump (Figure 70).

- Installation of a spray deflector to deflect spray back unto the WAIV netting (Figure 71 and Figure 72).

FIGURE 70. LINED AREA AROUND WAIV UNIT.

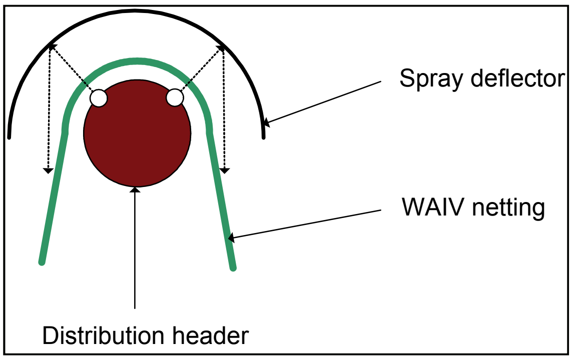


FIGURE 71. DIAGRAM OF SPRAY DEFLECTOR.

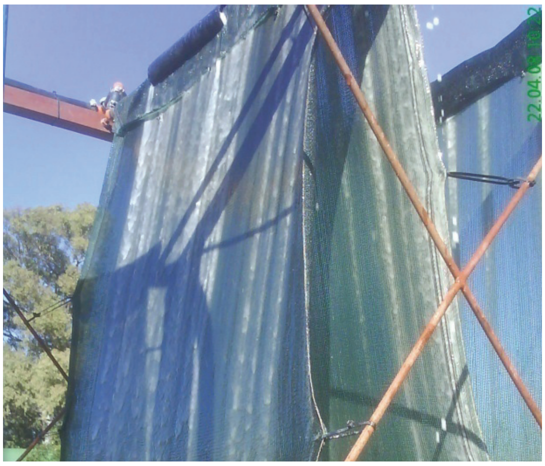


FIGURE 72. INSTALLED SPRAY DEFLECTOR.

Initial results from these modifications are indeed promising, although surface efficiencies significantly above that of Ben Gurion were still achieved.

9.1.7 Operation with salty water

To test evaporation efficiency with a saturated salt solution, the sump was emptied and then filled with a 12% sodium chloride solution. Within three days of continuous operation, white crystals were starting to form on the WAIV netting and support structures (**FIGURE 73**).

FIGURE 73. WHITE SODIUM CHLORIDE CRYSTALS ON WAIV NETTING

Evaporation efficiency over the entire period whilst operating with salt in the system remained above 100% (**FIGURE 74**). Two instances of negative efficiency were reported. These are a result of differences in timing of reporting and measurement between the weather station and manual readings on the plant.

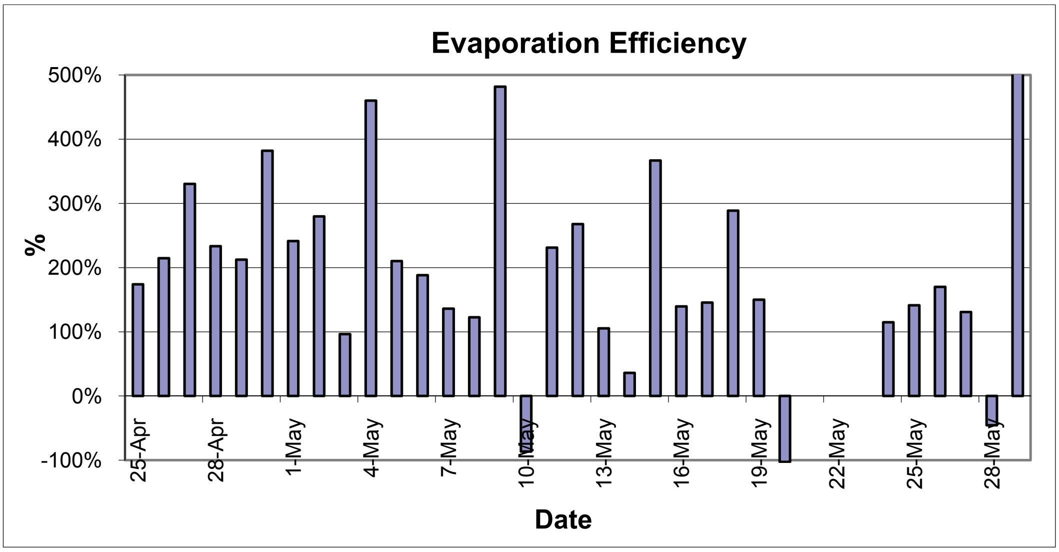


FIGURE 74. WAIV EFFICIENCY WITH SATURATED SODIUM CHLORIDE SOLUTION

9.1.8 Conclusions and recommendations regarding on-going work

The objective of "proof-of-concept" was achieved by demonstrating successful increased evaporation rates from WAIV surfaces under (limited) local conditions compared to evaporation ponds. In addition, limited wind drift losses and spray formation was demonstrated.

It should be noted, however, that the present data does not allow a detailed assessment of the technology and results reported to date should viewed as indicative only and not absolute. It is recommended that the present pilot plant operation continue to gather more reliable data and verify design concepts in more detail. In this regard, the following specific research actions are on-going:

- Change feed in the sump from potable water to a sodium chloride solution. The concentration of sodium chloride will be steadily increased to saturation levels in order to monitor corrosion, effect of salt crystals, evaporation efficiency at increased salt load, *etc.* (Presently, a salt concentration of 19% has been achieved);

- At the same time, physical water losses will be quantified by using a sodium chloride mass balance in the system.

- Verify corrosion issues at high salt load;

- Verify management of salt crystals in distribution headers and on WAIV surfaces;

In addition to this, it is recommended that the following on-going research is considered, particularly as previous reports confirmed financial viability of the WAIV option:

- Once experience is gained with sodium chloride, move on to different salts such as gypsum, lime, limestone, etc.

- Verify the performance of WAIV at different sites, particularly in the following areas:

  - Areas with high occurrence of fog – possibly Mpumalanga and/or the West Coast;

  - Areas with below freezing temperature in winter (possibly Sasolburg/Secunda/Witbank);

  - Dry conditions (Northern Cape – possibly Upington);

- If these tests are successful, a larger scale demonstration unit should be considered to solve construction and maintenance issues at larger scale;

- Finally, it is recommended that a floating design is considered to make use of existing evaporation pond infrastructure. This may be particularly useful where existing ponds are not able to dispose of excess salt water.

9.2 DEWVAPORATION

9.2.1 Introduction

As described previously, dewvaporation utilizes the basic principle of air humidification and dehumidification. The technology is considered innovative for the following reasons:

- Energy released during the dehumidification cycle is re-used in the humidification cycle, thus reducing the energy requirement;

- Evaporation is not forced from an intensely heated surface area such as in a traditional evaporator, thus salt precipitation is anticipated to take place in the bulk liquid and not so much directly on the heat transfer surface, possibly resulting in reduced scaling and maintenance requirements.

- Low temperature operation allows the use of engineering plastics, resulting in reduced cost and maintenance requirements.

- Compared to WAIV, Dewvaporation allows the recovery of fresh water;

- Waste heat or low pressure steam may be used to drive the process.

The present work focused on developing the Dewvaporation concept to be potentially better applicable to larger scale applications. This was considered important as the existing module design by L'Eau is perceived to suffer from several potential limitations in terms of full scale application. These include:

- Rectangular flow channels, resulting in significant dead space and air distribution problems. This problem was identified by the designers of the module;

- Manufacturing concerns for large systems, particularly as the present design relies on attaching different chambers with glue/PVC weld;

- Relatively bulky inlet/outlet plenums;
- Relatively low packing density of heat transfer areas.

9.2.2 Conceptual design for alternative dewvaporation module

Two major alternative module designs were considered, principally evaluating

- Materials of construction;
- Flow patterns;
- Energy requirements;
- Pressure drop profiles;
- Control.

9.2.2.1 Design option I: Plate and Frame module

To eliminate the distribution plenum at the top and bottom of the unit, a typical plate & frame design was considered analogous to the classical plate heat exchanger design (**FIGURE 75**).

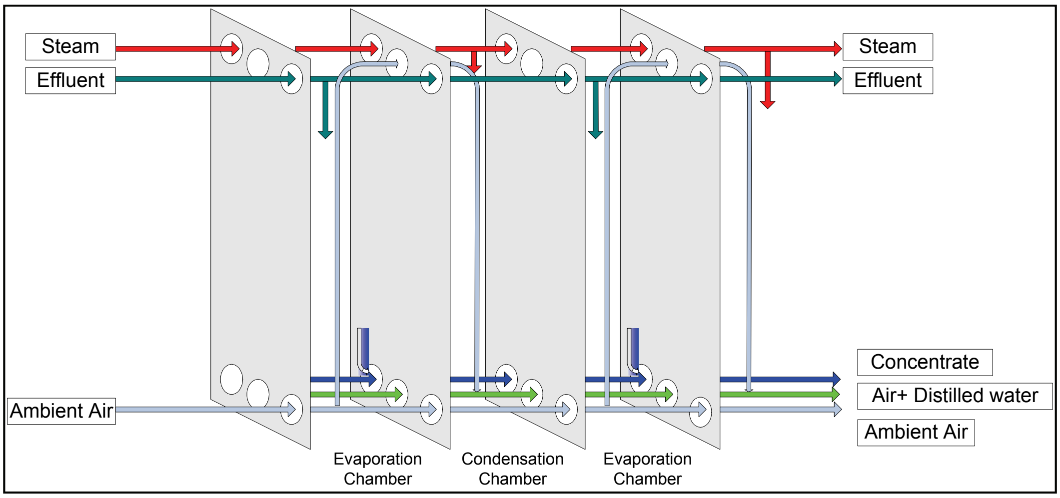


FIGURE 75. ALTERNATIVE DEWVAPORATION DESIGN.

In this design, evaporation and condensation chambers are separated by plates, with pre-formed O-ring seals and pre-punched flow-orifices. Stacking these plates will thus form the alternating evaporation/condensation chambers of the dewvaporation module. The inlet/outlet plenum is eliminated by integrating an air flow path into the plate. Air, effluent (brine), steam and concentrate flow-paths are illustrated in Figure 75.

Conceptually, plates may be manufactured from any suitable material, ranging from engineering plastics with high thermal conductivity and high softening points to corrosion resistant metals stainless steels and exotic materials such as titanium.

The main benefits of this module design are:

- Well known physical format, analogous to plate heat exchanger, thus the hydrodynamic and heat transfer design approaches are well established.
- Relatively simple means of manufacturing/construction, provided large enough volumes of modules may be produced to justify the manufacturing of specific extrusion/pressing tools and punches;
- Good mechanical sealing arrangement;
- Relatively small footprint.

The major disadvantages of the module concept are:

- High cost of research and initial production;
- Uncertainty as to mechanical stability of plates when produced from engineering plastics;
- Practicality of producing thin walled plates from engineering plastics;
- Wetability of plastic heat transfer surfaces;
- Rectangular shaped chambers which is not ideal for flow distribution.

9.2.2.2 Design option II: Shell and tube heat module

An alternative design approach is a modification to the classical shell & tube heat exchanger design (Figure 76). In this instance, the evaporation chamber will be inside the tubes and the condensation chamber will be on the shell side. A different analogy, with which water treatment plant owners and operators will be familiar, is modern capillary ultra filtration membranes.

Provided that the module design is proven practical, a conceptual full scale module may be housed in a large diameter PVC tube of up to 2 m long, which is considered the maximum practical length for ease of handling. The diameter of the tube could range from 100 mm up to 400 mm and is limited only by practical considerations and availability of commercial plastic pipes.

The internal tubes need to be manufactured from an engineering plastic with high thermal conductivity and high softening point. In addition, the tubes should have a relatively small diameter, possibly smaller than 1 inch and potentially as small as 4 mm, provided that a proper flow distribution can be demonstrated inside the tube.

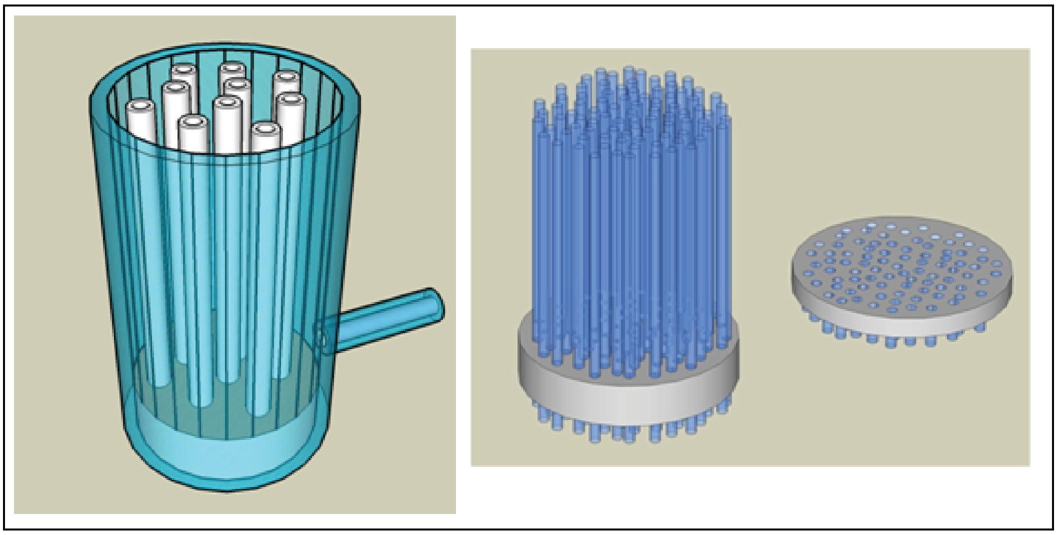


FIGURE 76. CONCEPTUAL DESIGN FOR DEWVAPORATION MODULE

In order to test the practicality of small diameter tubes, a manufacturer of cool drink straws was approached. Discussions confirmed that it will be relatively simple to modify existing extrusion equipment to produce tubes of different diameter and wall thickness. Tubes may be cut at any desired length, following some modification to existing cutting equipment. To demonstrate the flexibility of this approach, a single production run was performed, producing a single straw of 500 m length (**FIGURE 77**). This particular straw had in external diameter of 4.5 mm with a wall thickness of 250 micron (**FIGURE 78**). The straw was manufactured from high density polyethylene (HDPE).

Whilst this exercise demonstrated the flexibility of tube extraction, it also highlighted some of the limitations, particularly with regard to handling of long lengths of small bore plastic tubing. As can be seen from **FIGURE 77**, the tubes are very flexible and require careful handling to prevent damage by excessive bending. However, extensive experience with the manufacture of tubular, capillary and hollow fibre membranes for reverse osmosis and ultra-filtration demonstrated that these limitations may be overcome by appropriate engineering solutions.

FIGURE 77. ONE LENGTH OF 500 M OF COOL DRINK STRAW

FIGURE 78. PICTURE SHOWING DIAMETER OF COOL DRINK STRAW

Practically, production methods will depend on the diameter and number of tubes selected for the final module. However, as it is the intention to increase packing density as much as possible, it is anticipated that tubes will be fitted into the external housing by means of an epoxy ring as shown in **FIGURE 76**. This approach has been proven to be successful in the capillary membrane industry and is reliable for both mechanical strength and leak integrity.

The main benefits of this module design are:

- High packing density for heat transfer surfaces;
- Relatively low production costs;
- Well defined flow patterns in the evaporation chamber (inside the tube);
- Reduced potential for leaks compared to present available module design;
- Proven methods of construction from capillary and tubular membrane modules.

The main concerns with this design concept include:

- The ideal flow pattern of brine inside the tubes is that of a falling film as this will maximize heat transfer efficiencies and reduce air flow pressure drop. A major uncertainty in the design of this module configuration is the formation and stability of the falling film inside the tube and the practical engineering limitations regarding feed distribution and internal tube diameter;
- Wetability of heat transfer surfaces, thus fluid distribution and heat transfer efficiency;
- Damage of thin walled tubing during assembly and operation. However, this is not expected to be worse than for the present module design;
- A potential disadvantage of this module design compared to the present module design by L'Eau, or the alternative plate & frame design proposed in this project, is that it cannot be dismantled easily to facilitate mechanical cleaning of scaling, *etc.* This should, however, be off-set to a certain degree

by the well designed flow path inside the evaporation chamber;

- Pressure drop of the carrier gas is uncertain at present.

However, from a cost and space saving perspective, the shell and tube design approach is preferred above the plate and frame design. It was thus decided to test the dewvaporation concept on bench scale using the shell and tube design.

9.2.3 Design of test unit

The test unit consisted of 9 tubes, each 1 m in length in a module of 100 mm in diameter. There were 3 tubes of 6 mm diameter, 3 of 12 mm diameter and 3 of 20 mm diameter. Wall thickness of each tube was 1 mm. The diagram on the next page shows the design for the operation of the test unit.

9.2.3.1 Materials of Construction

The main factors considered in evaluating different tube materials were:

- Cost of the material;
- Chemical inertness;
- Softening temperature;
- Thermal conductivity;

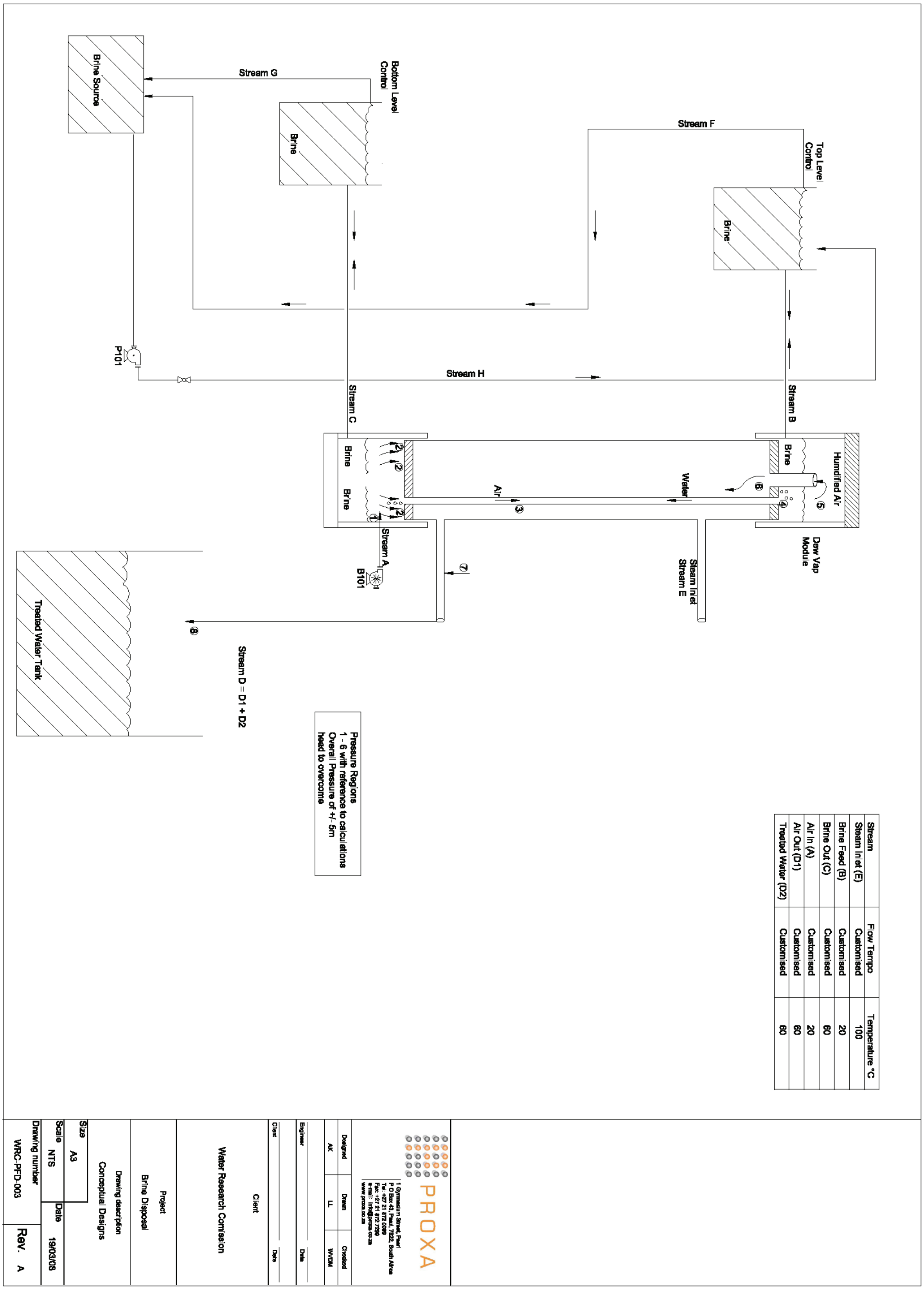
Wetability of heat transfer materials was not included in the present evaluation.

The melting temperature and thermal conductivity of materials considered are given in **Table 35**. Although metals provide the best thermal properties, their cost and chemical inertness are not attractive. Of the engineering plastics considered, HDPE offered the highest thermal conductivity with acceptable softening point characteristics. Incidentally, this is also the material from which the cool drink straws discussed previously were manufactured.

Table 35. Physical Properties of Different Materials.

Material	Melting Temperature	Thermal Conductivity
	˚C	W/m.K
Perspex	70	0.189
PVC	76	0.19
Polypropylene	160-170	0.11-0.22
Polysulfone	190	0.26
Polyamide	220	0.33
HD Polyethylene	100	0.42-0.51
Stainless Steel 316	1400	16.3
Titanium	1950	21.9
Copper	1360	401

For the purpose of the initial test unit, Perspex tubes were chosen for construction of the entire unit as it offers complete translucency for visual inspection of flow patterns and condensation, although operation will have to be at reduced temperature.



9.2.3.2 Energy Source

From the literature it was found that companies promoting dewvaporation claimed that waste heat or steam can be used as energy source. When this claim was investigated more fully, it was found that it would be better to use low pressure steam as energy source as explained below. Waste heat, however, could potentially be used to drive dehumidifiers of the inlet air.

Example: the air at the top of the condensation chamber is at a dry bulb temperature (T_{DB}) of 25 °C and a relative humidity (RH) of 100%. To increase the T_{DB} of the air by 5 °C with waste heat that has very little water content follow the grey line on **FIGURE 79**.

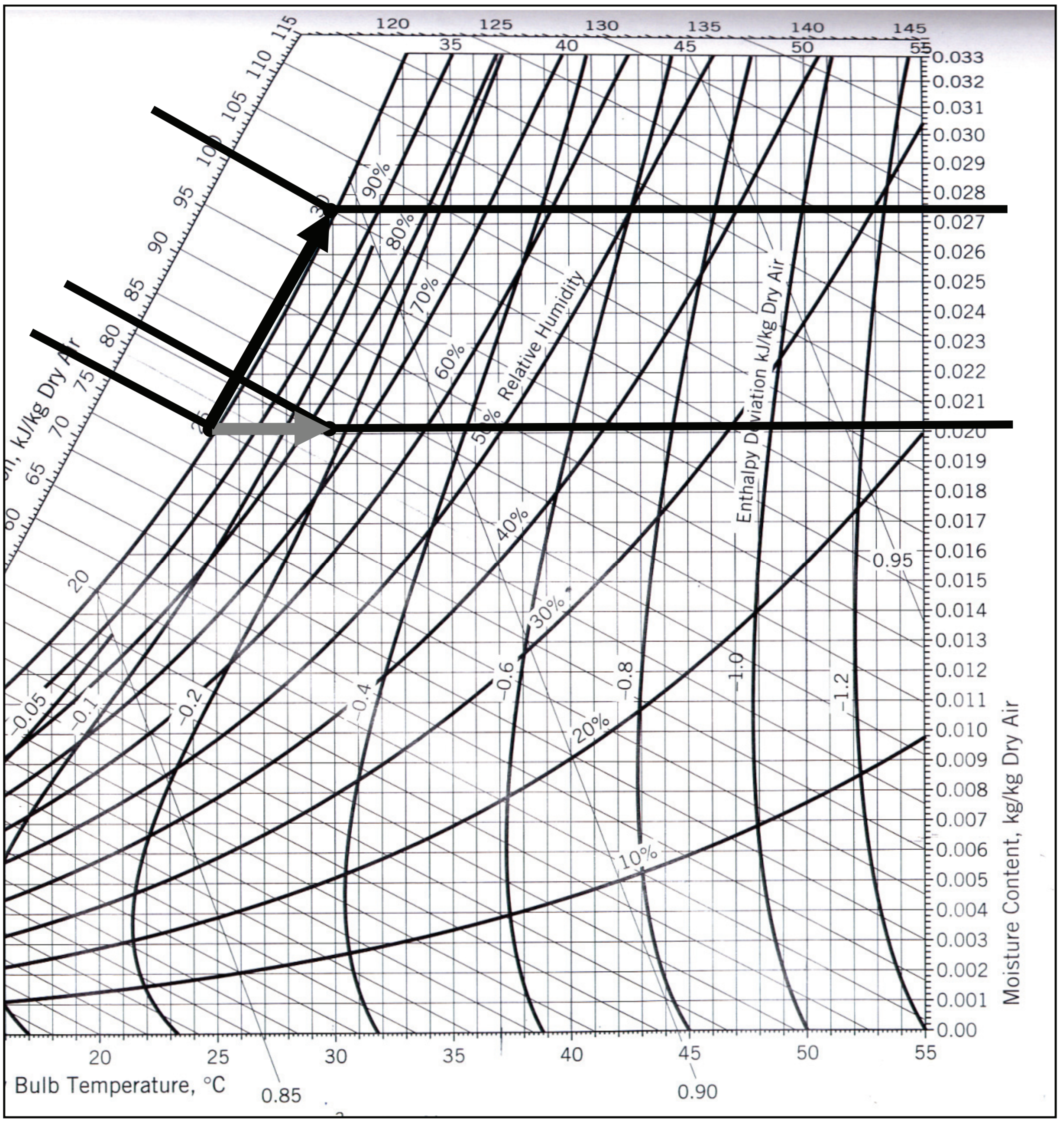


FIGURE 79. PSYCHROMETRIC CALCULATION OF ENERGY REQUIREMENTS: STEAM VS. WASTE HEAT

When increasing the temperature 5 °C without adding any moisture to the air the RH will decrease from 100% to 75%. For the air to condensate in the condensation chamber it is necessary that the RH be at (or very close to) saturation (RH of 100%).

When the RH falls to 75% the efficiency of the system will reduce significantly.

The enthalpy of the air after increasing the temperature with waste heat is 82 kJ/kg of dry air. This is an extra 5 kJ/kg of dry air that will be available for heating of the evaporation chamber.

Using steam to increase the temperature 5°C (dark line on **FIGURE 79**) the RH stays at 100%. This is ideal for condensation to start immediately in the condensation chamber. More importantly, is the fact that the enthalpy of the air increased to 100 kJ/kg making an extra 23 kJ/kg of dry air available for heating the evaporation chamber.

9.2.4 Mass and Energy Balance for Pilot Plant Unit

The detailed mass and energy balance for the dewvaporation process is complex and requires iterative solving. The ideal approach will be a finite element approach using a mass & energy balance at each stage and then integrating to arrive at a final design. This approach requires a rigorous theoretical approach, which is considered not appropriate at this stage of the conceptual development. Instead, a simplified approach was taken to design the pilot plant. It is proposed that once the concept has been demonstrated, that a more detailed theoretical analysis be performed.

In simplifying the design approach, the following assumptions were made:

- The inlet temperature (T_{DB}) of the ambient air is 17 °C and the RH 55%;
- The air temperature at the top of the evaporation chamber will be controlled to 55 °C and will be saturated with water (RH = 100%). Note that 55°C was selected as the maximum temperature to prevent softening of Perspex;
- Low pressure steam will be used as energy source;
- The condensation chamber air outlet will be at 35 °C and a RH of 100%;
- Convection and radiation heat transfer factors were ignored for the present approach and only conductivity through the walls of the tubes was considered. This will result in an optimistic required heat transfer area. However, this approach is considered adequate for the purposes of demonstrating the concept.

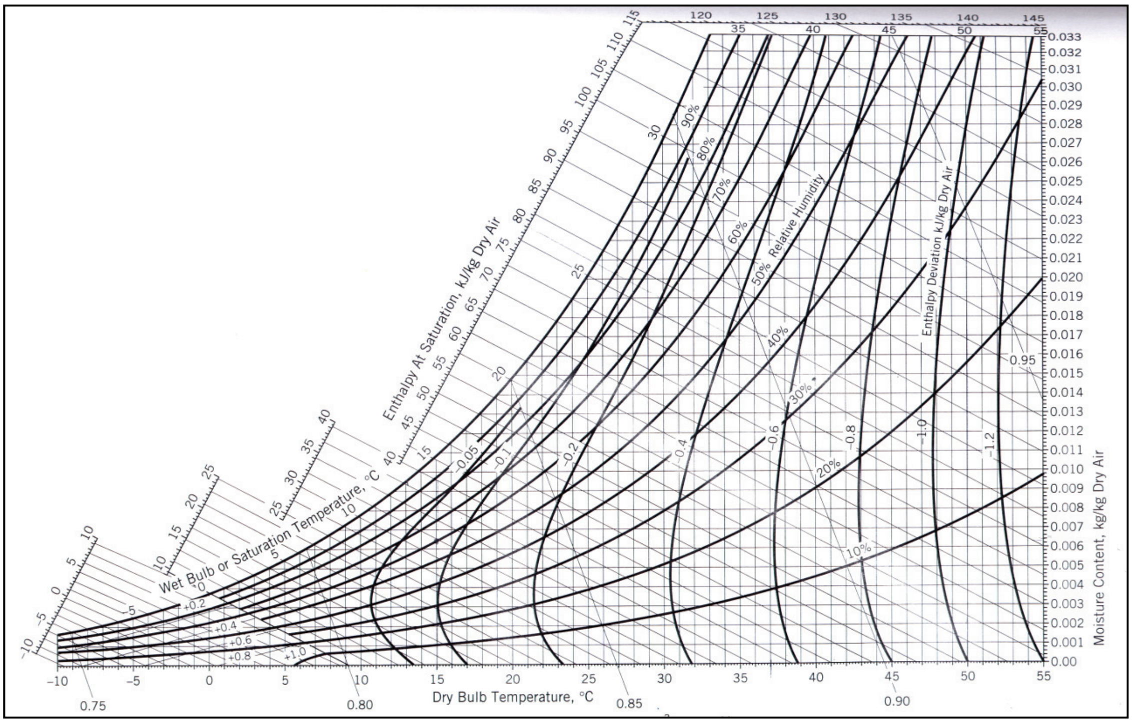


FIGURE 80. PSYCHOMETRIC CHART AS APPLIED FOR SIMPLIFIED DESIGN APPROACH

9.2.4.1 Heat Transfer

Energy transferred through the tube walls is given by:

$$E_{transfer} = \frac{\Delta T}{\dfrac{\ln\left(r_2 / r_1\right)}{2\,\pi\,k\,L}} \tag{9.2}$$

Where k = Heat transfer coefficient (W/m.K)

r_1 = inside tube radius

r_2 = outside tube radius

ΔT = temperature driving force (°C)

L = Length of the tube

The mean temperature difference along the length of the tube is 11 ˚C. Therefore:

$$E_{transfer} = \frac{11}{\dfrac{\ln\left(3.5 / 3\right)}{2\times\pi\times 0.189\times 9}} \tag{9.3}$$

$$E_{transfer} = 1322 \quad kJ/hr$$

9.2.4.2 Evaporation Chamber

The main mass and energy balance was done using the psychometric chart. Figure 52 shows a diagram of the evaporation chamber.

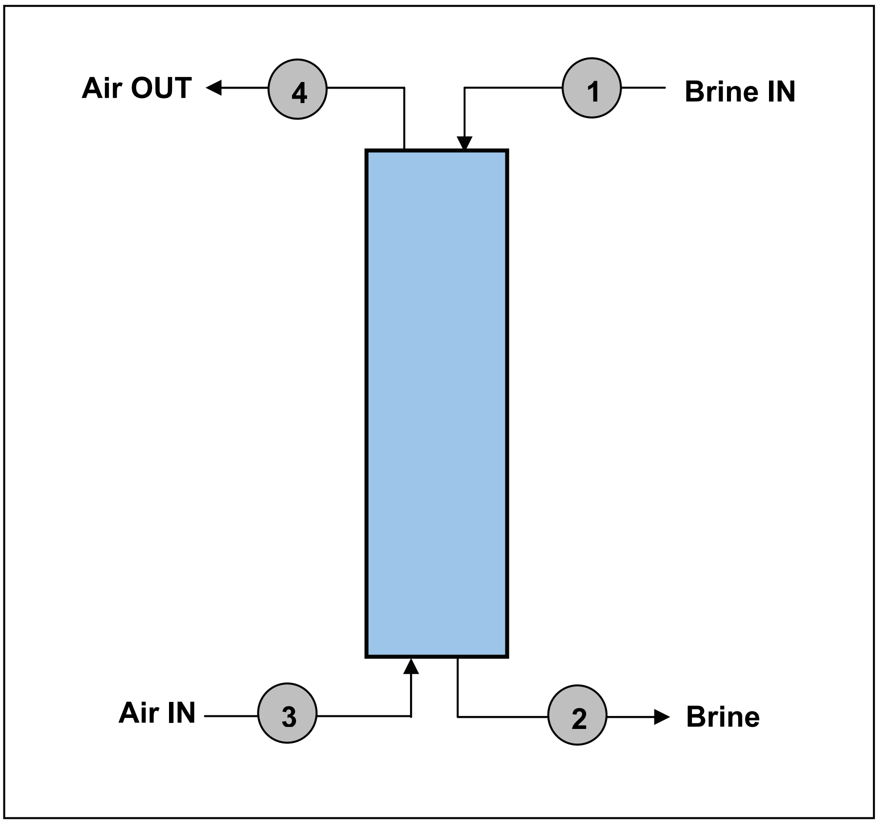


FIGURE 81. SCHEMATIC DIAGRAM OF EVAPORATION CHAMBER.

The physical properties of the inlet air **(3)** as assumed and read from the psychometric chart are given in **TABLE 36**.

TABLE 36. INLET AIR PROPERTIES (3)

T_{DB3}	17	°C
RH_3	55	%
SH_3	0.006661	kg water/kg dry air
$Enthalpy_3$	33.87	kJ/kg dry air

(Note: T_{DB}: Dry bulb temperature; RH_3: Relative humidity at (3); SH_3: Specific humidity at (3))

The properties of the outlet air from the evaporation chamber will be controlled by the amount of steam added in the condensation chamber and is given in **TABLE 37**.

TABLE 37. OUTLET AIR PROPERTIES (4)

T_{DB4}	55	°C
RH_4	100	%
SH_4	0.11576	kg water/kg dry air
$Enthalpy_4$	356.7	kJ/kg dry air

To determine the amount of water evaporated is an iterative calculation. The amount of water evaporated (W_{EVAP}) is assumed for the first iteration. The amount of air required to evaporate the water can be calculated using the difference in specific humidity's between **(3)** and **(4)**:

$$M_{AIR} = W_{EVAP} \times (SH_4 - SH_3) \qquad (9.4)$$

Knowing the mass flow rate of air through the chamber, the energy requirement on the evaporation side can be calculated:

$$E_{EVAP} = M_{AIR} \times (Enthalpy_4 - Enthalpy_3) \qquad (9.5)$$

This energy should be equal to the maximum energy transfer calculated previously. The equation was solved iteratively and the following results were obtained:

W_{EVAP} = 0.45 l/hr

M_{AIR} = 4 kg/hr **(3)** & **(4)**

E_{EVAP} = 1332 kJ/hr

It was decided to circulate 1 l/hr of brine through the system to ensure complete wetting of all surfaces. Therefore:

$M_{BRINE\ IN}$ = 1 kg/hr **(1)**

$M_{BRINE\ OUT}$ = 0.55 kg/hr **(2)**

9.2.4.3 Condensation Chamber

The calculations for the condensation chamber will be done using the same principles as the evaporation chamber.

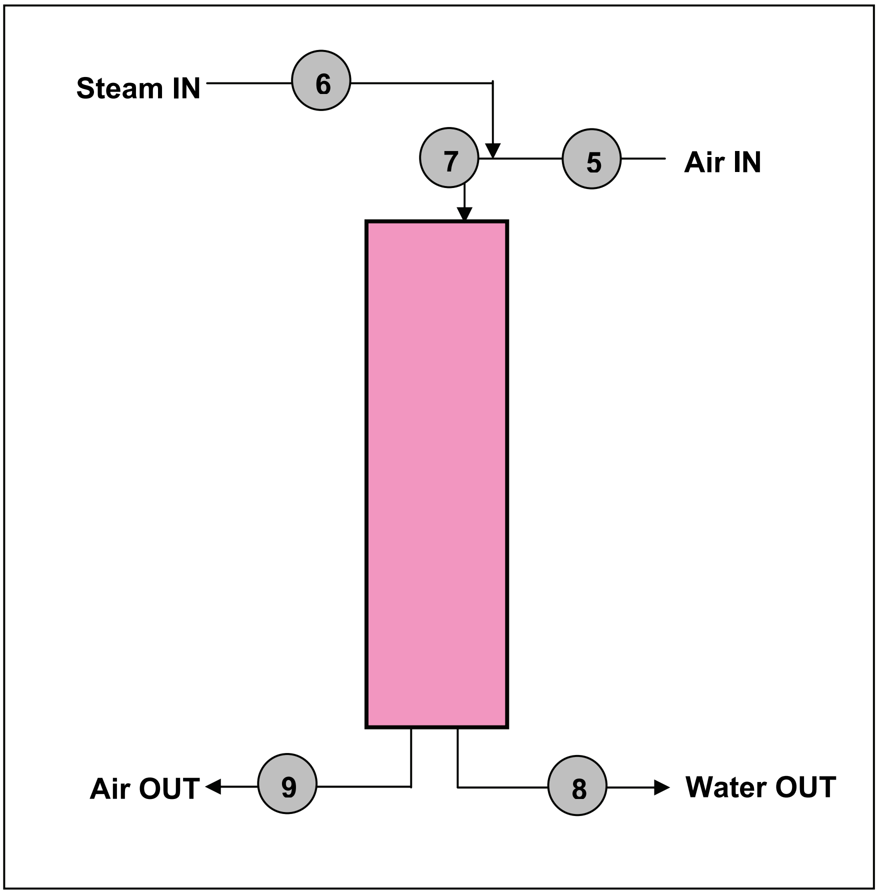


FIGURE 82. SCHEMATIC DIAGRAM OF THE CONDENSATION CHAMBER.

The inlet air **(5)** in the condensation chamber is the outlet air **(4)** from the evaporation chamber. Its properties are given in **TABLE 37**.

. The outlet conditions of the air **(9**) are assumed (Table 38).

TABLE 38. OUTLET AIR PROPERTIES (9)

T_{DB9}	35	°C
RH_9	100	%
SH_9	0.03688	kg water/kg dry air
$Enthalpy_9$	129.77	kJ/kg dry air

Knowing the volume of air in the system, the energy states of both the inlet and outlet air and the required energy release to the evaporation chamber, the amount of steam needed can be calculated. Firstly the enthalpy of the combined air and steam stream **(7)** is calculated iteratively:

$$E_{EVAP} = M_{AIR} \times (Enthalpy_7 - Enthalpy_9) \quad (9.6)$$

The equation was solved and the enthalpy was calculated to be 452.6 kJ/kg of dry air. At this energy condition the RH of the air will still be 100% as water was added to the system in the form of steam. The properties of the air **(7)** are given in **TABLE 39**.

TABLE 39. PHYSICAL PROPERTIES OF COMBINED AIR AND WATER STREAM (7).

T_{DB7}	59.61	°C
RH_7	100	%
SH_7	0.1504	kg water/kg dry air
$Enthalpy_7$	452.6	kJ/kg dry air

$$M_{STEAM} = M_{AIR} (Enthalpy_7 – Enthalpy_5) / Enthalpy_{STEAM} \quad (9.7)$$

Enthalpy of steam at 101 kPa is known as 2676 kJ/kg, therefore

M_{STEAM} = 0.15 kg/hr **(6)**

The amount of water produced (W_{OUT}) will be the difference in water retention capacity of the air at the top **(7)** and bottom **(9)** of the condensation chamber.

$$W_{OUT} = M_{AIR} \times (SH_9 – SH_7) \quad (9.8)$$

W_{OUT} = 0.47 l/hr **(8)**

9.2.4.4 Water Balance

The water balance was done over the whole system to check the calculations done with the psychometric chart. Figure 81 and Figure 82 shows the schematic representation of the balance:

(1) + **(3)** + **(6)** = **(9)** + **(8)** + **(2)**

$$M_{BRINE\ IN} + SH_3 \times M_{AIR} + M_{STEAM} = SH_9 \times M_{AIR} + W_{OUT} + M_{BRINE\ OUT} \quad (9.9)$$

$$1 + 0.006661*(4) + 0.15 = 0.03688*(4) + 0.47 + 0.55$$

$$1.17 = 1.17$$

9.2.5 Conceptual Design of a Possible Full Scale Module

To check the practicality of the approach, a conceptual full scale module was designed in order to verify the number of modules required for a large scale application (say 1 ML/d of brine).

9.2.5.1 Tube Design

Referring back to Table 35, the engineering plastic with the best heat transfer properties is polypropylene (k=0.42 W/m.K). As indicated previously, a practical length for a full scale module will probably not exceed 2 m. Now, a 4 mm cooldrink straw would probably be too small for the water to form a film inside the straw and therefore a 6 mm straw with a 0.25 mm wall thickness was used in the design. As mentioned previously, the practicality of this has to be verified using the pilot test unit where different tube diameters will be tested.

9.2.5.2 *Module Housing Design*

For the module housing readily available PVC piping can be used. A practical diameter for available PVC piping is 10 inch (nominally 250 mm). The lowest void fraction that can be achieved in this instance with the 6 mm straw is 0.22. To allow for proper flow distribution in the condensation chamber a relatively high void fraction of 0.6 was used for the conceptual module.

9.2.5.3 *Mass and Energy Balance*

For the design of the full module to be installed in a 1 Ml/d brine disposal unit, the same methodology was followed as for the pilot plant unit. Figure 83 shows a diagram of the system.

The physical properties of the inlet air **(3)**, outlet air **(6)** and saturated air **(7)** is assumed and controlled with the amount of steam added to the system. The volume of air can be calculated using the amount of water evaporated. **TABLE 40** shows the physical properties of the air:

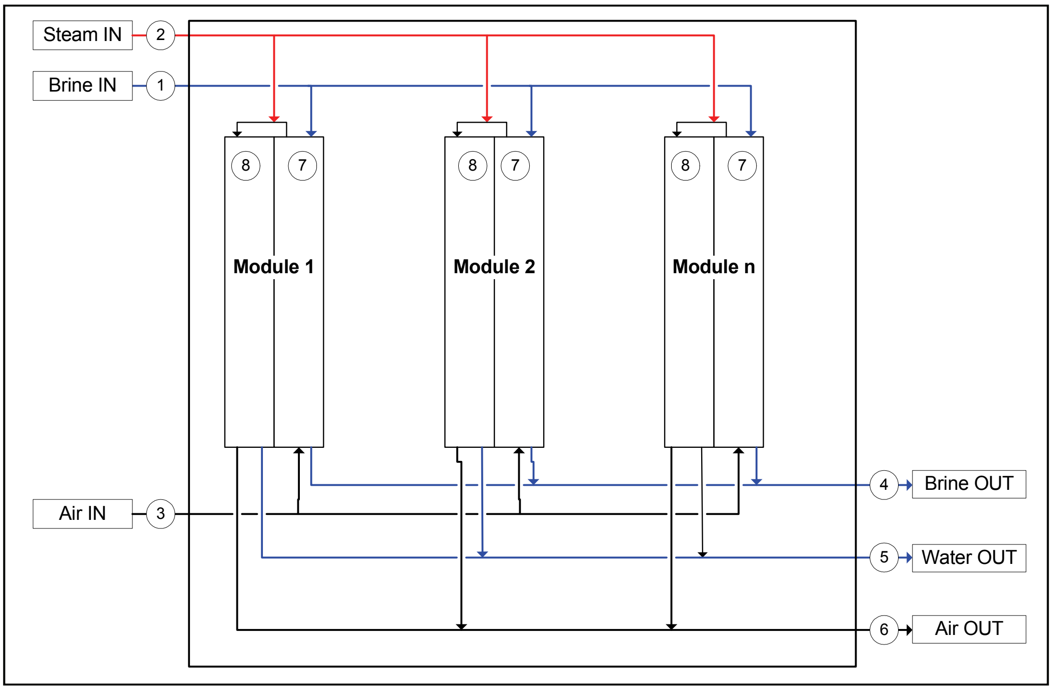


FIGURE 83. SCHEMATIC OF FULL SCALE PLANT.

TABLE 40. PHYSICAL PROPERTIES OF AIR.

	Inlet Air (3)	Outlet Air (6)	Saturated Air (7)
Flow rate (kg/hr)	76 000	76 000	76 000
T_{DB} (˚C)	17	80	55
RH (%)	55	100	100
SH (kg/kg dry air)	0.006661	0.55294	0.11533
Enthalpy (kJ/kg dry air)	33.87	1545.85	355.58

From this information the air properties at **(8)**, the amount of steam required and the amount of water produced can be calculated, yielding the following:

Steam required = 9200 kg/hr

Water produced = 42.5 m^3/hr

TABLE 41. PHYSICAL PROPERTIES OF AIR AT (8)

	Air (8)
T_{DB} (˚C)	82.5
RH (%)	100
SH (kg/kg dry air)	0.6724
Enthalpy (kJ/kg dry air)	1867.5

The energy transfer required form the condensation to the evaporation chamber was calculated to be 115 324 MJ/hr. Using this value, the size of the dewvaporation plant can be estimated. The log mean temperature difference along the heat exchange surface is calculated to be 15.1 ˚C, thus the total tube length and therefore the total number of tubes required can be calculated (**TABLE 42**).

TABLE 42. CALCULATION FOR THE NUMBER OF TUBES.

E	32034488.8	W
ΔT	15.1	˚C
k	0.42	W/mK
d_1	6	mm
r_1	0.003	m
d_2	6.5	mm
r_2	0.00325	m
L	64348	m
Nr of Tubes	32174	

Using volume fraction assumption made earlier, the number of tubes per module and the number modules can be estimated:

Tubes per module: 592

Number of Modules: 43

As mentioned previously, the design assumptions made in this report will result in an optimistic view of the required heat transfer area. Therefore, assuming a 100% error margin, a total of 86 modules will required, or say a total of 100 modules. Comparing this to typical other modular plants such as reverse osmosis and ultra filtration plants, it is not a large installation.

Conceptually, the installation may be done using a modular rack approach such as for capillary ultra filtration plant (**FIGURE 84**).

One important area which still requires further work is the calculation of pressure drop – specifically for air flow – through the system.

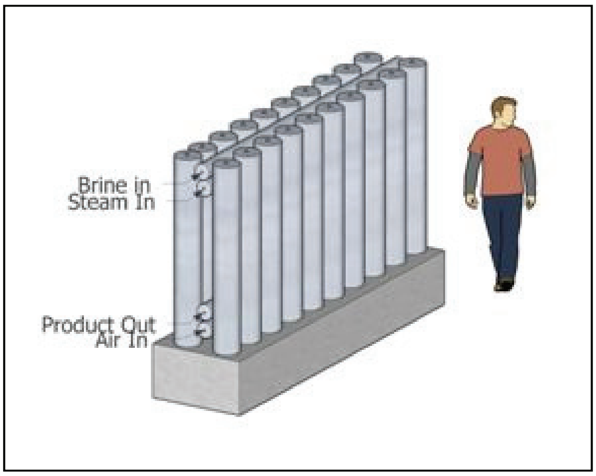


FIGURE 84. CONFIGURATION OF DEWVAPORATION PLANT.

9.2.6 Operation of bench scale model

A general view of the Perspex model is given below (**FIGURE 85**).

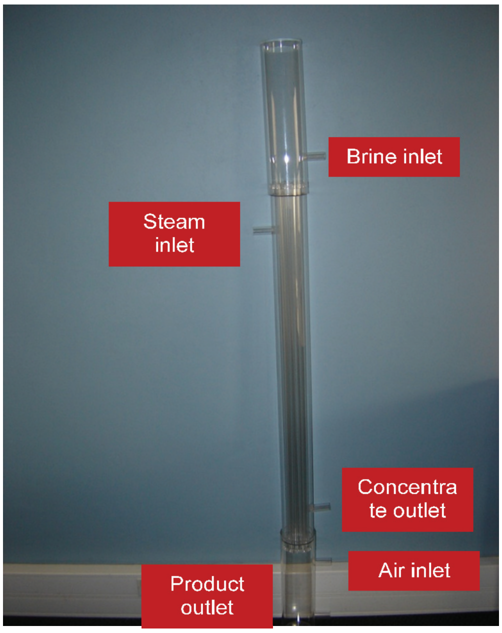


FIGURE 85: VIEW OF PERSPEX DEWVAPORATION MODEL

The model was fixed vertically (**FIGURE 86**) and water circulated under controlled flow rate from the bottom reservoir, through the top reservoir into the evaporation chamber. Concentrate from the bottom of the unit was returned to a bottom reservoir. Air was moved through the system using a small air blower, whilst steam was generated using a standard gas cooker. Product water was collected from the product outlet and stored in the product reservoir.

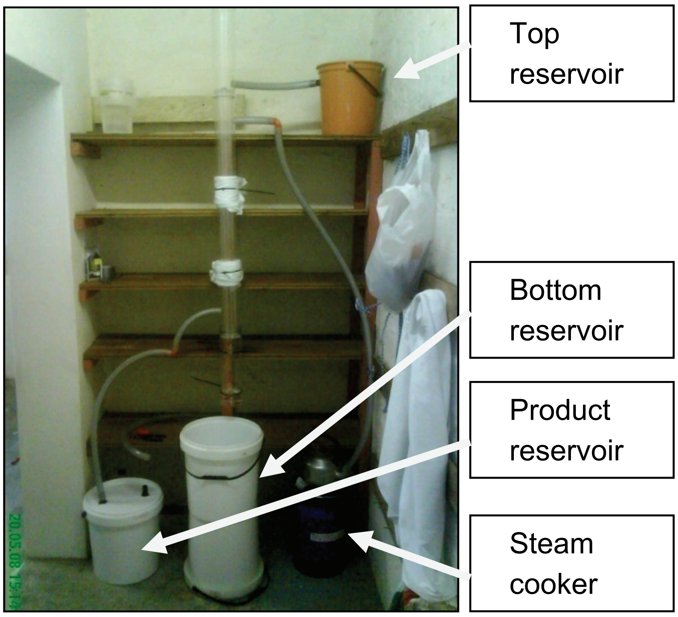


FIGURE 86: BENCH SCALE INSTALLATION OF DEWVAPORATION MODULE

The amount of steam evaporated was determined volumetrically by determining the volume of water in the steam cooker at the start and end of the experimental run. Similarly, the volume of water product produced was determined by measuring the amount of product in the product reservoir at the end of the run. For the present experiments, air humidity was ignored.

FIGURE 87 shows condensation in the condensation chamber as well as product leaving the unit at the bottom. Measurements taken during the runs are summarised in **TABLE 43**.

On average, approximately 400-600 ml/hr of steam was produced. At the same time, 100 ml/hr of raw water was evaporated. Total product water from the system averaged about 500-700 ml/hr, consisting of the evaporated raw water, condensed steam and moisture recovered from the air entering the system (labelled as "unexplained water make").

Overall, the salinity of the product water was significantly lower than that of the raw water. The salt load of the raw water increased roughly in proportion to the volume of water evaporated, although a small amount of salt collected in the product reservoir. On average the overall salt balance did not close which can be ascribed to experimental error.

FIGURE 87: VIEW OF CONDENSATE AND PRODUCT FROM DEWVAPORATION UNIT

Overall the total steam production was about 3-4 times the design rate, whilst net evaporation rate was only 25-30% of the design rate. Whilst the principle of dewvaporation was demonstrated successfully, thermal efficiency is significantly below expectations. The low thermal efficiency can be ascribed to the experimental error and inefficient experimental equipment.

TABLE 43: RESULTS OF DEWVAPORATION RUNS

Description	Unit	Run 1			Run 2			Run 3		
		Steam	Raw water	Product	Steam	Raw water	Product	Steam	Raw water	Product
Volume start	ml	500	2000	0	1000	2000	0	1480	2000	0
Volume end	ml	50	1900	600	55	1805	1135	55	1655	1790
Volume evaporated/collected	ml	450	100	600	945	195	1135	1425	345	1790
Unexplained water make	ml			50			-5			20
Run length	min	60	60	60	120	120	120	180	180	180
Rate	l/hr	0.45	0.1	0.6	0.47	0.1	0.57	0.48	0.1	0.60
TDS start	µS/cm		18922			18875			18822	
TDS end	µS/cm		19201	190		21430	155		22320	166
Mass of salt start	g		37.8			37.8			37.6	
Mass of salt end	g		36.5			38.7			36.9	
Salt lost from feed tank	g		1.4			-0.9			0.7	
Salt gained in product tank	g			0.11			0.18			0.30

Despite the use of translucent construction materials, steam flow does not allow observation of flow paths. Thus, it is unfortunately not possible to make any conclusions on flow distribution in the various tubes.

9.2.7 Conclusions and recommendations regarding on-going work

Two alternative module designs were developed and the shell and tube module concept tested on bench scale.

It was possible to effectively demonstrate the principle of dewvaporation. However, experimental errors due to the small scale of experimental set-up resulted in many inaccuracies which are manifested in low thermal efficiencies.

It is recommended that research into dewvaporation be continued, with the following major investigation areas:

- Hydrophilic materials of construction to improve film formation on evaporation surfaces;
- Optimisation of design in terms of module design and thermal efficiency;
- Production of a commercial prototype in order to verify commercial viability.

9.3 Freeze desalination

9.3.1 Bench scale tests

Initial bench scale tests were done using a simple micro ice-making machine to produce ice from a 10% sodium chloride solution. The brine solution was circulated between a small batch tank and the ice machine until sufficient ice was produced to collect a small sample of ice. The ice was allowed to drain by placing it on a wire mesh for 20 minutes and then allowed to melt. The resulting water was collected and TDS measured.

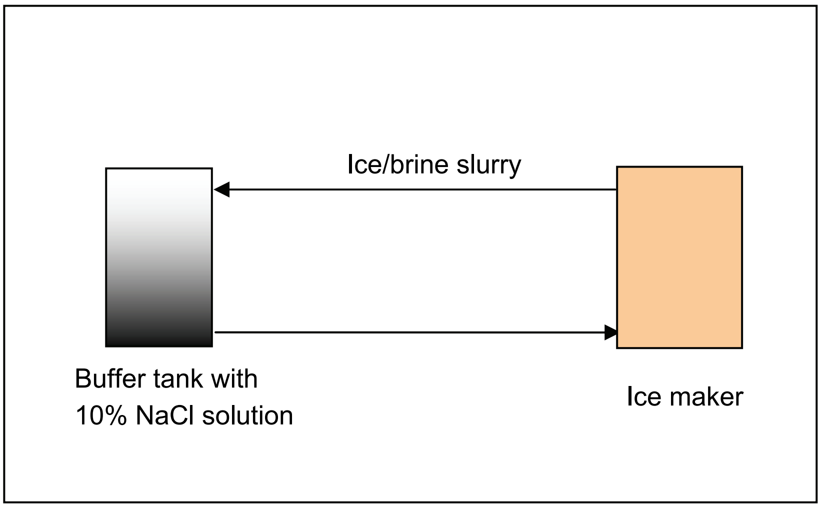


FIGURE 88: EXPERIMENTAL SET-UP TO PRODUCE MICRO-ICE

Figure 89 shows a typical ice/brine mixture as collected from the small buffer tank during bench scale experiments. Although the slurry was allowed to stand for 20 minutes, very little liquid actually drained from the sample. TDS reduction of less than 50% was achieved.

FIGURE 89. ICE/BRINE MIXTURE FROM FIRST BENCH SCALE EXPERIMENTS

Despite these disappointing results, a field visit to a full scale installation confirmed that extensive desalination by freezing could be obtained by allowing the correct draining set-up and drain time. In this instance, sea water was used for ice production for commercial fish trawlers. The seawater, with a TDS of 36000 mg/l and a temperature of 12ºC was used to produce bulk ice, stored in 50 m^3 insulated GRP tanks. Ice/brine slurry was pumped into the bottom of the storage vessels and the ice allowed to rise to the top, whilst brine was withdrawn from the bottom and returned to sea. Ice was harvested at the top of the storage vessel using a rotating cutting device. Unfortunately, no pictures could be taken, but the operation and construction was similar to the counter-current wash column of COLT INDUSTRIES (**FIGURE 44**).

The TDS of the harvested ice was less than 100 mg/l, resulting in a desalination efficiency of more than 99%. Again, unfortunately, no system design data was allowed to be taken from the premise, but nevertheless, the principle of desalination by freezing could now be confirmed on a relatively large scale (about 150 t ice per day). It was decided to simulate the observations from the site visit on bench scale using a simple vertical retention vessel as shown in **FIGURE 90**. Again, a 10% NaCl solution was used as feed to the freeze unit, but this time the salt removal rate increased to 87%.

FIGURE 90. IMPROVED ICE/BRINE SEPARATION ON BENCH SCALE

It should be noted that the primary objective for this project is not the production of potable water, but the disposal and management of brine. As such, whilst an overall salt rejection rate of 87% does not compare well with that of other desalination techniques such as reverse osmosis and thermal desalination, it should be noted that:

- The product water from the freeze desalination technique could potentially be polished using standard approaches as described in previous reports;
- The freeze desalination technique is not limited by osmotic pressures such as membrane processes, thus desalination of very high salinity brines should be possible;
- The observed salt removal rate of 87% is based on preliminary “proof-of-concept” tests and the ice was not “washed” with fresh water to remove residual salts. As such, it is expected that salt removal could potentially be improved substantially.

9.3.2 Conclusions and recommendations regarding on-going work

Freeze desalination has been proven on a commercial scale. Further development work will therefore be required to demonstrate the following:

- Limits to economic application
- Applications on brine
- The VCF obtainable
- Utilisation of ice for cooling of deep mining applications.

CHAPTER 10

10. CONCLUSIONS

This study was initiated by the WRC in 2005 in order to evaluate the current and projected sources of brine and sludge, treatments and new concepts in managing brine from desalination plants. The study has shown that brine disposal is a global challenge – particularly from inland desalination plants. South Africa, being a relatively arid region with major industrial and mining activities away from the coast, faces the dual challenge of water re-use from these activities, whilst controlling salinity build-up. With increasing economic development and mining activities, it is projected that brine volumes will increase significantly through the next 5 to 20 years. Disposal of unwanted salts will thus form an increasingly important consideration in the selection of treatment schemes to minimize overall lifecycle cost and environmental liability.

Whilst disposal of unwanted salts have to be managed from a range of desalination activities, this study focused on brines from reverse osmosis plants, as this technology most frequently forms the basis for final salinity control in South Africa.

10.1 Brine and sludge volumes

An extensive review was performed on current and future anticipated brine volume generation. Whilst this data base will never be absolute, it is probably sufficiently accurate to determine general trends. In broad terms it can be concluded that:

- Brine volumes generated as a result of coal and gold mining will probably represent the most important challenge over the medium term. Cumulatively, it is possible that brine volumes could be around 4000 t/d within 5 years, and as much as 15 000 t/d of brine within 20 years.
- In terms of the areas in which brine will be generated, in the short term (depending on future strategies to manage the West and East Rand Basins) brine generation could be relatively evenly split between the Johannesburg area, and the Witbank area;
- However, the greatest area of increasing brine generation is expected (in the longer term) to be in the Witbank Coal Fields;

Other factors to be considered in interpreting this data include:

- The East and West Rand basins are generating water primarily from defunct gold mines. It is uncertain as to the extent to which government or the remaining gold mines will be able to fund membrane technology treatment in the short term, the increasing value of water notwithstanding. This in turn will influence whether the brine volumes predicted for the Johannesburg area will materialise;
- In the Witbank area, the cost of brine disposal is resulting in considerable effort to minimise the volumes of brine. For mines with low sodium water,

these opportunities are significant, and include the generation of water for process purposes in addition to potable water;

The similarity in water treatment technologies for water produced by the coal and gold mining industries offers benefits to technology developers in optimising processes. It is likely that developments in the field of brine minimisation and management will also be similar, albeit that there will be some differences in the chemistry and nature of the brine.

10.2 Legal framework

Disposal of brine and sludge is covered by several laws and regulations which have to balance economic development and job creation with environmental protection. Improving the understanding of these risks by government and industry will ensure a balanced and sustainable approach. South African legislation is of a high standard and is able to protect as well as enable the water industry to flourish. The challenge will be for the legislated framework to be implemented and policed effectively to demonstrate its feasibility and sustainability. It is unfortunately true that at present, implementation and policing capacity lacks and do not match the high ideals of existing legislation.

10.3 Current brine management strategies

A review of international practices confirms that a large number of factors influence brine disposal strategies, including:

- Size of installation;
- Composition of brine;
- Physical and geographical location of the installation;
- Availability of acceptable receiving site;
- Legal/regulatory permissibility;
- Public acceptance;
- Capital and operating costs;
- Ability for future expansion;
- Long term environmental risks;
- Remedial options available in case of failure;
- Economic drivers for primary desalination application.

To date, the most important disposal strategies employed in various regions of the world include:

- Discharge to evaporation ponds;
- Disposal to surface water bodies;
- Disposal through pipelines to municipal sewers;
- Deep-well injection;
- Concentration into solid salts;
- Land application and irrigation of plants tolerant to high salinity (halophytes);

Presently, brine management strategies in South Africa focuses mainly on disposal to lined evaporation ponds, installation of mechanical evaporators and disposal to ash systems. Capital, operating and long term environmental liability frequently limit successful application of these systems, thus the need for innovative solutions to brine management.

10.4 Innovative approaches

The various innovative brine management strategies may be grouped as follows:

- Brine minimization;
- Product recovery;
- Final disposal.

In order to evaluate different innovative concepts against existing alternatives as well as against each other, a conceptual brine was developed and conceptual designs developed for a system to treat 1 Ml/d of brine. Based on this evaluation, the most promising innovative techniques are summarised below.

10.4.1 Brine minimization

10.4.1.1 Brine softening and treatment

The most cost effective manner to manage brine is to reduce the volume thereof as much as possible. Traditionally, the target water recovery for inland desalination system varied between 75 and 85%, resulting in a brine TDS of about 10 000 mg/l-30 000 mg/l. By comparison, brine from seawater RO plants may be as high as 70 000 mg/l. It is clear that if inland desalination plants are operated at similar brine TDS levels, the volume of brine can at least be reduced by 50%. Factors contributing to inland RO plants not being operated at these high TDS levels include:

- Scaling chemistry, including complex and unpredictable synergistic effects;
- Limited understanding of high salinity desalination technology;
- Variable incoming raw water quality;
- Oil, organic material and colloidal matter;
- Commercial risk to contractors who have to guarantee plant performance;
- Operational skill and shortage of expert skills in supporting these high recovery systems;
- Lack of inclusion of long term cost for brine disposal in project evaluation, resulting in preference to schemes with lower capital costs.

Many of these concerns may be addressed by advanced and comprehensive pre-treatment, buffering, automated control and using state-of-the-art technology. However, despite encouraging field results from such modern schemes, significant challenges remain in ensuring trouble free operation of desalination systems in cases of complex and variable feed streams. In these situations, design and operation of systems should preferably be performed by specialist teams.

One promising option which appears to be emerging as a preferred way to reduce brine volumes is brine softening-and-recycle. Several schemes have been proposed in the past, including options such as SPARRO, ICCON, HIPRO, *etc.* The major challenges in recycling of brine are:

- Overcoming the inhibitory effect of anti-scalants;
- Controlling scaling in the membrane units and piping;
- Osmotic pressures.

Modern designs overcome these limitations in a number of ways, most notably as follows:

- The inhibitory effect of anti-scalants may be overcome by two major process routes, including:
  - Selection of the appropriate anti-scalant. Generally two types of anti-scalants are available, *viz.* those interfering with crystal growth (and being incorporated into the crystal structure), and those modifying solubility of certain salts. Generally, the second class of anti-scalant is preferred when attempting to neutralise the effect of anti-scalants;
  - Simple over-saturation. By returning the brine to a slurry reactor and causing super-saturation of the sparingly soluble salts, the anti-scalant is simply overwhelmed and not able to continue preventing precipitation;
- Scaling in membranes may be controlled principally by the following means:
  - Routing of the brine to a slurry reactor to where super-saturation is removed. The process have been demonstrated in the SPARRO process;
  - Designing the desalination system in distinct units running at increasing water recovery. This approach reduces the overall process risk for catastrophic scaling in the system.

In recent years, several innovative pre-treatment schemes for brine treatment were proposed to increase water recovery above 95%. Presently, the technology is virtually market ready, although some concerns still apply.

Enhanced evaporation systems

Two promising alternatives were identified, *viz.* WAIV and Dewvaporation.

<u>WAIV</u>

WAIV exploits wind to enhance evaporation above brine ponds through the use of extended vertical surfaces. Small scale pilot tests have shown that evaporation rates may be increased by as much as 20-30 times compared to natural evaporation from open ponds. The technology may also be adapted to be used to increase the lifespan of existing evaporation ponds.

One of the main benefits of the technology is its perceived level of simplicity and reduced maintenance requirements. In addition, the technology utilises primarily a natural, renewable energy source, i.e. wind.

The technology has primarily been developed for smaller systems in dry climates, although conceptual designs in local conditions are proving to be an interesting alternative to existing preferred options.

Despite some concerns, it is likely that the technology may reach full scale application in a reasonably short time.

Dewvaporation

This technology utilises the natural cycle of humidification and de-humidification and may utilise waste heat or low energy steam to evaporate brine. Compared to traditional thermal evaporators, evaporation of water in dewvaporation occurs from the surface of the liquid and not from a highly heated metal surface. As such, it is thought that scaling will be reduced.

Compared to WAIV, the technology is more complex, but offers the advantage of recovering high quality water from brine streams.

As the process operates below 100º C, a typical Dewvaporation unit may be constructed from non-corrodible materials (engineering plastics), thus reducing capital and maintenance requirements significantly. An innovative module design was developed, combining the characteristics of a shell and tube heat exchanger with that of a capillary ultra filtration membrane.

A small scale test module was produced and tested on bench scale. It was possible to produce product water of a quality comparable to mechanical evaporators. However, thermal efficiency of the test unit was low due to size and inherent design limitations of small scale equipment.

Whilst conceptual designs show that dewvaporation could hold significant capital and operating cost benefits compared to conventional systems, the technology requires significant additional development to reach pilot scale. The main uncertainties include:

- Materials of construction, particularly relating to wetability and thermal efficiency;
- Scaling control;
- Fluid distribution in the proposed module design;
- Cost associated in harvesting waste heat sources.

10.4.1.2 Freeze desalination

The conversion of saline water to fresh water by freezing is based on the difference between liquid water and ice in terms of salt solubility. Nowhere is freeze desalination so vividly illustrated in nature as in the production of fresh water from ice collected in icebergs.

Two primary approaches is possible, *viz.* direct and indirect freezing, with direct freezing being more efficient. Despite significant research effort in the mid 1950s-late 1980s, freeze desalination was never commercialised successfully, compared to other techniques such as RO and evaporation. The main concerns were inclusion of salt in the ice produced, resulting in the production of low quality product, as well as the efficiency of large vacuum pumps required for low temperature processes.

Lately, and due to the problems and inefficiencies associated with standard evaporative systems, freeze desalination has received increased interest, particularly for the following reasons:

- Reduced energy demands;
- Reduced corrosion at low temperature;
- Reduced risk of scaling at low temperature;
- Improved energy efficiency of large scale vacuum pumps;
- Development of freeze desalination through clathrate formation;
- Possibility of utilising eutectic freeze crystallisation to produce pure water and solid salt by-product in a single unit operation.

A further reason for investigating freeze desalination was that compared to previous efforts to produce potable water from sea water, the present focus was to only partially desalinate brine so that it may be further treated in a standard RO plant. Thus, the main focus of freeze desalination in brine treatment is the removal of the bulk of the osmotic pressure in order to further reduce brine volumes by RO.

To test the concept, a series of small scale tests using indirect freezing was performed. It was found that 50% desalination could be achieved using a very simple approach from a brine starting at 18900 mg/l. This increased to 87% when residual brine attached to the ice was drained under vacuum. Actual full scale installations in the fishing industry of South Africa proved desalination efficiency of more than 99% if sufficient draining of residual brine from ice is allowed (I&J on West Coast of South Africa).

To evaluate options to further treat this partially desalinated brine, a theoretical simulation was performed using RO as polishing step and WAIV as final brine disposal step. Whilst the process did not achieve the target energy efficiency of 12 kWh/kl, a theoretical energy efficiency of 19 kWh/kl was achieved at lower potential capital cost than a comparative evaporator/crystalliser. It is anticipated that energy efficiency will improve with direct freeze desalination.

10.4.2 By-product recovery

Globally, many by-product recovery opportunities have been explored. To date, these schemes have been met with limited success, primary as a result of unfavourable economics and access to markets. Based on imported chemical products into South Africa and equivalent brine volumes, the most promising options for by-product recovery include:

- Sulphur;

- Calcium carbonate
- Gypsum – high quality without metals contamination.

The most successful schemes appear to be those where access to markets have been pre-arranged. In cases where a derivative product from the recovered salt is produced, the barrier to competitive entry is raised, improving the financial evaluation of by-product recovery options significantly. It was also found that waste products in solid form are preferred to those in liquid form, due to ease of handling and reduced transport costs.

It is believed that by-product recovery will gain importance as markets and technologies develop. However, the main benefit of by-product recovery will probably remain the reduction in long term risk associated with brine disposal.

10.4.3 Sludge disposal

It was found that:

- Sludge production is generally from pre-treatment activities to RO processes and frequently originates from acid mine water neutralisation or softening activities of raw water and effluent.
- A weakness of the typical approach is that the precipitation process generally does not minimise the volume of hazardous material. The toxicity of sludge is frequently controlled by the concentration of metals in the sludge, which may, or may not, be quite a small proportion of the total waste stream.
- More recently, staged neutralisation has found increasing application, thus allowing the production of a smaller volume of hazardous sludge, whilst the bulk of the sludge is either high purity gypsum of calcium carbonate.
- Often, lined lagoons are used for brine as well as sludge disposal;
- A range of uses have been found or tried for sludge from Acid Mine Drainage, but there are limitations in terms of the volumes being generated (large), the location of the material (often remote) and the potential uses (certain select possibilities rather than a general or widespread application suggesting relatively small volumes will be used);
- Selective metal removal using sulphides, or the precipitation of minerals such as jarosite at low pH appear to have the potential to produce lower volumes of sludge, and possibly significantly lower volumes of high hazard sludge;
- On any large mining operation, there are normally significant volumes of waste to be managed. Technologies that result in the potential disposal of significant volumes of sludge back into the mining operation or on to existing waste facilities must be highly desirable;
- To this end, technologies that result in a low hazard sludge such as the formation of more stable crystalline structures that may be able to limit the leachability of metals appears to have significant possibilities, particularly if

the metal removal can be selectively controlled. While the focus for sludge management is quite correctly on minimising sludge volumes, possibly a more important focus should be to limit the volume of high hazard sludge, and maximising the volume that can be co-disposed either within the mine, or with the mine waste;

- An important further consideration is whether the techniques used to classify the sludge are appropriate. The correct approach will depend on the final disposal option or use, but consideration may have to be given to other techniques rather than the Acid Rain Test, as well as requiring an understanding of the potential impact of bacteriological action.

Finally, the study has answered on the current situation of brine management strategies and treatment technologies. An initial database of the current and projected brine volumes was compiled, confirming rapidly expanding brine management challenges. In particular, water recovery rates, life-cycle costs and ongoing long term environmental liabilities were identified as major obstacles. This project identified several opportunities to improve sustainability and identified specific areas for future research. It is urgent to pursue these through vigorous debate, collaborative research and appropriate resourcing.

CHAPTER 11

11. RECOMMENDATIONS

11.1 Raising awareness

The need for addressing South Africa's increasing salinisation has been accepted by the legislators and much of industry. The legislative environment is also conducive to a sustainable and integrated approach to brine handling. It is clear however, that significant work is still required to implement some of the best brine handling legislation in the world. Improving the understanding of the risks and strategic options for government and industry alike will promote a balanced and sustainable approach.

It is therefore recommended that:

- Additional government funding be allocated to improving the understanding of the risks and opportunities relating to brine and to develop innovative solutions in treating the projected brine volumes;
- As part of the WRC's initiative to date, awareness of the challenges and opportunities in the dynamic field of desalination must be increased by workshops and further technology transfer opportunities. These campaigns should include the legislature.
- However, relevance of awareness initiatives must be ensured by updating the data base in terms of brine volumes to be generated. In order to obtain such a data base, it is recommended that:
    - The focus should be on coal and gold mines.
    - Several mines are undertaking additional work on their water balances. Data should be available within the next year that will allow far more reliable predictions to be made and the database must therefore be updated accordingly.

11.2 Future Research Requirements

In line with global trends and current South African legislation, the hierarchical waste treatment approach should guide future research into the various innovative brine management strategies. Firstly, a generally recommendation is made:

- Energy efficiency of brine treatment processes should be critically reviewed;

A number of innovative technologies were identified and the most promising of them can be grouped as follows:

- Brine minimization;
- Product recovery;
- Final disposal.

11.2.1 Brine minimization

Future research should aim at the following:

11.2.1.1 Brine softening and treatment

Brine softening-and-recycle as an important opportunity to recover by-products and reduce brine volumes. Significant work has already been done in this regard (SPARRO, Emalahleni projects, *etc*.) and specific attention should be given to:

- Selection of the appropriate anti-scalant and anti-scalant system;
- Overcoming and managing the inhibitory effect of anti-scalants;
- Control of scaling in membranes and pipe-lines;
- Further investigation of treatment in a slurry reactor where super-saturation is removed. (See SPARRO process);
- The effects and manipulation of osmotic pressures;
- Development of controlled crystallisation systems to harvest by-products in an economical manner. In particular, fluidised seeded bed reactors or similar process configurations could offer interesting opportunities;
- Design of desalination systems in distinct units running sequentially at increasing water recovery. This approach reduces the overall process risk for catastrophic scaling in the system.

11.2.1.2 Enhanced evaporation systems

Two promising alternatives were identified, *viz.* WAIV and Dewvaporation and await either further development or implementation on a commercial scale.

WAIV

- It is recommended that development and research into the WAIV technology is accelerated. The technology is still in its infancy and the following concerns must be addressed:
  - Scaling in pipelines;
  - Fog harvesting;
  - Salt deposition of evaporation surfaces;
  - Applicability to large scale systems;
  - Applicability in areas of increased humidity;
- A data-set of the performance of WAIV technology across different climatic conditions in South Africa should be developed through:

- Installing small scale systems in areas typical of dry, windy, humid and wet areas;
- Correlate performance of these systems with standard A-Pan or Penmann evaporation rates;
- Develop a methodology to design these systems using the above data set in order to speed-up the design cycle for industrial applications;

- In order to minimize maintenance requirements of the WAIV system, it is recommended that various materials of construction should be evaluated, in particular by considering:
  - Cost;
  - Structural and UV stability;
  - Wettability of evaporation surfaces;
  - Pumping systems.
- Design of the WAIV system should be optimized by considering the following important parameters:
  - Recycle ratio in order to minimize energy consumption, whilst ensuring proper wetting of evaporative surfaces;
  - Design of the manifold system.

Dewvaporation

Dewvaporation technology offers the advantage of recovering high quality water from brine streams. It is recommended that research into this be extended to pilot scale as follows:

- Investigate optimum materials of construction by considering the wetability of materials viz-a-viz durability and strength;
- Detail the design of a prototype dewvaporation module for laboratory scale testing;
- Produce the prototype module
- Verify the performance of the system and re-evaluate economic and technical benefits, particularly with regard to corrosion resistance, temperature stability and scaling potential;
- Use the above data to design, construct and operate a pilot plant with capacity which will allow upscale to demonstration scale.

11.2.1.3 Freeze Desalination

The feasibility of freeze desalination was proven in full scale installations in the fishing industry. However, in order to evaluate the long term benefits of freeze desalination, further research work need to be performed in the following areas:

- Addressing its application to brine;
- Using direct freeze desalination as alternative to indirect freezing as demonstrated during the present work;
- The limits to economic application;
- Utilisation of the ice for cooling purposes.; and,
- Possibly combining freeze desalination with Eutectic Freeze Desalination to further enhance the potential of low temperature brine treatment.

11.2.2 By-product recovery

Globally, many by-product recovery opportunities have been explored with limited success, primarily as a result of unfavourable economics and access to markets. It is recommended that:

- A regional approach be followed jointly by industry and legislators to encourage by-product recovery options. In this manner, competition between various desalination plants may be reduced, whilst economics of scale will improve the likelihood of success against cheaper imported materials;
- High opportunity by-products should be targeted first, particularly sulphur, high quality gypsum and precipitated calcium carbonate.

11.2.3 Sludge disposal

Sludge disposal research needs are as follows:

- Investigate minimisation of the volume of hazardous material;
- Staged neutralisation should be vigorously pursued;
- Find further uses for sludge from acid mine drainage;
- Selective metal removal using sulphides, or the precipitation of minerals such as jarosite at low pH appear to have the potential to produce lower volumes of hazardous sludge, and must be pursued;
- Technologies that result in the potential disposal of significant volumes of sludge back into the mining operation or on to existing waste facilities must be explored;
- Investigate the formation of more stable crystalline structures that may be able to limit the leachability of metals;

- While the focus for sludge management in the mining industry is quite correctly on minimising sludge volumes, possibly a more important focus should be to limit the volume of highly hazardous sludge, and maximising the volume that can be co-disposed either within the mine, or with the mine waste;

- Determine whether the techniques used to classify the sludge are appropriate.

11.3 Implementation Recommended

Regulatory environment

- South African legislation is of a high standard and implementation of the full extent of the law is required.

- The most pressing challenges are the implementation, policing and testing of these in the courts to demonstrate the feasibility and sustainability thereof.

- It is therefore recommended that the regulating bodies/structures and officers prescribed in the legislation be appointed and financed.

- Steps must be taken to ensure that the required skills be developed, acquired and retained for implementation of the above.

WAIV

Small scale pilot tests have shown that evaporation rates may be increased by as much as 20-30 times compared to natural evaporation from open ponds. Finalisation of the design methodology as recommended above should be one of the final technical hurdles to clear. It is recommended that specific industries/companies with a high potential need for brine disposal be targeted in order to explore potential implementation of the technology on demonstration scale. The objective of this should be to evaluate system performance at a relatively large scale over an extended period of time.

CHAPTER 12

12. REFERENCES

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APPENDIX I: DATABASE OF POTENTIAL BRINE SOURCES

LIST OF RESPONDANTS

Sector	Company	Contact	Site number	Location	Region	Vol (kl/d)	Salinity	Salt load to environment	Present disposal	Existing desal	Desal planned	Total effluent	Total effluent to marine	Total effluent load excl marine	Total salt load	Total salt to marine	Total salt load-excl marine
							mg/l	t/day				kl/day	kl/day	kl/day	t/day	t/day	t/day
Paper & Pulp/Wood	Sappi	Tony Leske	1	Saiccor	Mpumalanga	120000	11024	1322.9	Marine			272001	183000	89001	1323	1360	79.9
	Sappi	Tony Leske	2	Enstra	Johannesburg	28000	1020	28.6	AS/River						29		
	Sappi	Tony Leske	3	Tugela	Mpumalanga	39000		0.0	Marine						0		
	Sappi	Tony Leske	4	Stanger	KZN	24000	1560	37.4	Marine						37		
	Sappi	Tony Leske	5	Ngodwana	Mpumalanga	27000	1015	27.4	Irrigation						27		
	Sappi	Tony Leske	6	Adamas	KZN		1174	0.0	?						0		
	Sappi	Tony Leske	7	Cape Kraft	Cape Town	900	3870	3.5	Sewer						3		
	Sappi	Tony Leske	8	Usutu	Mpumalanga	28800	118	3.4	?						3		
	Mondi	Tony Scheckel	9	Piet Retief	Mpumalanga	2000	4000	8.0	UF/RO/Burner	1					8		
	Kimberley Clarke	Bob Heiman	10	Springs	Johannesburg	2000	2300	4.6	Sewer		1				5		
	Fibre Form	Jabobus Strydom	11	Atlantis	Cape Town	1		0.0	Sewer						0		
	Global Forest Products	Shaun McCartney	12	Sabie	Mpumalanga	300	15000	4.5	Irrigation		1				5		
General Packaging	Consol	David Engel	13	Cape Town	Cape Town	300	3000	0.9	Sewer			1950		1950	1		1.6
	Consol	David Engel	14	Belvillle	Cape Town	150		0.0	Sewer						0		
	Consol	David Engel	15	Johannesburg	Johannesburg	450		0.0	Sewer						0		
	Nampak	Thepiso Dumasi	16	Cape Town	Cape Town	400	300	0.1	Sewer						0		
	Polyoak	Barry Bekker	17	Cape Town	Cape Town	50		0.0	Sewer						0		
	APL	Alwyn van Wyk	18	Worcester	Western Cape	200	1000	0.2	Sewer						0		
	Versapak	Ebbe Domisse	19	Paarl	Western Cape	100		0.0	Sewer						0		
	Xatic	Henk de Klerk	20	Johannesburg	Johannesburg	300	1400	0.4	Sewer						0		
Steel/metals processing	Columbus	Pieter Scurr	21	Witbank	Gauteng	4000	2890	11.6	RO/Evap	1		30500		30500	12		71.6
	Mittal Saldanha	Gideon Visagie	22	Saldanha	Western Cape	2500	3420	8.6	RO/Evap	1					9		
	Mittal Meyerton	Jan Theron	23	Meyerton	Vaal Triangle	300	2410	0.7	Sewer						1		
	Mittal VdBijlpark	Jan Theron	24	VdBijl	Vaal Triangle	4000	1915	7.7	Soft/SF/RO/Evap	1					8		
	Mittal Newcastle	Ronnie de Valence	25	Newcastle	KZN	1680	1880	3.2	Bio/Soft/UF/RO/Evap	1					3		
	DSP	Kobus van Rensburg	26	Saldanha	Western Cape	500	6500	3.3	Precip/Sewer		1				3		
	Cape Gate	Allister Morrison	27	VdBijl	Vaal Triangle	800	3000	2.4	Sewer		1				2		
	Cape Galvanising	Louis Carstens	28	Cape Town	Cape Town	140	340	0.0	Sewer						0		
	Zincor	No Response	29	Springs	Johannesburg	4000	3000	12.0	Evaporation pond		1				12		
	Assmang	Joe Schoeman	30	Machadodorp	Mpumalanga	240	2300	0.6	Evaporation pond		1				1		
	Arwin Meritor	Ted Wells	31	Cape Town	Cape Town	200	1300	0.3	Sewer						0		
	Denel	Hannes Carstens	32	Cape Town	Cape Town	240	1400	0.3	Precip/Sewer						0		
	Impala Platinum	Steven Ralph	33	Springs	Johannesburg	1000	2540	2.5	RO/Evap	1					3		
	Xtrata	Dewald Steyn	34	Steelpoort	Mpumalanga	2000	3200	6.4	Evaporation		1				6		
	Xstrata	Melcom Curror	35	Brits	North West	2000	1300	2.6	Evaporation		1				3		
	Rustenburg Platinum	No Response	36	Rustenburg	North West	1500	980	1.5	Evaporation		1				1		
	Namakwa Sands	Allan Ramsay	37	Saldanha	Western Cape	2000	1230	2.5	Pond						2		
	Samancor	No Response	38	Meyerton	Vaal Triangle	1800	2300	4.1	River		1				4		
	Samancor	No Response	39	Delmas	Gauteng	1000	1050	1.1	Evaporation						1		
	Satchwell	Arno Muller	40	Cape Town	Cape Town	600	750	0.5	Precip/Sewer						0		
Petroleum	Sasol - Secunda	Du Toit Roux	41	Secunda	Mpumalanga	15000	6500	97.5	TRO	1		83900	14800	69100	98	54	300.4
	Sasol - Secunda	Du Toit Roux	42	Secunda	Mpumalanga	6500	300	2.0	SRO	1					2		
	Sasol - Secunda	Du Toit Roux	43	Secunda	Mpumalanga	15000	6500	97.5	TRO	1					98		
	Sasol - Secunda	Du Toit Roux	44	Secunda	Mpumalanga	12000	4500	54.0	EDR	1					54		
	Sasol - Secunda	Du Toit Roux	45	Secunda	Mpumalanga	8000	500	4.0	SRO	1					4		
	Sasol - Sasolburg	Du Toit Roux	46	Sasolburg	Vaal Triangle	10000	4000	40.0	Evaporation pond	1					40		
	Natref	Martin Ginster	47	Sasolburg	Vaal Triangle			0.0	Sasol						0		
	Engen	Mark Allan	48	Durban	KZN	4000	3400	13.6	Marine						14		
	Sapref	No Response	49	Durban	KZN	3800	5300	20.1	Marine						20		
	FFS	Mike Sands	50	Cape Town	Cape Town	800	2100	1.7	Skimming/sewer						2		
	FFS	Mike Sands	51	Durban	KZN	800	2100	1.7	Skimming/sewer						2		
	FFS	Mike Sands	52	Johannesburg	Johannesburg	1000	2100	2.1	Skimming/sewer						2		
	PetroSA	Carl Steyn	53	Mosselbay	Western Cape	2000	2000	4.0	Marine						4		
	Caltex	Deon v Zyl	54	Cape Town	Cape Town	5000	3200	16.0	Marine	1					16		

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Sector	Company	Contact	Site number	Location	Region	Vol (kl/d)	Salinity	Salt load to environment	Present disposal	Existing desal	Desal planned	Total effluent	Total effluent to marine	Total effluent load excl marine	Total salt load	Total salt to marine	Total salt load-excl marine
							mg/l	t/day				kl/day	kl/day	kl/day	t/day	t/day	t/day
Chemical	Omnia - Sasolburg	Tjaart vd Berg	55	Sasolburg	Vaal Triangle	1000	3280	3.3	Pond		1	13070	2000	11070	3	7	44.3
	Omnia - Rustenburg	Tjaart vd Berg	56	Rustenburg	North West	800	3450	2.8	Pond		1				3		
	NCP - Chloorchem	Willie Britz	57	Johannesburg	Johannesburg	1500	4500	6.8	RO/Evap		1				7		
	PPC Cement	Moleleki Dlodlo	58	Malmesbury	Western Cape	0		0.0	Sewer/pond						0		
	PPC Cement	Moleleki Dlodlo	59	Pretoria	Gauteng	0		0.0	Sewer						0		
	Phoskor	Dr Gert vd Linde	60	Palaborwa	North West	4500	6400	28.8	Evaporation pond						29		
	Phoskor	Dr Gert vd Linde	61	Richardsbay	KZN	2000	3400	6.8	Marine						7		
	Kynoch	Ig Ferreira	62	Paarl	Western Cape	200	1200	0.2	Sewer						0		
	Kynoch	Waldo Fortman	63	Potchefstroom	North West	1200	1200	1.4	Sewer/pond		1				1		
	Kynoch	Ig Ferreira	64	Malmesbury	Western Cape	300	800	0.2	Sewer						0		
	Sasol Polymers	Bruce Rackham	65	Sasolburg	Vaal Triangle	800	400	0.3	Sasol						0		
	SANS Fibres	Thys Loubser	66	Cape Town	Cape Town	200	300	0.1	Sewer						0		
	Nitrophoska	Dr Johan Beyers	67	Malmesbury	Western Cape	140	1800	0.3	Sewer						0		
	Plascon	Dr Piet Steyn	68	Johannesburg	Johannesburg	250	300	0.1	Sewer						0		
	Plascon	Dr Piet Steyn	69	Durban	KZN	180	250	0.0	Sewer						0		
Power Generation	Eskom	Dirk Hanekom	70	Duhva	Duhva	10000	1200	12.0	Ashing		1	132000		132000	12		158.4
	Eskom	Dirk Hanekom	71	Tutuka	Tutuka	12000	1200	14.4	Ashing	1					14		
	Eskom	Dirk Hanekom	72	Lethabo	Lethabo	10000	1200	12.0	Ashing	1					12		
	Eskom	Dirk Hanekom	73	Matimba Exist	Matimba Exist	10000	1200	12.0	Ashing						12		
	Eskom	Dirk Hanekom	74	Matimba New	Matimba New	10000	1200	12.0	Ashing						12		
	Eskom	Dirk Hanekom	75	Komati	Komati	10000	1200	12.0	Ashing		1				12		
	Eskom	Dirk Hanekom	76	Arnot	Arnot	10000	1200	12.0	Ashing		1				12		
	Eskom	Dirk Hanekom	77	Hendrina	Hendrina	10000	1200	12.0	Ashing						12		
	Eskom	Dirk Hanekom	78	Kendal	Kendal	10000	1200	12.0	Ashing						12		
	Eskom	Dirk Hanekom	79	Kriel	Kriel	10000	1200	12.0	Ashing		1				12		
	Eskom	Dirk Hanekom	80	Matla	Matla	10000	1200	12.0	Ashing		1				12		
	Eskom	Dirk Hanekom	81	Grootvlei	Grootvlei	10000	1200	12.0	Ashing		1				12		
	Kelvin Power	Jaco vd Merwe	82	Johannesburg	Johannesburg	10000	1200	12.0	Ashing		1				12		
Mining (5yr projected)												145025		145025	350		350
Platinum	Implats - Springs	David Smith	83	Springs		25	2000	0.1			?						
	Implats-Rustenburg		84	Rustenburg		0	2000	0.0			?						
	Anglo Plat		85	Rustenburg		0	2000	0.0			?						
Gold	Freestate Mines		86	Welkom/Virginia		0	2000	0.0			?						
	KOSH		87	Klerksdorp / Orkney		0	2000	0.0			?						
	Carltonville / Westonaria		88	Carltonville / Westonaria		0	2000	0.0			?						
	Harmony		89				2000	0.0			?						
	East Rand Basin	Marius v Biljon	90	Springs		75000	2800	210.0	River		1						
	West Rand Basin	Marius v Biljon	91	JHB		12000	2000	24.0			?						
Coal	Sasol Secunda		92			8000	2000	16.0			?						
	Sigma and Wonderwater		93			0	2000	0.0			?						
	Coalbrook		94			0	2000	0.0			?						
	Grootvlei		95			0	2000	0.0			?						
	Majuba		96			0	2000	0.0			?						
	Ermelo area		97	Includes Usutu/Ermelo		0	2000	0.0			?						
	Natal Mines		98	Total estimate		0	2000	0.0			?						
	Witbank area	Golder	99	Olifants catchment		50000	2000	100.0			?						

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Sector	Company	Contact	Site number	Location	Region	Vol (kl/d)	Salinity	Salt load to environment	Present disposal	Existing desal	Desal planned	Total effluent	Total effluent to marine	Total effluent load excl marine	Total salt load	Total salt to marine	Total salt load-excl marine
							mg/l	t/day				kl/day	kl/day	kl/day	t/day	t/day	t/day
Chemical suppliers	Buckman	Lionel Hughes	100	Hammersdale	KZN	400	300	0.1	Pond/Sewer			528		528	0		0.2
	Protea Chemicals	Timothy Machanon	101	Johannesburg	Johannesburg	24	3000	0.1	Sewer						0		
	Johnson Diversey	Buks Harding	102	Cape Town	Cape Town	24	200	0.0	Sewer						0		
	Johnson Diversey	Buks Harding	103	Johannesburg	Johannesburg	40	200	0.0	Sewer						0		
	Crest Chemicals	Yolanda Anneveld	104	Johannesburg	Johannesburg	30	320	0.0	Sewer						0		
	Rohm&Haas	Peter Cable	105	Durban	KZN	10		0.0	Sewer						0		
Dairy	Clover	No Response	106		No response			0.0	Irrigation			2700		2700	0		4.2
	Parmalat	Ters Conradie	107	Bonnivale	Western Cape	2000	1800	3.6	Pond						4		
	Fairview	Charles Back	108	Paarl	Western Cape	60	1400	0.1	Pond						0		
	Lancewood	Kobus Lessing	109	George	Western Cape	340	840	0.3	Sewer						0		
	Butlers	Mike Williams	110	George	Western Cape	300	840	0.3	Sewer						0		
Sugar	Illovo	Gavin Dalgleish	111	Merebank	KZN	2400	1800	4.3	Marine		1	8100	4200	3900	4	8	1.7
	Illovo	Gavin Dalgleish	112	Sezela	KZN	1800	2140	3.9	Marine						4		
	Transvaal Sugar	Nico Stolz	113	Nkomati	Mpumalanga	800	400	0.3	Irrigation		1				0		
	Transvaal Sugar	Nico Stolz	114	Malelane	Mpumalanga	1000	400	0.4	Irrigation						0		
	African Producs	Lorenzo Naidoo	115	Belvillle	Western Cape	500	450	0.2	Sewer						0		
	African Producs	Derek Botha	116	Germiston	Gauteng	600	430	0.3	Sewer						0		
	African Producs	Derek Botha	117	Meyerton	Vaal Triangle	1000	500	0.5	Sewer						1		
Canning	Ashton Canning	Pieter Durand	118	Ashton	Western Cape	800	350	0.3	Pond			2200		2200	0		1.0
	Delmonte	Boetie Beets	119	Tulbach	Western Cape	1400	540	0.8	Pond/Irrigate						1		
General food	Anchor Yeast	Gert Steenkamp	120	Johannesburg	Johannesburg	1800	1200	2.2	Sewer		1	13970	3000	10970	2	6	4.8
	Anchor Yeast	Gert Steenkamp	121	Cape Town	Cape Town	600	500	0.3	Sewer						0		
	British America Tobacco	Henk Paxton	122	Paarl	Western Cape	0		0.0	Sewer						0		
	British America Tobacco	Henk Paxton	123	Heilderberg	Johannesburg	200	300	0.1	Sewer						0		
	National Brands	Tawanda Mushuko	124	Johannesburg	Johannesburg	800	315	0.3	DAF/Sewer						0		
	Dynamic Commodities	No Response	125	Port Elizabeth	Eastern Cape			0.0	Sewer						0		
	Oceana	Robin Albrich	126	Lambertsbay	Western Cape	3000	2000	6.0	Marine						6		
	Ovipro	Charl vd Walt	127	Bronhorstspruit	Gauteng	300	340	0.1	Sewer		1				0		
	Rooibos Bpk	Martin Berg	128	Clanwilliam	Western Cape	250	200	0.1	Sewer						0		
	Pioneer	Jan Schoeman	129	Worcester	Western Cape	300	450	0.1	Sewer						0		
	Pioneer	Jan Schoeman	130	Upington	Northen Cape	240	500	0.1	Pond						0		
	Pioneer	Jan Schoeman	131	Wellington	Western Cape	180	400	0.1	Sewer						0		
	McCains	Johan v Tonder	132	George	Western Cape	1000	230	0.2	Sewer						0		
	McCains	Johan v Tonder	133	Delmas	Gauteng	3500	230	0.8	Skimming/sewer						1		
	Simba Chips	Ansutte McCartney	134	Johannesburg	Johannesburg	1000	300	0.3	Skimming/sewer						0		
	Simba Chips	Ansutte McCartney	135	Cape Town	Cape Town	800	300	0.2	Skimming/sewer						0		
Pharmaceutical & personal care	Tiger Brands	Johan vd Merwe	136	Johannesburg	Johannesburg	400	340	0.1	Sewer			1430		1430	0		1.3
	Adcock Ingram	Johan vd Merwe	137	Johannesburg	Johannesburg	300	340	0.1	Sewer	1					0		
	Johnson & Johnson	No Response	138	Cape Town	Cape Town	240	150	0.0	Sewer	1					0		
	Fine Chemicals	No Response	139	Cape Town	Cape Town	240	150	0.0	Sewer	1					0		
	Seravac	Jacobus Strydom	140	Cape Town	Cape Town	250	4000	1.0	Pond						1		
Animal Nutrition	Meadow Feeds	No Response	141	Worcester	Johannesburg	450	445	0.2	Sewer			1205		1205	0		0.6
	Meadow Feeds	No Response	142	Paarl	Western Cape	330	320	0.1	Sewer						0		
	Epol	No Response	143	Worcester	Western Cape	425	660	0.3	Sewer						0		
Poultry & Meat	Rainbow Chickens	Johan Roussouw	144	Worcester	Western Cape	2400	1000	2.4	DAF/Sewer			12100		12100	2		8.5
	Rainbow Chickens	Johan Roussouw	145	Hammersdale	KZN	4800	800	3.8	DAF/Sewer	1					4		
	County Fair	Oswald Midgely	146	Cape Town	Cape Town	600	1200	0.7	Irrigate						1		
	Manjoh Ranch	Tony da Costa	147	Nigel	Gauteng	1100	400	0.4	Aeration/irrigate						0		
	Karan Beef	Johan v Niekerk	148	Delmas	Gauteng	3200	340	1.1	Aeration/irrigate						1		

LIST OF RESPONDANTS

Sector	Company	Contact	Site number	Location	Region	Vol (kl/d)	Salinity	Salt load to environment	Present disposal	Existing desal	Desal planned	Total effluent	Total effluent to marine	Total effluent load excl marine	Total salt load	Total salt to marine	Total salt load-excl marine
							mg/l	t/day				kl/day	kl/day	kl/day	t/day	t/day	t/day
Beverage	Ceres Fruit Juices	Jurgens Benz	149	Ceres	Western Cape	1200	540	0.6	UASB			14670		14670	1		10.6
	Pacmar	Kabous Mulder	150	Wellington	Western Cape	120	330	0.0	Sewer	1					0		
	SAB	Josiah Mpho	151	Cape Town	Cape Town	2800	300	0.8	UASB/Sewer	1					1		
	SAB	Elspeth Grahn	152	Port Elizabeth	Eastern Cape	1500	400	0.6	UASB/Sewer	1					1		
	SAB	Lionel Hughes	153	Alberton	Johannesburg	800	400	0.3	Precip/Clar/UF	1					0		
	SAB	Deon Maritz	154	Pretoria	Gauteng	2400	450	1.1	UASB/Sewer	1					1		
	ABI	No Response	155	Midrand	Gauteng			0.0	Sewer	1					0		
	Peninsula Beverages	No Response	156	Cape Town	Cape Town	800	150	0.1	Sewer		1				0		
	Cape Good Hope Beverages	Hennie Wagener	157	Cape Town	Cape Town	230	243	0.1	Sewer						0		
	Distell	Brink Lienbenberg	158	Worcester	Western Cape	340	1200	0.4	Pond		1				0		
	Distell	Brink Lienbenberg	159	Wellington	Western Cape	1300	750	1.0	UASB						1		
	Distell	Brink Lienbenberg	160	Robertson	Western Cape	320	650	0.2	Irrigate						0		
	Distell	Brink Lienbenberg	161	Stellenbosch	Western Cape	400	660	0.3	Sewer		1				0		
	Roodezandt	Allewyn Jordaan	162	Robertson	Western Cape	250	350	0.1	Pond						0		
	Simonsvlei	Francois v Zyl	163	Paarl	Western Cape	180	400	0.1	Aeration/river						0		
	Robertson Winery	Allewyn Jordaan	164	Robertson	Western Cape	180	430	0.1	Pond						0		
	Fairview	Charles Back	165	Paarl	Western Cape	200	300	0.1	Aeration/irrigate						0		
	Landskroon	Paul de Villiers	166	Paarl	Western Cape	150	340	0.1	Aeration/irrigate						0		
	KWV	Ernst Oliver	167	Worcester	Western Cape	400	4000	1.6	Pond		1				2		
	KWV	Ernst Oliver	168	Robertson	Western Cape	300	2300	0.7	Irrigate						1		
	KWV	Ernst Oliver	169	Upington	Northern Cape	230	3200	0.7	Pond						1		
	KWV	Ernst Oliver	170	Vredendal	Western Cape	120	2310	0.3	Pond						0		
	Brenn-O-Kem	Wyndand du Toit	171	Worcester	Western Cape	300	4500	1.4	Pond						1		
	Brenn-O-Kem	Wyndand du Toit	172	Wolseley	Western Cape	150	300	0.0	Pond						0		
Textile	Da Gama	Ralph Jones	173	King Williams Town	Eastern Cape	2500	3000	7.5	Bio/UF/RO	1		6000		6000	8		12.8
	Wellington Industries	Charles Kritzinger	174	Wellington	Western Cape	1000	280	0.3	Sewer						0		
	Hammersdale	Lionel Huges	175	Hammersdal	KZN	2500	2000	5.0	Sewer		1				5		
Waste management	Enviroserve	Esme Gaumbault	176	Vissershok	Western Cape	70	30000	2.1	Irrigation		1	190		190	2		5.5
	Durban Metro	Lyndsy Strachan	177	Durban	KZN	120	28000	3.4	Irrigation						3		
	Enviroserve	Esme Gaumbault	178	Holfontein	Gauteng			0.0	Evaporation						0		
Fish Processing	Oceana	Robin Albrich	179	Saldanha	Western Cape	5000	36000	180.0	Marine			220700	220500	200	180	7920	0.8
	Oceana	Robin Albrich	180	Hout Bay	Western Cape	3000	30000	90.0	Marine						90		
	Oranjevis	Jaco Strydom	181	St Helena	Western Cape	2500	36000	90.0	Marine						90		
	Abagold	Pierre Hugo	182	Hermanus	Western Cape	200000	36000	7200.0	Marine						7200		
	I&J	No Response	183	Saldanha	Western Cape	4000	36000	144.0	Marine						144		
	Southern Seas Fishing	Gilbert Ruiters	184	Saldanha	Western Cape	6000	36000	216.0	Marine						216		
	Three Streams Smokehouse	Gregory Stubbs	185	Franschoek	Western Cape	200	4000	0.8	Irrigation						1		