

Development of a small-scale electro-chlorination system for rural water supplies

Report to the
Water Research Commission

by

David L Key, Julian DV Key, Gautier Okolongo & Maxhobandile Siguba

University of the Western Cape
Chemistry Department

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EXECUTIVE SUMMARY

1. BACKGROUND OF THE STUDY AND PROBLEM STATEMENT

There are probably close to five million people in South Africa's rural areas that rely on untreated drinking water from small informal water sources (DEAT, 2008). These water sources are numerous and spread far and wide throughout the country. They include small dams, springs, wells and boreholes, and are often used by small communities of less than 100 people. Because of their small size and remote distribution, such communities are the least likely to receive pipelines from water treatment plants, and thus face the highest risk of waterborne disease. Therefore, in lieu of pipelines, it is necessary to consider smaller-scale water treatment options that can be self-managed by these communities.

Amidst an array of existing disinfection technologies, hypochlorite generators are amongst the most suitable for rural areas. This is because the dosing of hypochlorite provides a chlorine residual in the water, and the generators can be run at low cost requiring just common salt and solar panels. The running costs of hypochlorite generators are lower than buying commercial produced hypochlorite. However, if they are to run in an automated manner (i.e. using electrical pumps for brine supply and hypochlorite dosing) their capital costs can be inhibitive for small communities. Consequently, such automation is governed by an economy of scale that generally excludes its use at small-scale water sources. Therefore, the development of an alternative, lower cost, automated system would be of considerable benefit to small communities.

The aim of this study was to further develop and implement a small-scale membrane-based hypochlorite generator, or "membrane electrolyser", previously developed in WRC project 964/1/02 (Linkov, 2002). The membrane electrolyser bears similarities to hypochlorite generators, MOGGOD, and MIOX® systems, but has the defining feature of producing chlorine as hypochlorous acid during electrolysis (rather than hypochlorite: as in standard hypochlorite generators). Owing to this feature, the membrane electrolyser is considerably more efficient than standard hypochlorite generators at producing chlorine. However, owing to its design it is limited to a small size and operates on a disinfection scale of 2.5-20 kL of water per day, i.e. appropriate for communities of less than 200 people. Therefore, the key research questions addressed in this project were:

- Can the membrane electrolyser produce a consistent concentration of disinfectant for accurate dosing on a sustainable basis?
- Can a system be developed to control the electrolyser and dosing that is affordable, low maintenance and reliable?
- Can such a system be maintained and managed by a small rural community?
- What kinds of water sources are most appropriate for its implementation?

2. OBJECTIVES OF THE PROJECT

The project had two main objectives: (1) to develop a water disinfection system in which the electrolyser can operate automatically, and (2) to establish and test the disinfection system at a typical water source used by a rural community and determine its viability.

The specific aims of the project were as follows:

- (i) To establish the most suitable electrolyser design, construction materials and operational parameters to provide a device that is reliable, affordable, energy efficient and durable.
- (ii) To develop a disinfection system that incorporates the electrolyser, and accurately doses water in a manner that is automatic, low maintenance, solar powered, low cost and sustainable.
- (iii) To establish and operate the disinfection system at a rural water site following the necessary laboratory testing, authorization from the relevant water authority, and the rural community's consent.
- (iv) To determine the viability of the system and its acceptance among the rural community with regard to its operational performance and intended maintenance by the community.
- (v) To hand over, on the successful outcome of the above, the technology to the community along with training regarding running instructions and maintenance.

3. RESEARCH APPROACH

The research approach adopted was to first determine the optimal running conditions and anodic materials for the membrane electrolyser. The characteristics of the electrolyser were obtained by establishing the figures of merit of the electrochemical system. These characteristics formed a basis for determining the scale of the disinfection system and the size of the community it could serve.

A disinfection system was designed to operate on a low pressure, gravity-flow model because water pressure above 1 bar (i.e. ~10 m surface head) might be unavailable at small rural sites, e.g. water storage tanks of ~2-5 m high elevation are commonly used. In order to minimise costs of electrical equipment and power consumption, gravitational energy was targeted to control both the supply of brine to the electrolyser and dosing of chlorine to water. Construction materials, where possible, were limited to adapting common plumbing and hardware store components. The disinfection system was developed and tested in the laboratory and an appropriate design was eventually selected. A suitable rural site was found for the pilot plant and the necessary permissions obtained. The system was installed and its technical viability tested by a remote monitoring system. The social acceptability of the system was attempted by means of a social survey.

4. SUMMARY OF MAJOR RESULTS AND CONCLUSIONS

Electrolyser design and capacity – Three types of metal oxide anode coatings were prepared on coiled titanium metal wire and investigated for their dimensional stability (corrosion resistance) and figures of merit (chlorine production efficiency). The anodes were: DMTA (dioxide of manganese / titanium anode); COTA (cobalt oxide / titanium anode) and ROTA (Ruthenium oxide / titanium anode). The COTA anode with a platinum sub-layer to prevent oxidation of the titanium surface was eventually selected. The membrane electrolyser comprised two concentric tubes: the outer containing water and a steel wire cathode wound around the inner tube – a zirconium-alumina based membrane which contained brine and the anode. Testing and optimisation of the membrane electrolyser in the laboratory revealed the following:

Capacity and optimal running conditions:

- Chlorine production: ~15 g/day (24 h)
- Salt consumption: ~70 g/day
- Energy consumption per day: ~50 W.h
- Brine feed concentration: 25 g/L (table salt in water)
- Operating power: ~2 W (using 4 V DC)
- Water chlorination capacity: 1.5-15 kL /day (chlorine dose range of 1-10 mg/L)

Batch supply system – Continuous operation of the electrolyser required a constant supply of brine and water to its anolyte and catholyte chambers respectively. The study found that a supply system comprising batches of brine and water (equalling the volume of the chambers) supplied at eight minute intervals to the electrolyser resulted in ~2× faster chlorine production and energy efficiency at ~7% less salt efficiency (chlorine yield from salt) than a slow continuous drip feed method. Overall the batch supply method was found to be more efficient and reliable than a slow continuous feed.

An undivided electrolyser comparison and option – An “undivided” electrolyser was constructed without a membrane to evaluate the function of the membrane. This electrolyser retained the same anode and brine volume as the membrane electrolyser but had a stainless steel pipe cathode which also functioned as its casing. Under the above operating conditions, the membrane electrolyser produced 2.2× more chlorine than the undivided cell, consumed 1.7× less energy and was 2.2× more salt efficient. These results demonstrate the advantages of the membrane in chlorine production, at least under the running conditions used in the study. The undivided electrolyser provides an alternative to the membrane electrolyser for use at locations that have hard water where lime-scale blockage of the membrane could occur.

Disinfection system design and capacity – The disinfection system was constructed from three plastic tanks through which a 30 L batch of water is disinfected at a rate equivalent to that of chlorine production. Two versions of the system were made, one incorporating two small electrically controlled solenoid valves and the other controlled purely by the mechanical movement

of water. The former system ultimately proved the most reliable and simplest to operate. Both systems successfully controlled adjustable brine supply to the electrolyser and chlorine dosing without the need for electrical pumps. The solenoid-controlled version was chosen for field testing, given that sufficient solar power was installed at the site (see below: “Performance of the disinfection system at the pilot plant”) to allow remote monitoring of the system. The capacity and characteristics of the disinfection system’s operation at the site were as follows:

Capacity and characteristics:

- Water disinfection: 5.4 kL/day or 225 L/h
- Batch disinfection rate: 30 L of water per 8 min cycle
- Chlorine dose range: ~1-7 mg/L
- Maintenance: < 30 min /week (brine replenishment, preparation and system check)
- Population served: 100-200 people (no less than 25 L/person/day)

Location and characteristics of the pilot plant – The disinfection system was installed and run at a farm near Worcester in the Western Cape. The site was sourced through the help of the Worcester East Water Users Association (WEWUSA). The local water supply came from an irrigation pipeline that received rapid high pressure sand filtration and supplied the farm worker community of over 100 people. Once established and operational, chlorinated water from the system was tested for chlorine residual, and supplied as an optional drinking water source at two standpipes taps.

Performance of the disinfection system at the pilot plant – Operation over a period of one year was achieved and closely monitored onsite and remotely, but was not without its problems. These arose from unexpected and erratic increases in turbidity of the source water, which in late summer rose to over 120 FNU and made chlorination unreliable due to: (i) the possible masking effect on disinfection, and (ii) the increased risk of toxic trihalomethane formation from the organic content of the turbidity. However, during an uninterrupted two-month winter period of low turbidity (below 5 FNU), the system gave a reliable chlorine output of ~4 mg/L. The results were promising and demonstrated successful operation could be achieved at the maximum recommended turbidity for chlorination (i.e. 5 FNU).

Effect of Turbidity on the brine electrolyser’s membrane – High turbidity (~120 FNU) caused a current drop of < 0.1 A, most likely due to sediment blockage of the membrane. However, below the maximum recommended turbidity level for chlorination (i.e. 5 FNU), current levels remained unaffected throughout the duration of use, wherein the same membrane was used throughout the year of testing.

Maintenance and the community – Various community members helped in the construction and maintenance of the system. Preparation and maintenance of the brine supply to the disinfection system was maintained successfully by two community operators. Regular cell phone

communication with one of the operators was used for arranging site visits and reporting checkups and alerts.

Emergency response to system failure and alerts – The remote monitoring system detected the effects of turbidity on the system, which at 120 FNU manifested as a current drop across the electrolyser. The project team managed to contact the community operator (within an hour of the alert) to shut the system down (i.e. to close the outlet valve from the system and remove the tap head from the stand pipe tap).

Involvement of local authorities and technicians – The WEWUSA office is situated less than 20 km from the site and its members helped in the construction of the pilot plant. It has regular meetings with the farming community, where water issues are discussed, and the project team presented a talk on the pilot plant at one of these meetings. Cooperation was also established with the local health inspector who regularly visits the surrounding farm community and collects water samples for broad analyses. The well established communication between these bodies affords a stable system for the plant's future operation and the community's safety.

Social survey and acceptability – Owing to the fluctuating levels of turbidity of the rural water and consequent frequent downtime of the system, the results of the intended social acceptability study were inconclusive. During the two-month uninterrupted period of operation less than 200 L of water were used from the system. Results of the social survey suggest that the low level of use was due to both the clean appearance of the un-chlorinated water in their existing water supply during winter. However, disappointment was expressed at the system's operational down time during the autumn harvest. During this period, the community boils its drinking water in response to the water's high turbidity, and therefore less drinking water is available at the hottest time of the year in the middle of the fruit harvest.

Conclusions from rural site operation:

- Despite the difficulties experienced with turbidity, the system reliably generated and dosed a reproducible quantity of chlorine in water during periods of acceptable turbidity of < 10 FNU.
- Community involvement in the project shows promise for establishing micromanagement of small-scale water treatment.
- The combination of remote monitoring equipment and water analysis kits (chlorine and turbidity) proved a reliable research method.

Capital and running costs – The estimated costs cited below are those applicable only to the prototype disinfection system and do not include the remote monitoring system (required for project use only) or the various additional components required at different types of site, e.g. housing, storage tanks, pipeline supply, pre-treatment equipment, etc.

Estimated costs of disinfection system:

Capital costs:

- Electrolyser: ~R2 000
- 10 W Solar power system: ~R4 000
- Dosing control: ~R3 000

Total: ~R 9 000

Running costs:

- Salt (< 2 kg/month): ~R15/month
- Operator (2 h/month): ~R100/month*

Total: ~R15-115/month

*Alternatively, maintenance could be managed for free within the community.

Overall project conclusions and recommendations – The initial pilot-scale testing of the brine electrolyser and disinfection system developed in this study indicated that the overall system is both cost effective and reliable. However, in view of the problems encountered from turbidity, the recommended future installation sites for the system are presented below:

Recommended future installation sites:

- Groundwater sources (boreholes and protected well points)
- Clarified surface waters (recommended research partnership)
- Treated water requiring chlorine residual boosting.

Future of the pilot plant in Worcester – The project is indebted to the farm community for providing a venue for the pilot plant and giving their time and support. While the project was run under the clear auspices of a research programme, the pilot plant remains a functional entity that has shown all promise to be a reliable chlorination system of potential value to the community. However, since the existing system's function will be limited to winter periods of low turbidity, it will not address the community's most urgent need for clean water in summer. Therefore, the need for water clarification provides an excellent opportunity for projects in this field, and it is recommended (pending the community's consent) that the pilot plant remains as a venue for continued studies on small-scale micro-manageable water treatment.

Commercialisation – The results from the pilot plant suggest that both the electrolyser design and dosing system are suitable candidates for commercialisation either separately or in a combined package. However, in view of the factors that limited the test period in this report, it is recommended that an uninterrupted running time of at least six months is needed to fully confirm the consistency of the system and allow the identification of potential any future running problems (see below: Recommendations for Future Research)

5. RECOMMENDATIONS FOR FUTURE RESEARCH

- The disinfection system should receive six months further testing prior to commercialisation, either at the existing pilot plant (if clarification measures are installed) or at any of the above-mentioned recommended installation sites.
- Collaborative research with an equivalent low cost, low tech, rural water clarification project would form an ideal partnership, which would address the larger problem of small-scale surface water treatment. The clarification project could be installed with immediate effect at the existing pilot plant, which would also benefit the community.
- Continued running of the project at the existing site will allow further experience to be gained in micromanagement issues, such as the drafting of running instructions, routines, maintenance and emergency procedures.

6. RESEARCH OUTPUTS

In addition to this report the research outputs consist of a prototype brine electrolyser and associated disinfection system.

CONTRIBUTORS

In addition to the authors of this report, important contributions were also made by the following:

Professor VM Linkov (Director SAIAMC, UWC) – Electrochemical testing of electrode materials

Dr RD Chebotareva and co-workers – Dumanski Institute, Ukraine

Dr R Hasler (Environmental Unit, UCT) – Social assessment advice

Mr I Sprinceana (SAIAMC, UWC) – Monitoring and solar panel system advice

Students and assistants in Professor DL Key's research group – UWC

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Dr G Offringa (Chairperson) – Water Research Commission

Dr J Burgess (Co-chairperson) – Water Research Commission

Dr I Pearson (Steering committee member) – Private consultant in water and sanitation

Professor VN Belyakov (Director INMA, Kiev, Ukraine) – Supply of anode materials

Mr Frikkie Joubert (Worcester East Water Users Association) – Selection of research site

Mr Willie Naude (Oude Wagon Drift Farm, Over Hex Crossing, Worcester) – Use of research pilot site

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Mr Peter Boon (UWC electrical workshop) – Construction of electrical components and advice.

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LIST OF ABBREVIATIONS

CCT	Chlorine contact time
COTA	Cobalt oxide/titanium anodes
DEAT	Department of Environment and Tourism
DMTA	Dioxide of manganese/ titanium anodes
DSA	Dimensionally stable anode
DWAF	Department of Water Affairs and Forestry
FAC	Free available chlorine
FNU	Formazin nephelometric unit
MIOX®	Mixed oxidants generating system
MOGGOD	Mixed oxidant gas generated onsite for disinfection
NTU	Nephelometric turbidity unit
OSEC	Onsite electrochlorination
POE	Point of entry
POU	Point of use
ROTA	Ruthenium oxide/titanium anodes
SAIAMC	South African Institute for Advanced Material Chemistry
SWTPs	Small water treatment plants
THM	Trihalomethane
UWC	University of the Western Cape
WEWUSA	Worcester East Water Users Association

CHAPTER I GENERAL INTRODUCTION

The concept that small rural communities can self-manage the treatment of their local water sources to obtain safe potable water has many potential benefits. When successful, such schemes not only provide the sustainable benefit of using local water, but also relieve the burden of expense on municipalities to supply potable water over great distances. In South Africa, this is particularly relevant where small rural communities of often less than 100 people are common and widely distributed. Many such communities rely on untreated water from boreholes, small dams, streams and springs, using less than 2.5 kL of water per day. They are also at high risk from waterborne disease (Mail & Guardian, 2007-2009), particularly with the worsening condition of water quality in many rural watersheds. Therefore, where the delivery of pipelines to such communities is delayed, or cannot be accomplished, self-management options for water treatment have to be considered.

Water disinfection using hypochlorite can be easily adapted to small-scale applications and has the added benefit of providing a chlorine residual in the water (DWAF *et al.*, 2002; Freese and Nozaic, 2004). However, hypochlorite either as liquid sodium hypochlorite (bleach) or solid calcium hypochlorite (e.g. HTH) is both costly to buy and not always available in rural areas. Therefore, an alternative option is to produce sodium hypochlorite onsite using a hypochlorite generator. This requires the inputs of electricity and common salt and when using solar panels becomes highly sustainable and cost effective. The process is known as OSEC (onsite electrochlorination).

The aim of this study was to further develop and implement a small-scale membrane-based hypochlorite generator, or “membrane electrolyser”, that was previously developed in WRC project 964/1/02 (Linkov, 2002). The membrane electrolyser bears similarities to hypochlorite generators, MOGGOD, and MIOX® systems, but has the defining feature of producing chlorine as hypochlorous acid during electrolysis (rather than hypochlorite: as in standard hypochlorite generators). Owing to this feature, the membrane electrolyser is considerably more efficient than standard hypochlorite generators at producing chlorine. However, owing to its design it is limited to a small size and operates on a disinfection scale of 2.5-20 kL of water per day, i.e. appropriate for communities of less than 200 people. Therefore, the key research questions addressed in this project were:

- Can the membrane electrolyser produce a consistent concentration of disinfectant for accurate dosing on a sustainable basis?
- Can a system be developed to control the electrolyser and dosing that is affordable, low maintenance and reliable?
- Can such a system be maintained and managed by a small rural community?
- What kinds of water sources are most appropriate for its implementation?

1.1 OBJECTIVES OF THE PROJECT

The project had two main objectives: (1) to develop a water disinfection system in which the electrolyser can operate automatically, and (2) to establish and test the disinfection system at a typical water source used by a rural community and determine its viability.

The specific aims of the project were as follows:

- (i) To establish the most suitable electrolyser design, construction materials and operational parameters to provide a device that is reliable, affordable, energy efficient and durable.
- (ii) To develop a disinfection system that incorporates the electrolyser, and accurately doses water in a manner that is automatic, low maintenance, solar powered, low cost and sustainable.
- (iii) To establish and operate the disinfection system at a rural water site following the necessary laboratory testing, authorization from the relevant water authority, and the rural community's consent.
- (iv) To determine the viability of the system and its acceptance among the rural community with regard to its operational performance and intended maintenance by the community.
- (v) To hand over, on the successful outcome of the above, the technology to the community along with training regarding running instructions and maintenance.

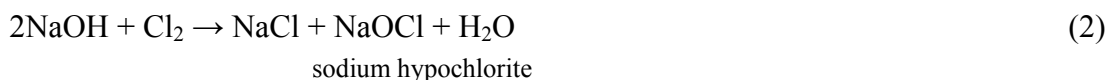
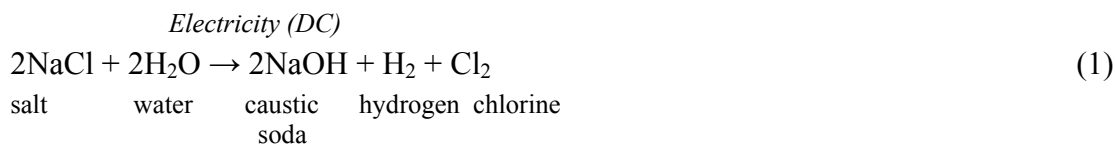
CHAPTER II

LITERATURE REVIEW

This chapter reviews existing technologies for onsite hypochlorite production and water chlorination and examines the characteristics of the membrane electrolyser. Discussion and comparison of other water disinfection methods such as UV-radiation and ozonation is not made because chlorination exists in a category of its own, being one of the few methods that provide a residual disinfection property in the water. The chapter includes an overview of onsite hypochlorite production (section 2.1) followed by a mini review on the basic types of available hypochlorite generators (section 2.2) and their feasibility in rural areas (section 2.3). This is followed by an introduction to the membrane electrolyser (section 2.4) and considerations to its potential use in water chlorination for small rural water sources (section 2.5-2.6).

2.1 ONSITE ELECTROCHLORINATION

Onsite electrochlorination (OSEC) is a term used for the production of chlorine onsite using brine electrolysis. Brine electrolysis requires two inputs: brine (NaCl + water) and electricity. The process is carried out in an electrolytic cell (or electrolyser) in which DC-powered electrodes drive the conversion of brine to chlorine (see below).



Depending on the design, the cells usually produce chlorine either as a gas, or in the hydrolyzed form of hypochlorite (OCl^-): forming sodium hypochlorite (NaOCl) otherwise known as bleach. Cell designs that produce chlorine gas, owing to the dangers, are mostly restricted to large centralized operations (e.g. chlor-alkali plants). On the other hand, cells that produce hypochlorite can be much smaller and safer, requiring minimal expertise and basic safety precautions (White, 1999), and are therefore also suited to much smaller on-site operations see below.

2.1.1 Hypochlorite generators

Hypochlorite generators are electrolytic cells that produce sodium hypochlorite. In these cells, hypochlorite is produced rather than chlorine gas, because the products of electrolysis formed at the anode and cathode (i.e. molecular chlorine and the hydroxide ion (OH^-) respectively) are free to mix and form hypochlorite (OCl^-) (reaction 2). The hypochlorite concentration obtained from the process can be measured in terms of its chlorine content, i.e. the Cl component of OCl^- (Appendix 5). However, inherent limitations in the process (section 2.4) limit chlorine concentrations to no higher than ~10 g/L or ~1% chlorine (White, 1999; Wallace & Tiernan OSEC® 2002). This is in contrast to the higher concentrations of chlorine found in household and industrial-strength bleach

(e.g. ~30 and 150 g/L respectively) that are produced by mixing chlorine gas and caustic soda (NaOH) that are formed separately in chlor-alkali cells.

2.1.2 On-site hypochlorite production and water chlorination

The ~1% chlorine concentration of sodium hypochlorite produced by hypochlorite generators is ideal for water chlorination. Higher concentrations of hypochlorite in commercial bleach decompose to chlorate, a toxic by-product (Gordon *et al.*, 1997). However, even at ~1% chlorine, sodium hypochlorite solutions should be adjusted to pH 11-13 with NaOH, and not stored longer than a month. Therefore, water chlorination sites that use sodium hypochlorite have the following options:

- (i) To regularly buy high-strength sodium hypochlorite and use it immediately
- (ii) To periodically buy high-strength sodium hypochlorite and dilute it for on-site storage
- (iii) To buy low-strength sodium hypochlorite, or...
- (iv) To produce low-strength sodium hypochlorite onsite using a hypochlorite generator.

The most suitable option for a given site is a question of cost and availability. The choice of onsite hypochlorite generation is suited to the following conditions:

- Where sodium hypochlorite is expensive to buy or obtain.
- Where sodium hypochlorite cannot be obtained regularly or easily.
- Where dilute sodium hypochlorite cannot be suitably stored (e.g. limited storage space, unsuitable storage conditions, and safety reasons).
- Where electricity is inexpensive (e.g. existing solar powered installations).
- Where a regular and dedicated operator is available.

2.1.3 Onsite electrochlorination running costs vs. purchased hypochlorite in water chlorination

The running costs of hypochlorite generation are considerably cheaper than buying commercially produced bleach (see below). However, these must be weighed against capital cost of equipment (section 2.2) and maintenance of the technology (sections 2.3 and 2.6).

Hypochlorite dosing

Cost of sodium hypochlorite (~100 g/L chlorine): R4.68/L*:	R46.80 /kg Cl ₂
Cost of calcium hypochlorite (68% Cl ₂): R16.00/kg*:	R23.53 /kg Cl ₂

* As delivered inc. VAT, (sourced from Momba *et al.*, 2008)

Hypochlorite production

Cost of coarse salt: R2.00 /kg*: 4 kg (NaCl) / kg Cl ₂ :	R8.00 /kg Cl ₂
Electricity: ~4 kW.h/kg Cl ₂ : Mains: ~30 c / kW.h*:	R1.20 /kg Cl ₂
Total:	<u>R9.20 /kg Cl₂</u>

* Cost of salt R/kg variable according to bulk (coarse salt cheapest, but must be minimum 95% NaCl)

* ESKOM. Tariff restructuring plan 2008/9 (<http://www.eskom.co.za/tariffs>.)

2.2 REVIEW OF HYPOCHLORITE GENERATORS

Hypochlorite generators come in many designs and sizes, ranging from small handheld portable units for hikers to disinfect water (e.g. the MSR MIOX® Purifier Pen) to large fully automated systems used at water treatment plants (e.g. Wallace & Tiernan OSEC® systems). The cost of hypochlorite generators is determined by their level of electrical automation and by their size and type of anode material used. Often patented or proprietary, dimensionally stable anodes (DSAs) are made of titanium metal with expensive platinum and catalytic oxide coatings that aid chlorine production and prevent anode corrosion (Pletcher, 1982; White, 1999).

2.2.1 Manual operation of “dip-type” hypochlorite generators

Manually operated hypochlorite generators are the simplest and least expensive. The process requires a container with a fixed volume of brine of known concentration (usually ~30 g/L of NaCl) into which the electrodes of the generator are immersed and left for electrolysis to run over a fixed time and voltage (usually ~4 V DC). The resultant hypochlorite (usually ~8 g/L Cl_2) can then be safely stored in containers and later used for dosing water.

The power source, if using mains electricity, requires a rectifier for DC output. When using solar panels, a 12 V battery and regulator unit are sufficient, and the Wattage of the panels must match the load size of the hypochlorite generator. The main equipment costs of manual systems are therefore determined by the size of the hypochlorite generator, rectifier, or, solar power equipment.

In South Africa, a locally manufactured model, the ***Envir-O-Cell 2.75®**, includes a timer, display panel and a rectifier, distributed by GR Solutions (Fig. 2.1). The stated hypochlorite output of the system is 2.75 kg Cl_2 /day (enough to chlorinate 2.75 ML of water/day at 1 mg/L Cl_2) and the input 15 kW.h/day and ~15 kg of salt. The cost of the Envir-O-Cell 2.75® unit is approximately ~R50 000 (personal communication with GR solutions, 2009).

*Envir-O-Cell 2.75® (http://www.grsolutions.co.za/sodium_hypochlorite_generator.htm).

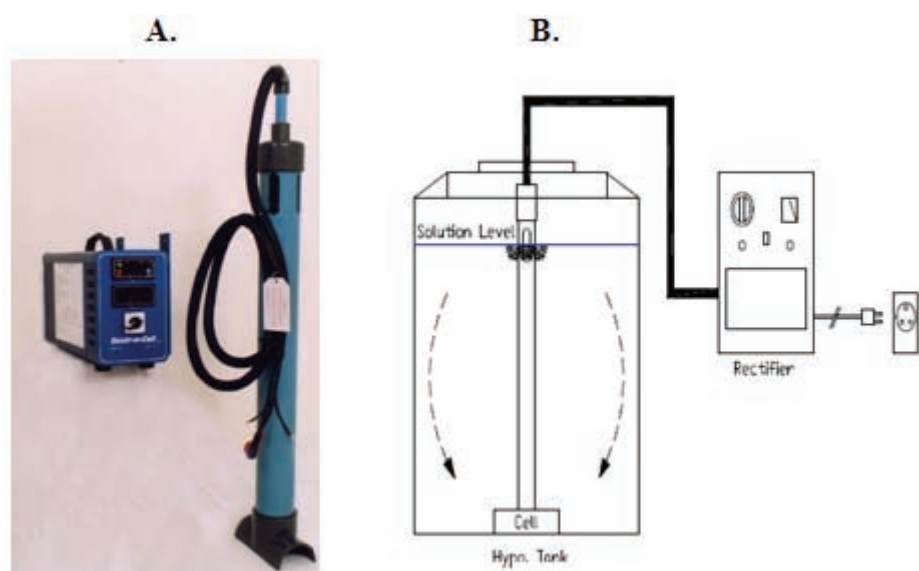


Fig. 2.1 Envir-O-Cell 2.75®. Timer controlled hypochlorite generator manufactured in South Africa: A. The hypochlorite generator and rectifier, B. Schematic. Images reproduced with permission from GR solutions® (<http://www.grsolutions.co.za>)

Smaller manual models are available internationally for producing less than 50 g of Cl_2 /day (for water volumes under 50 kL) from companies such as ***Aquachlor®** and ***WatAyls®**. The operating principle is essentially the same for these cells as the Envir-O-Cell 2.75®, and owing to their smaller size they are often marketed as a package including small solar panels, ideal for emergency water treatment in poverty stricken rural areas (also see: CDC (2008)).

*Aquachlor® : (<http://www.equipmentandsystems.com/>), WatAyls® : (www.bulane.com)

- The advantages of manual systems are: (i) they are relatively cheap and (ii) require electricity only for brine electrolysis (not electrical pumps and controls).
- The disadvantages of manual systems are: (i) they are fairly labor intensive (compared to automated systems) and (ii) require a regular and dedicated operator.

2.2.2 Saturated salt hypochlorite generators

A South African company, **Biochlor®**, manufacture hypochlorite generators that use a novel non-electrical saturated brine supply system. Here, instead of having to mix brine to a standard concentration, the operator tops up a dry salt level in a saturation tank, which pools saturated brine at its base. The saturated brine is gravity fed into water to provide a concentration of ~30 g/L, which collects in the hypochlorite generator (Fig. 2.2).

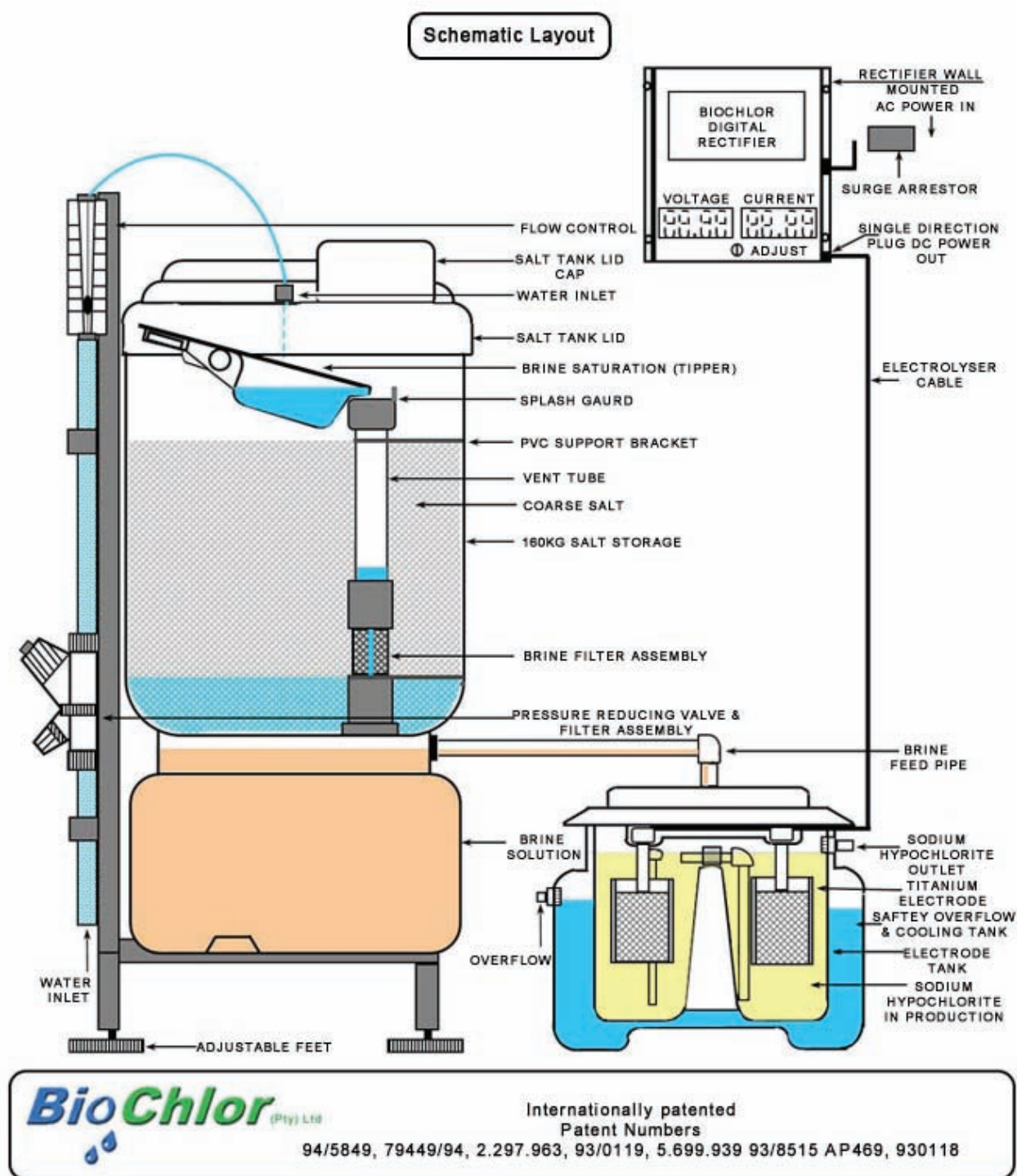


Fig. 2.2 Biochlor saturated brine-fed hypochlorite generator. Image reproduced with permission from Biochlor® (<http://www.biochlor.co.za/>)

The automated brine supply system, being non-electrical, is ideal for rural usage, since solar panel size can be limited to powering just the hypochlorite generator. The components shown in Fig. 2.2 depict the hypochlorite generator running on mains electricity via a rectifier for DC output. The hypochlorite generator has an adjustable chlorine output of 0.2-5.0 kg Cl_2 /day, sufficient to dose 0.2-5 ML of water per day at 1 mg/L of chlorine, and has a power consumption of ~3.8 kWh/kg of Cl_2 produced. The unit can produce hypochlorite continuously, which accumulates in a dose feeding tank. The depicted system costs ~R20 000 (communication with Biochlor® in 2009) depending on

the degree of additional equipment required at a particular site, e.g. dosing equipment, etc. The use of two such Biochlor® units at small water treatment sites in South Africa is reviewed in a previous WRC project (Pearson, 2000). The units are also modular and when assembled as such can collectively produce up to 200 kg of chlorine per day. Biochlor® also produces smaller hypochlorite generators for chlorinating less than 15 kL of water per day, and these units can be powered by alternative energy sources such as solar power and small wind powered turbines.

2.2.3 Concentrated brine circulating generators

Another South African company, Aquarius chlorinators®, produces hypochlorite generators that run on a circulating brine supply. The company makes a broad size range of generators (producing 0.16-32.0 L/h of 0.8% HOCl solution) that operate via a continuously pumped re-circulating brine supply through the cell. Once the maximum 0.8% chlorine concentration is reached (based on a timer mechanism) the hypochlorite is fed to a storage tank for dosing water. In general, the company focuses on larger scale potable water treatment operations exceeding 1 ML of water treatment per day, and based on the generator's requirement for automation (i.e. electrical brine pumps) the systems retail within a similar price range as the above mentioned Biochlor® units (once the cost of the pumps have been included in the price). Successful rural operation of the generators in water treatment has also been reviewed in the WRC report by Pearson (2000).

2.2.4 MIOX®

MIOX® is a USA-based company that produce a variety of water disinfection systems based on the electrolysis of brine. Some of these systems are highly automated comprising: electrical pumps; liquid level sensors in tanks to determine when brine should be pumped to the hypochlorite generator and when to power up the hypochlorite generator. An example of such a system is the **HYPO-10**, which is stated to produce about 4.5 kg of Cl₂ /day, enough to dose 4.5 ML of water at 1 mg/L Cl₂ (Fig. 2.3). At present MIOX® systems are not readily available in South Africa and due to their high degree of automation are more expensive than locally made systems, and models such as the HYPO-10 retail at well over R50 000.

MIOX® also makes systems that produce a dilute chlorine-based “mixed oxidant” disinfectant used in much the same way as hypochlorite. The essential difference is that a much more dilute brine solution is used at higher electrolysis voltages and the product although containing less free available chlorine (FAC) has been reported to have comparable disinfectant strength to that of higher chlorine concentration solutions. One of their smallest “mixed oxidant” units, the SAL-40, produces 1.8 kg of Cl₂/day, enough to disinfect, as stated 1.8 ML/day (at 1 mg/L Cl₂), but presumably with greater disinfecting power than just the stated chlorine content.

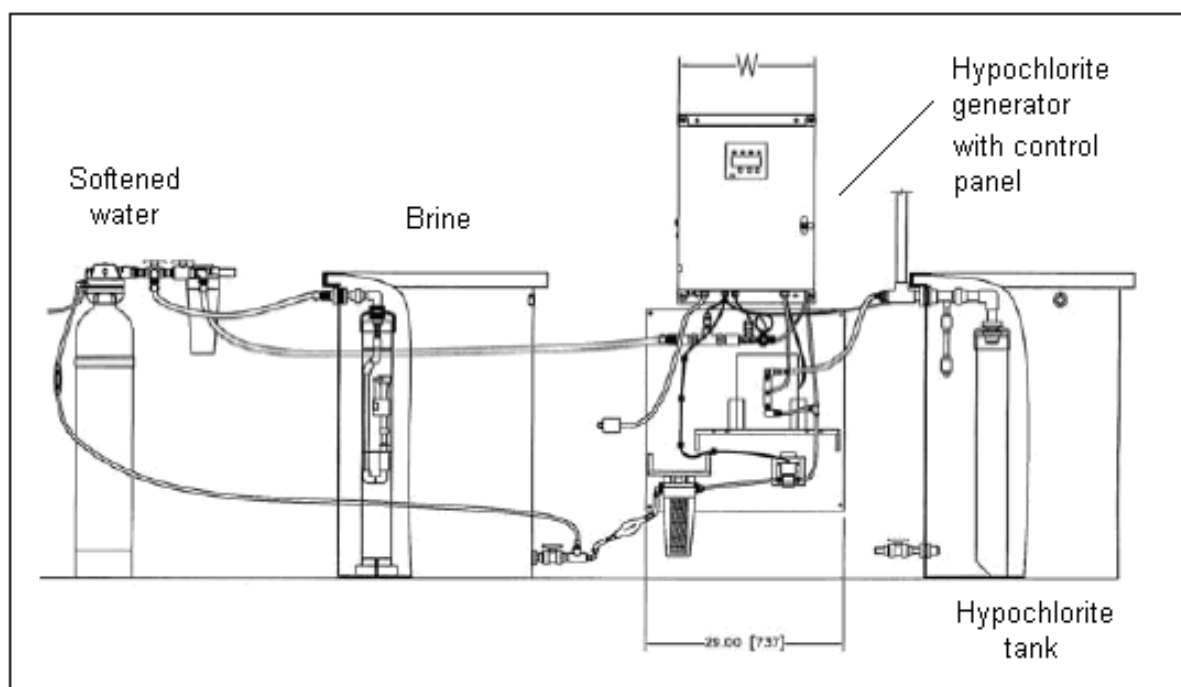


Fig. 2.3 A fully automated flow-through hypochlorite generator. (MIOX® HYPO-10 series). Schematic from MIOX® website (<http://www.miox.com/>), reproduced with permission.

2.2.5 Package OSEC and hypochlorite dosing systems for smaller water supplies

Small water supplies such as raised tanks that supply communities of 100-200 people are not normally targeted for installed OSEC applications. This is a good indication of the usual system's costs to number of people ratio, i.e. such size populations would seem to fall below the economy of scale for complete OSEC systems that also dose water.

However, at least one company, IEC Fabchem Ltd., based in India, advertises a package system to this scale. The model, Steriflo® OHT (overhead tank) – 3L, produces 30 g of Cl_2 /day and doses the hypochlorite to the outlet pipe from of an overhead tank using a Venturi eductor and small booster pump (Fig. 2.4). The operation of the hypochlorite generator is manual in the sense that: (i) brine is mixed by hand in a separate vessel and poured into the generator and (ii) that the generator is switched on and off manually after 22 h of electrolysis time. The system is stated to chlorinate 15 kL of water/day. The entire system is neatly and safely packaged in a small weatherproof housing.

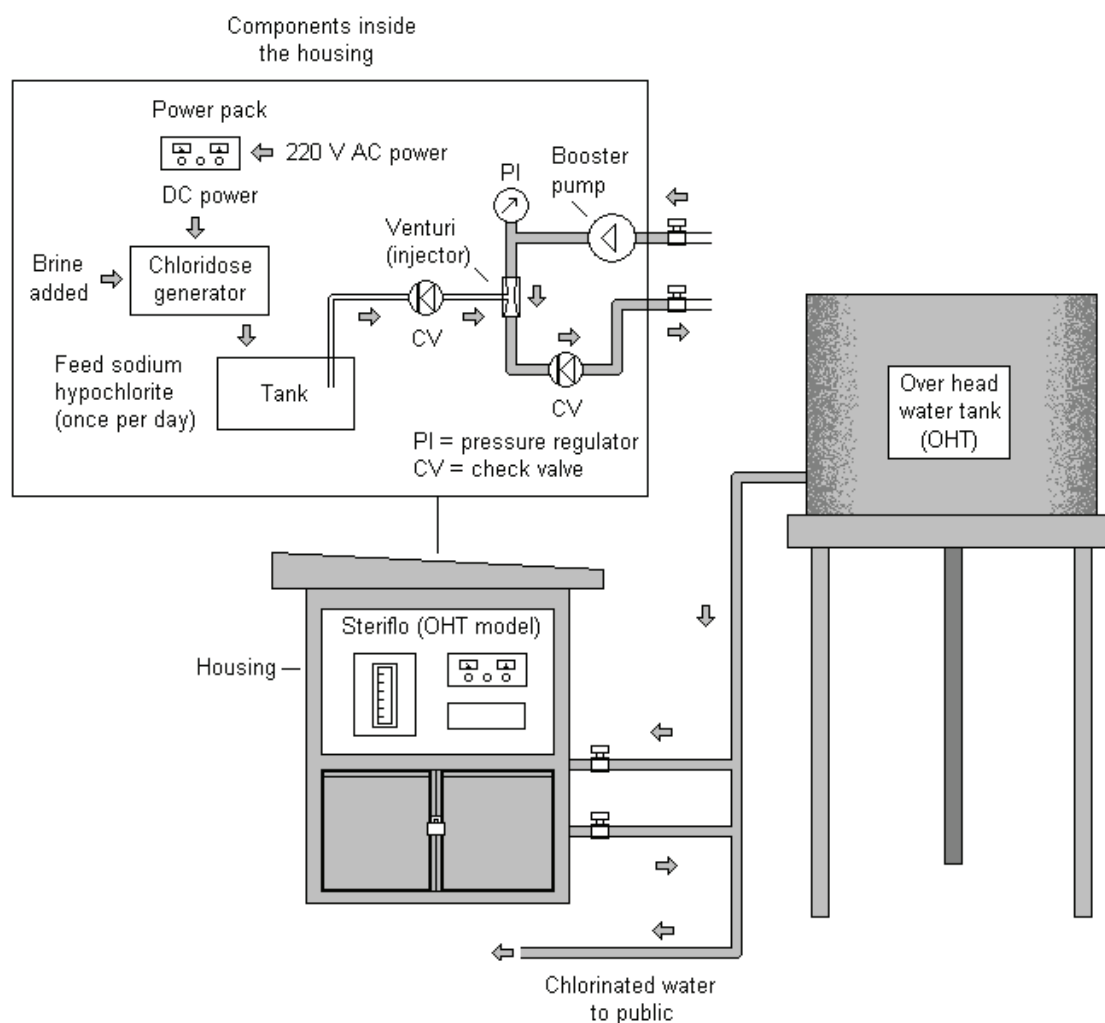


Fig. 2.4 Over-head tank with OSEC and dosing system by Steriflo® model OHT-3L (schematic adapted from: <http://www.iecfabchem.in>)

The above system, particularly if it was adapted to run by solar power, would be ideal for rural areas in South Africa that have supply tanks fed from small water treatment plants and boreholes. Recent studies show that in many cases water from such tanks requires chlorine residual boosting because by the time it reaches its point of use (POU), or taps, it has either insufficient or no chlorine residual left (Momba *et al.*, 2008).

2.3 HYPOCHLORITE PRODUCTION IN RURAL AREAS

Hypochlorite generators are well suited for operation at small water treatment plants in rural areas (Solsona and Pearson, 1995; Pearson, 2000). A major factor is that transportation for delivery of sodium hypochlorite can become costly, inconvenient, and sometimes hazardous. Therefore, the use of salt (particularly since it is cheap and can be stored easily and indefinitely) and locally available electricity (or solar power) becomes the favorable and sustainable option.

In particular, small, remote water treatment plants that use solar power as a source of electricity can benefit from hypochlorite generation. Once running, and beyond the returns from the initial investment (solar equipment, hypo. generator, etc.), such plants can operate sustainably at very low

running costs (e.g. the cost of salt, maintenance and labor) and can become the cheapest of all to operate.

2.3.1 Can OSEC be micromanaged by small communities?

Small communities (e.g. farms and villages) of less than 200 people that use local water sources are very common in South Africa's rural areas. Hypochlorination at such sites might need to cater for up to 30 kL of water/day, which depending on the dosing requirements (i.e. the chlorine demand of the water) could range from 30-200 g of Cl_2 /day. For all communities, systems with the lowest possible maintenance and cost requirements are preferable with the most important outcome being sustainability. How these factors relate is determined by the nature of the community.

If the community is to manage its own water chlorination the following questions might be asked:

- (i) Does the community have access to fresh commercially produced hypochlorite at least once a month?
- (ii) Can the community afford to buy commercially produced hypochlorite at least once a month?
*For example, for 200 people using 30 kL/day of water at 150 L/person in 2009: Bleach costs R46/kg Cl_2 so at 200 g/day: $46 \times 200 \text{ g} / 1,000 \times 30 \text{ days} = \sim \mathbf{R270 / month}$
or R1.35 /person/month or 66 c/person/month if using HTH (see 2.14)
Total: 60 L of bleach per month or 9 kg of HTH per month*
- (iii) Can the community provide reliable operators for the chlorination system?
- (iv) Can the community/municipality afford the chlorination system?

When the answer to all the above questions is yes, then a hypochlorination dosing system based either on commercially produced sodium hypochlorite or on calcium hypochlorite should be installed. This is because the use of commercial hypochlorite is easier to manage than including a hypochlorite production step. The system would require a dosing method for sodium hypochlorite (section 2.5), or an appropriate method for calcium hypochlorite dosing (Henderson *et al.*, 2005).

When the answer to questions (i) and (ii) is no, and (iii) and (iv) is yes, then a small-scale OSEC system becomes an appropriate possibility. Where this is the case, the following questions might be asked:

- (v) Can the community afford to buy salt?

*For example, for 200 people using 30 kL/day of water at 150 L/person in 2009:
Chlorine from salt is $\sim 5 \times$ cheaper than bleach: $\sim \mathbf{R54 / month}$
or 27c / person /month (section 2.14)
Total amount of salt: 24 kg/month*

Note: this calculation considers using mains electricity. If using solar, multiply the values by 0.8 (section 2.1.4)

(vi) Will the community use mains electricity or solar panels provided with the system?

For example, for 200 people using 30 kL/day of water at 150 L/person in 2009:

*Communities using mains electricity will pay **R7.20/month** collectively (section 2.1.4)*

If the community cannot afford to buy the salt, then deliveries from the municipality might be required: at no great cost (e.g. R54/month). If the community uses mains electricity but cannot afford the electricity cost (R7.20/month) something may be amiss. Questions (iii) and (iv) above are interrelated. Clearly manually operated OSEC systems are cheaper than automated ones (section 2.2), but require more maintenance and community involvement. Therefore, the chosen OSEC system must meet both requirements.

2.3.1.2 Advantages and disadvantage of OSEC

Advantages:

- Onsite electrochlorination is ~3-5× cheaper to run than buying hypochlorite (not considering labor).
- Salt stores easily and indefinitely (can be delivered annually).
- Salt is not hazardous to transport.
- Salt weighs ~2× less than commercial bleach (for the same amount of chlorine), and is cheaper to transport.
- Onsite electrochlorination has a smaller carbon footprint than using commercial bleach (considering transportation costs).
- Solar powered OSEC has a smaller carbon footprint than using any commercial hypochlorite.

Disadvantages:

- Equipment costs are much higher than would be required for commercial hypochlorite dosing.
- More complex maintenance tasks are required than using commercial hypochlorite.
- The production process can go wrong (i.e. lower yields of chlorine result in poor disinfection) if poorly maintained.
- Equipment breakage, repairs and replacement could be costly.
- Security risk of theft, e.g. solar panel equipment or rectifier unit, etc. (items that are not necessarily required in commercial hypochlorite dosing).

2.3.2 Conclusions concerning OSEC at small rural sites

Onsite electrochlorination has great potential benefit to small rural communities, especially regarding running costs. However, it is clear that equipment costs and management capacity will determine its success. In this regard, existing systems can be summarized as follows:

- (i) Existing systems that are low maintenance (i.e. automated) are high in cost;
- (ii) Existing systems that are low in cost are high maintenance (i.e. manually operated).

Consequently, neither option is particularly appealing for small community management, especially when compared to dosing systems that use commercial hypochlorite (if and when possible).

Existing OSEC systems, due to capital costs of equipment, appear to best suited for larger scale operations serving communities of 1,000 people or more. Therefore, a niche clearly exists for a cheaper small-scale OSEC/dosing system that is also low maintenance, i.e. an affordable automated system.

2.4 THE MEMBRANE ELECTROLYSER

The focus of the present study, the membrane electrolyser, is a small-scale device that can produce up to ~20 g of chlorine per day as either hypochlorous acid, or sodium hypochlorite (section 2.4.1 below). Its defining feature is a ceramic membrane (separating the anode and cathode), which improves the performance of the electrolyser over standard hypochlorite generators (Linkov *et al.*, 2002). Based on its chlorine output capacity, the electrolyser could serve to chlorinate water volumes between 2-20 kL/day (depending on dose concentration) for ~100-200 people (section 2.5.2).

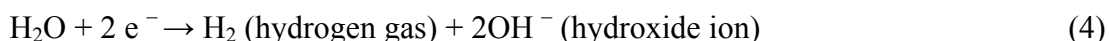
2.4.1 How it works

The main difference between the membrane electrolyser and standard hypochlorite generators is that it produces hypochlorous acid during electrolysis rather than hypochlorite (reactions 3-6 overleaf). This is achieved by a pH-limiting membrane made of aluminium-zirconium oxide that separates the brine-containing anode compartment from the water-containing cathode compartment (Fig. 2.5). Therefore, the electrolyser represents a hybrid between two forms of brine electrolysis. These are: (i) sodium hypochlorite generation in undivided electrolysis cells (i.e. hypochlorite generators) and (ii) chlorine gas generation in divided cells used in the chlor-alkali industry. These processes are discussed below in sections 2.4.2-2.4.4.

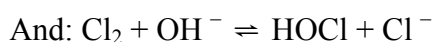
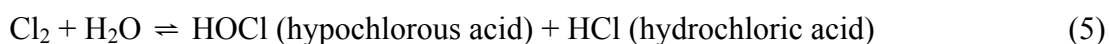
Anodic reaction:



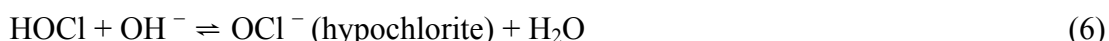
Cathodic reaction:



Hypochlorous acid formation:



Hypochlorite formation:



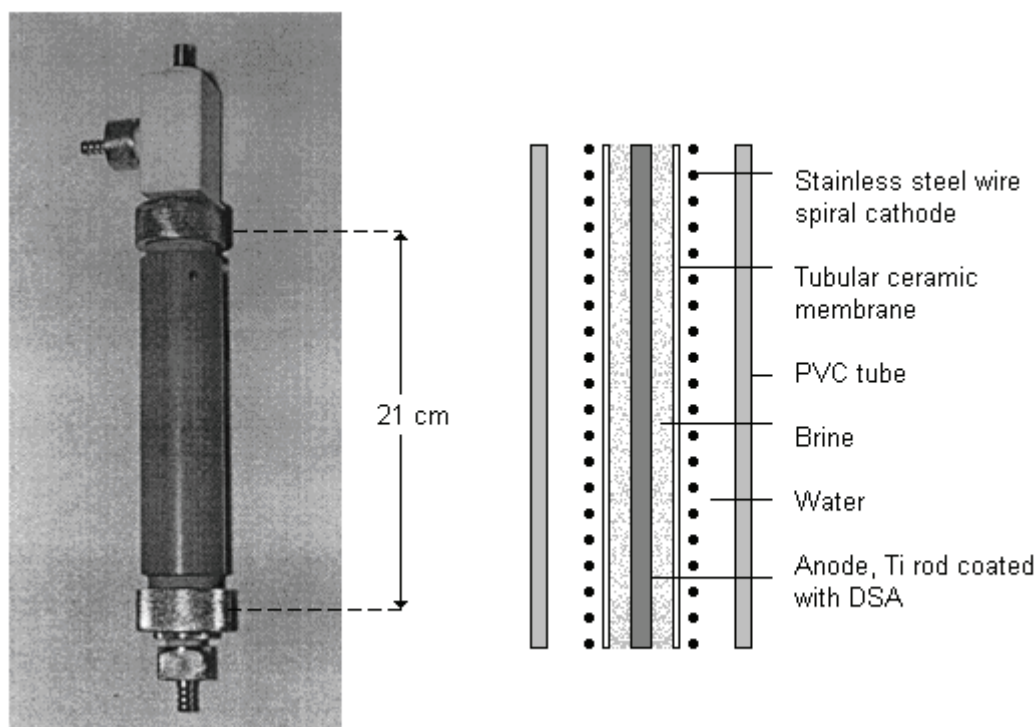


Fig. 2.5 The membrane electrolyser as developed by Linkov (2002). Photograph (left) and longitudinal cross section schematic (right).

2.4.2 Limiting factors of standard hypochlorite generators

The formation of hypochlorite (OCl^-) during electrolysis (reaction 6) in standard hypochlorite generators has a number of limiting effects on both electrolysis efficiency and the amount of chlorine produced. The major limiting factor is the reduction of OCl^- back to chloride (Cl^-) at the cathode (Wallace and Tiernan OSEC®, 2002):

Reduction of OCl^- at the cathode:



Hypochlorite is also oxidised at the anode to produce chlorate and Cl^- , particularly at high temperatures and OCl^- concentrations (Krstajic *et al.*, 1991). The production of toxic chlorate is particularly unwanted and is restricted to 0.7 mg/L in drinking water (WHO GDWQ, 2005).

Oxidation of OCl^- at the anode:



The net effect of these reactions during electrolysis results in:

- (i) Loss of current efficiency (i.e. energy is wasted);
- (ii) Loss of salt efficiency (i.e. salt is wasted);
- (iii) Toxic by-product formation (i.e. chlorate).

An ideal, 100%, conversion of NaCl to chlorine = 1.68 kg NaCl/kg Cl₂. In the undivided cell this is considerably lower, at 3-4 kg NaCl/kg Cl₂, and current efficiencies are 50-60% (i.e. 40-50% of the current does not yield chlorine). These losses can be accounted for by the above reactions (Pletcher, 1982 and Wallace and Tiernan OSEC®, 2002).

2.4.3 Chlor-alkali cells (Divided electrolysis cells)

By separating the anode and cathode reaction products by nafion (perfluoro-sulphonic acid resin: a cation selective membrane) the divided cell design is extremely efficient at producing chlorine gas (Fig. 2.6 B) yielding current and salt efficiencies close to 100% (Pletcher, 1982; White, 1999). The membrane prevents hydroxide ions formed at the cathode reacting with chlorine formed at the anode. This limits hydrolysis of chlorine gas into hypochlorous acid (HOCl) (reaction 5). This reaction occurs initially with water, but quickly reaches saturation point by the resultant decrease in pH as hydrochloric acid accumulates. The equilibrium at this low pH forces any further chlorine produced at the anode to leave the solution as a gas, which is subsequently collected. The purpose of the membrane is twofold:

- (i) To prevent hydroxide ions formed at the cathode (reaction 4) raising the anolyte pH, which would allow more hypochlorous acid and chloride to form (reaction 5).
- (ii) To allow sodium ions to migrate to the cathode chamber in order to balance the loss of chloride at the anode.

2.4.4 The pH limiting effect of the membrane electrolyser

The key design feature of the membrane electrolyser is that it employs a ceramic (aluminium – zirconium oxide based) tubular membrane (Bashtan *et al.*, 1999) that limits the mixing of anodic and cathodic reaction products (Fig. 2.6C). The difference between it and chlor-alkali cells is that it limits but does not completely exclude the migration of hydroxide ions. The membrane is not ion-selective as in the case of chlor-alkali cells, but rather, retards total ion movement through its small pores, which allows a balance between chloride conversion to chlorine and its hydration via hydroxide ions to establish. The limitation allows enough hydroxide ions to hydrolyse chlorine to hypochlorous acid (reaction 5), but not enough to form hypochlorite (reaction 6), i.e. the membrane limits pH increase to below pH 5 (Fig. 2.7). Thus, the prevention of hypochlorite formation in the cell allows higher chlorine yields than undivided cells owing to preventing the limiting factors discussed in section 2.4.2. The membrane electrolyser has salt and current efficiencies of 2-2.5 kg NaCl/kg Cl₂ and 77% respectively (Linkov, 2002; Bashtan *et al.*, 1999)

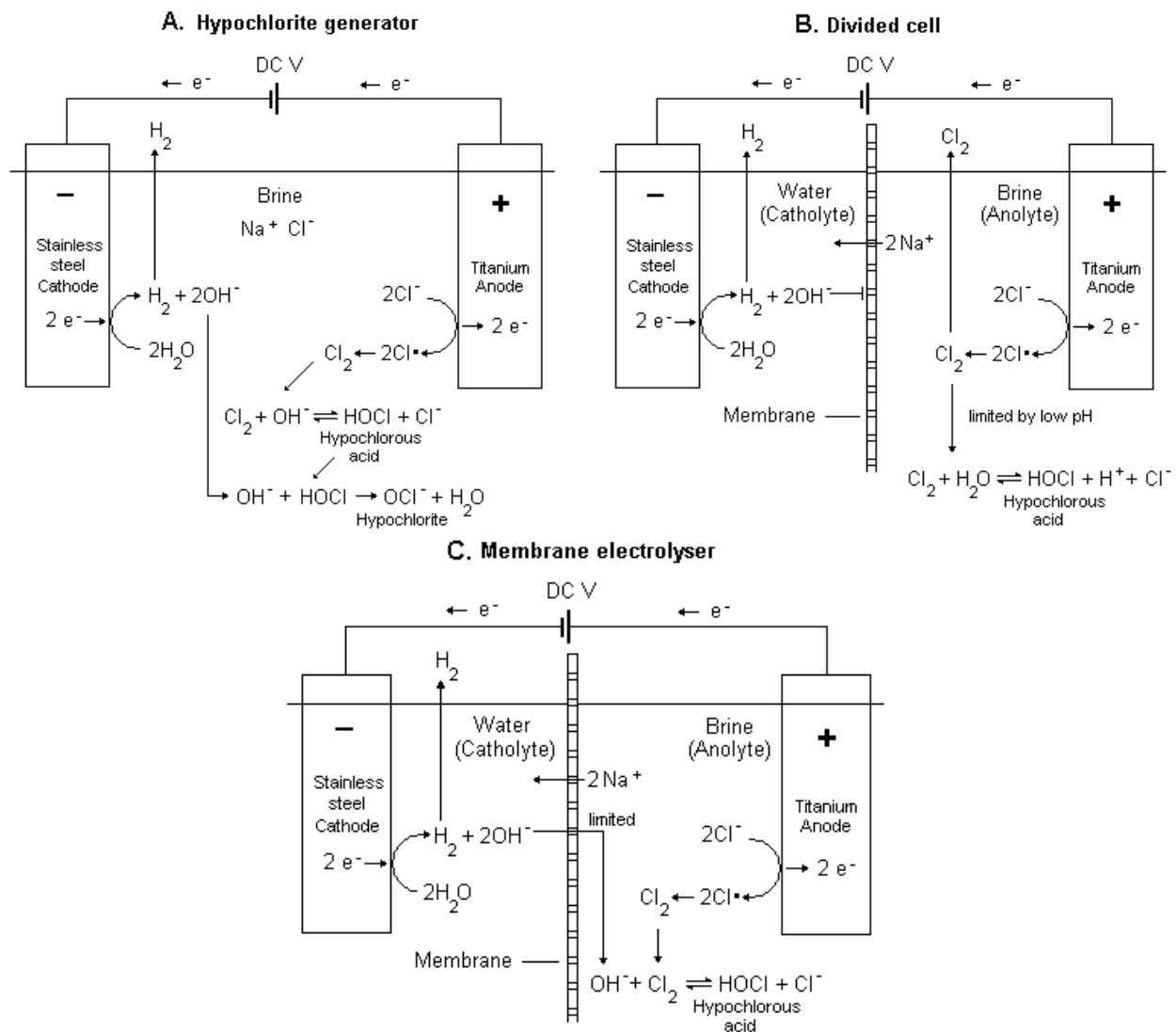


Fig. 2.6 Schematic of brine electrolysis cells. **A.** Hypochlorite production in a hypochlorite generator (undivided cell), **B.** Chlorine gas production in a divided cell, and **C.** Hypochlorous acid production in the membrane electrolyser.

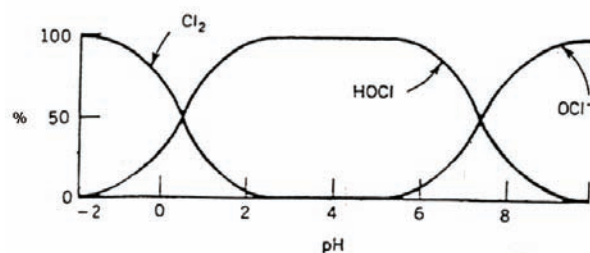


Fig. 2.7 Effect of pH on chlorine species in water

2.4.5 Comparison to MOGGOD (“Mixed Oxidant Gasses Generated On-site for Disinfection”)

Mixed Oxidant Gasses Generated On-site for Disinfection (MOGGOD) is a closely related technology of the chlor-alkali divided cell. In essence its function is the same as the chlor alkali cell (section 2.4.3), except that it is stated to produce a mixture of gasses (including chlorine and ozone)

that are injected into water much the same as chlorine gas would be. The cell (OXI-0.1 and 0.5 models) is a small compact cylindrical unit that can be used safely on-site (Solsona and Pearson, 1995; Pearson, 2000). It comprises an anode compartment fed with brine and a cathode compartment fed with water separated by an ion selective membrane. The major difference between it and the membrane electrolyser is that it produces gases and not hydrolysed chlorine (hypochlorous acid). The stated lifespan of the membrane and anode are stated at 6 and 30 months, respectively (this is no doubt variable according to the quality of the water where they operate).

On the basis of data presented by Solsona and Pearson (1995), the energy efficiency of MOGGOD might be slightly less than that of the membrane electrolyser, i.e. 4.5 kWh/kg Cl₂-equivalent compared to 3.1 kWh/kg Cl₂ (Bashtan *et al.*, 1999), and its salt efficiency 1.7 kg NaCl/ kg Cl₂-equivalent is better than the membrane electrolyser at 2-2.5 (section 2.4.4). One drawback however, is that the cell produces concentrated sodium hydroxide which needs to be collected and disposed of. In 1995, when compared to UV radiation and hypochlorite generators its total cost (cell + equipment + operation) fell evenly beneath that of UV and above that of the hypochlorite generator.

2.4.6 Cost comparisons and efficiencies

The figures presented in Table 2.1 provide a rough guide to the running costs of the respective cells. They do not include the energy costs of peripheral operational equipment, e.g. brine pumps, etc. The results do show however, that all else being equal, the membrane electrolyser could be ~35% cheaper to run than hypochlorite generators.

Table 2.1 Salt and energy efficiencies compared					
	Energy consumption		Salt consumption		Total
	kWh/kg Cl ₂	R/ kg Cl ₂	NaCl/ kg Cl ₂	R/kg Cl ₂	R/kg Cl ₂
Mem. electrolyser	~3	0.90	~2.5	5	5.90
MOGGOD	~4.5	1.35	~2	4	5.35
Hypo. generators	~4	1.20	~4	8	9.20
1 kWh = 30 c (ESKOM. Tariff restructuring plan 2008/9 (http://www.eskom.co.za/tariffs .)					
1 kg NaCl = R2 (variable according to bulk)					

The capital cost of the membrane electrolyser is, pending commercialisation and possible modifications, predicted to be ~R2 000-R2 500. The cost is primarily determined by the membrane material and DSAs (~R500 each per electrolyser in 2009).

2.4.7 Membranes in brine electrolysis: pros and cons

Any membrane-based technology must resign to the fact that the membrane has a definite life span. The pores of membranes are eventually blocked with time and their function (whether driven by pressure or electrical charge) will be reduced to a point where they need replacing.

Membrane blockage in brine electrolysis occurs primarily from salt precipitation of contaminant ions such as calcium and magnesium (Pletcher, 1982, and Kraft *et al.*, 1999), which form insoluble carbonates, particularly in the presence of heat and consequent loss of carbon dioxide from the solution (Pauling, 1970). Therefore, water hardness is a primary hindrance to membrane-based brine electrolysis, and more expensive operations (e.g. the chlor-alkali industry) often include water softeners to prevent the scaling phenomena. The pores of membranes can also block through aggregation and adsorption of colloidal particles, which maybe organic or inorganic in nature. In brine electrolysis, biofilm (i.e. from living microorganisms) blockage of the membrane is unlikely to occur due to the harsh conditions of chlorine and sodium hydroxide production.

The membrane of the membrane electrolyser is made from an alumina-zirconium oxide-based ceramic. It is thus hard and brittle in nature and requires careful handling on assembling and disassembling the electrolyser. The cost of the membrane, ~R500, must therefore be considered in terms of its life span, which in the intended application for this project was to be investigated. This must be weighed against the advantages of including it in the electrolyser (section 2.4.8, below) and thus its application must suit these advantages, e.g. where rapid production of small quantities of chlorine would be required.

2.4.8 Pros and cons of the membrane electrolyser

Pros:

- ~40% more salt efficient than hypochlorite generators.
- ~25% more energy efficient than hypochlorite generators.
- Produces no toxic by-products (chlorate).

Cons:

- The cell design makes electrodes more difficult to access for cleaning purposes.
- Membrane may be prone to blockage resulting in reduced chlorine yield.
- Flow through design limits its range of applications.
- Only applicable to small-scale applications (unless a multi cell-type is developed).

2.4.9 Conclusions concerning the membrane electrolyser

The membrane electrolyser offers cost saving features suitable for small-scale hypochlorination systems, if its viability can be proven. Its efficiency advantages over hypochlorite generators indicate that it will cost less to run, i.e. reducing costs in salt purchase, electricity usage and solar panel size requirements. Challenges facing the electrolyser, concern the practicality of the membrane and how easily the electrolyser can be incorporated into a water disinfection system. Moreover, its application must be carefully chosen to best suit what it can do (i.e. make small volumes of hypochlorite rapidly and cheaply).

2.5 APPLICATIONS OF THE MEMBRANE ELECTROLYSER

The main focus of this project was to determine whether the electrolyser could be used and managed by small rural communities to disinfect their water supplies. As a starting point, the chlorination capacity of the electrolyser determines the volume range of water it can chlorinate and therefore the size range of the community it can serve. These are ranges rather than precise values due to variable factors such as the chlorine demand of the water and the average consumption volume of water per person within the community (section 2.5.1).

2.5.1 Chlorination capacity of the membrane electrolyser based on a dosing range

The electrolyser was reported to produce 11 or 22 g of chlorine per day (24 h) depending on the level of production efficiency required (i.e. current and salt efficiency) (Linkov, 2002). Table 2.2 shows the possible daily volumes of water that could be chlorinated for potable use with this quantity of chlorine considering different dosing concentrations.

Table 2.2 Chlorination capacity of the membrane electrolyser										
Cl ₂ / day	Chlorine (mg/L) dose and water volumes (kL) / day (below)									
	1	2	3	4	5	6	7	8	9	10
11 g	1.1	5.5	3.7	2.8	2.2	1.8	1.6	1.4	1.2	1.1
22 g	22	11	7.3	5.5	4.4	3.7	3.2	2.8	2.4	2.2
15 g	15	7.5	5	3.8	3.0	2.5	2.1	1.9	1.7	1.5
Average										

The required chlorine dose of a water source depends on four main factors:

- (i) The chlorine demand of the water and system including storage tanks and reticulation (Momba and Brouckaert, 2005).
- (ii) Retention time required in storage tanks and reticulation systems (Hydes, 1999).
- (iii) The pH of the water, i.e. this determines the oxidative strength of dissolved chlorine (White, 1999).
- (iv) Nitrogenous compounds in the water that render chlorine in various less reactive forms such as chloramines (White, 1999).

In a recent survey of 181 small water treatment plants (SWTPs) in South Africa (Momba *et al.*, 2008), of capacities between 0.3-120 ML of water per day, ~15% of those examined used sodium hypochlorite for chlorination, and a 7 mg/L chlorine dose concentration was reported as a typical value. In smaller systems, treating between 120-150 kL/day, a chlorine dosing range of 3-6 mg/L has been reported (Pearson, 2000). The effectiveness of these dose concentrations at their particular sites is discussed in their above mentioned references. These doses provide an indication of typical chlorine demands at working SWTP's in South Africa.

As can be read from Table 2.2, a dose range of 3-7 mg/L of chlorine correlates to a water chlorination volume range of ~2-5 kL/day for the daily chlorine output (mean 15 g) from one electrolyser. However, it is highly probable that smaller water disinfection systems, i.e. appropriate to the electrolyser, might require smaller doses, considering that retention time in very long pipelines will not be a factor. Therefore a dose range of 1-3 mg/L can also be considered, especially if the electrolyser is to be used specifically for chlorine residual boosting (section 2.5.3). This range corresponds to a larger water volume of 5-15 kL/day (Table 2.2).

2.5.2 Servable population size of the electrolyser

In 2002, the South African government stipulated a minimum of 25 L of potable water per person per day as a service provision goal (DWAF, 2002) while the *Strategic Framework for Water Services* recognized that where possible this should be increased to 50 L per person per day (DWAF, 2003).

- Therefore, if a 3-7 mg/L dose is required, 2-5 kL shared as either 25-50 L/ person gives a population range of 40-100 people.
- And, if a 1-3 mg/L dose is required, 5-15 kL shared as either 25-50 L/ person gives a population range of 100-600 people.

However, in practice water consumption is determined by many factors. Table 2.3 shows the effect of accessibility to the water source. Table 2.4 shows how the water volumes chlorinated by the electrolyser relate to these factors.

Table 2.3 Third world domestic water consumption and accessibility (Sourced from Heber, 1985, compiled by IRC/WHO, 1981).		
Type of Water Supply	Average Consumption (L/person/day)	Range (L/person/day)
Communal water source:		
Distance > 1 km	7	5-10
Distance 0.5-1.0 km	12	10-15
Village well:		
Distance > 250 m	20	15-25
Public Standpipe:		
Distance > 250 m	30	20-50
Courtyard connection	40	20-80
House connection:		
One tap	50	30-60
Several taps	150	70-250
30% should be allowed for (unaccounted for) losses.		

Table 2.4 Effect of water accessibility on consumption, and servable population of the electrolyser (Adapted from Table 2.3 above)			
		Community size (No. of people)	
Type of Water Supply	Average Consumption (L/ person/day)	3-7 mg/L dose (2-5 kL)	1-3 mg/L Dose (5-15 kL)
Communal water source:			
Distance > 1 km	7	285-714	714-2142
Distance 0.5-1.0 km	12	166-416	416-1248
Village well:			
Distance > 250 m	20	100-250	250-750
Public Stand post:			
Distance > 250 m	30	66-166	166-498
Courtyard connection	40	50-125	125-375
House connection:			
One tap	50	40-100	100-300
Several taps	150	13-66	33-100
30% should be allowed for (unaccounted for) losses.			

2.5.3 Potential applications for the membrane electrolyser based on chlorination capacity

The chlorination capacity of the membrane electrolyser indicates it has two potential uses in drinking water chlorination:

- (i) Small-scale water disinfection (2-5 kL of water per day, with a 3-7 mg/L dose).
- (ii) Small-scale chlorine residual boosting (5-15 kL of water per day, with a 1-3 mg/L dose).

2.5.4 Small-scale water disinfection (potential sites and considerations)

The use of the electrolyser to fully disinfect water might require the high dosing concentration range of 3-7 mg/L. This equates to 2-5 kL of water per day to serve 40-100 people 50 L each. This number of people might be found at small rural farms, villages, schools, and clinics.

2.5.4.1 Target rural water sources

For drinking water purposes, chlorination must only be used on waters that have turbidity of < 5 NTU (SANS 241, 2005). Higher NTU values have high and uncontrollable chlorine demands (Obi *et al.*, 2008) and increase the risk of toxic trihalomethanes (THMs) forming in the water (Carlsson, 2003). Therefore, unless turbidity is < 5 NTU chlorination is not a safe option and pre-treatment clarification methods will be required. Table 2.5 shows the typical type of pre-treatment

required at surface waters of different turbidities. The use of the membrane electrolyser at surface water therefore requires suitable small-scale pre-treatment options.

However, the electrolyser does have more immediate site options where turbidity is not an issue. Examples of these are:

- Ground water sources (e.g. boreholes, wells and springs protected by a spring box).
- Roof-top rain harvesting tanks.
- Sites where turbidity is moderate and simple sand filtration is sufficient (Table 2.5).
- Sites where some form of pretreatment system already exists.

Such sites are common enough throughout the country and thus form the primary target for the project's implementation.

Table 2.5 Guidelines for the selection of a water treatment system for surface waters in rural areas (from Swartz, 2000)				
Average raw water quality	Water demand (kL/d)	Treatment suggested	Skills needed	Capital + Operating costs
Turbidity < 5 NTU Faecal coliform 0 CFU/100 mL Bilharzia not endemic	up to 2000	No treatment (filtration and disinfection recommended for surface water treatment)	nil (low-med)	nil (low- med)
Turbidity < 10 NTU Faecal coliform 0 CFU/100 mL Bilharzia endemic	up to 5000	1. Rapid sand filtration 2. Slow sand filtration	med low	med + low med + low
Turbidity 20-50 NTU Faecal coliform 1-500 CFU per 100 mL	up to 5000	1. Rapid sand filtration + disinfection (Cl ₂) 2. Slow sand filtration + disinfection (Cl ₂) if possible	med low	med + med med + low
Turbidity < 50-150 NTU Faecal coliform 1-500 CFU per 100 mL	up to 5000	1. Sedimentation + rapid sand filtration + disinfection (Cl ₂) 2. Sedimentation + slow sand filtration + disinfection (Cl ₂) if possible	med med	high + med high + low
Turbidity < 50-150 NTU Faecal coliform > 500 CFU per 100 mL	up to 5000	Pre-treatment (coag, floc & sedimentation) + filtration (rapid or slow sand + disinfection)	high	v. high + high
Turbidity > 150 NTU	Detailed investigation and possible pilot study work may be required			

2.5.5 Small-scale chlorine residual boosting

A second application option for the membrane electrolyser is to boost chlorine residual in water supplied from SWTPs. Maintaining the correct chlorine residual (0.1-0.5 mg/l) in water after it has been chlorinated, piped, stored, piped again and reaches the point of use (POU), (e.g. a tap), is an important but often difficult task to achieve. Loss of residual at taps appears to be a fairly common problem for SWTPs (Momba *et al.*, 2008; Pearson, 2000). Here, the losses occur for a variety of reasons including, under dosing of chlorine, interruptions in pipe flow, prolonged stagnation in storage tanks, increases in turbidity and other changes in the pretreated water quality.

Chlorine boosting near the POU with doses of 1-3 mg/l (depending on the point of application) provides the chlorine residual required in water. In terms of the daily chlorine output (15 g) from the membrane electrolyser, a corresponding maximum of 15 kL of water could be residual boosted at 1 mg/l or 5 kL at 3 mg/l (Table 2.4). These volumes might represent one small reservoir (or many smaller tanks) supplying up to 300 people (depending on the chlorine demand) assuming a consumption of 50 L for each person per day. The numbers can be simply divided by the appropriate factor for greater levels of personal consumption.

2.6 IMPLEMENTING THE MEMBRANE ELECTROLYSER AND APPROPRIATE TECHNOLOGY

The question of how best to implement the electrolyser requires careful consideration. In particular, the cost of the equipment necessary to run the electrolyser must correlate to the number of people that it can serve. The electrolyser by nature of its design and small size makes this a difficult task. This is because:

- (i) The constant flow-through design of the electrolyser is not suited to manual operation and thus requires some level of automation
- (ii) The small size and capacity of the electrolyser does not justify the costs of standard electrical automation control equipment, particularly for poor rural areas.

However, one advantage is that the requirement for automation would make the technology low maintenance. The challenge is therefore how to automate the process in an affordable manner. To achieve this it can be assumed that electrical components must be small, low power, and kept to a minimum, and where possible nonelectrical control mechanisms should be used.

2.6.1 Basic components a complete disinfection system

The basic components of equipment required to form a disinfection system incorporating the membrane electrolyser are:

- Water delivery infrastructure (including abstraction, possible pre-treatment, storage and distribution).

- Electrical power source (mains or solar power).
- Control of hypochlorite production (see below).
- Control of hypochlorite dosing (see below).

Hypochlorite production and hypochlorite dosing form the two main control points for consideration. Their respective components are:

2.6.1.1 Control of hypochlorite production:

- Control of power to the electrolyser
- Control of brine flow-through supply to the anode chamber
- Control of water flow-through supply to the cathode chamber

2.6.1.2 Control of hypochlorite dosing:

- Control of dosing rate (see 2.6.3)

2.6.2 Minimum electrical power requirements and solar panels

The use of solar panels to power the electrolyser may be a necessity in some rural areas. While high in capital cost, solar panels can provide a sustainable source of power for over 20 years (a commonly stated estimate for their predicted life-span). Based on previous reports (Linkov, 2002; Bashtan *et al.*, 1999) it can be calculated that the electrolyser if run continuously over 24 h would require 62 Wh/day: (i.e. at 1.3 kWh/kg Cl₂ and 20 g/day = 20 /1000×3.1 = 62 Wh/day). Therefore, for a 6-hour strong daylight period, a 30 W PV solar panel would provide 30×6 = 180 Wh/day or nearly double the draw from the electrolyser. The cost of such a panel (~R1 200) including 12 V battery and regulator (controller) comes to ~R2 500 (2009 prices, source: Sunpower® <http://sunpower.co.za/>). Each additional electrical control component added to the system increases the cost dramatically in terms of solar panel requirements. For example inclusion of one of the smallest available types of dosing pumps the “Min-E-Wash” model (Manufacturer: HydroNovaEurope®) requires 30 W (section 2.6.) and if run for more than two hours per day requires another 30 W solar panel in addition to its own capital cost of over R1 000. Therefore, this illustrates the need to keep electrical components to a minimum.

2.6.3 Sodium hypochlorite dosing methods: costs and considerations

Dosing of sodium hypochlorite to water can be carried out in a variety of ways ranging from manual to highly automated. Dosing equipment can therefore be another major component of capital cost in hypochlorination treatment. Above all, dosing must be consistent and reliable, ensuring that chlorine is evenly distributed in the water and given enough time to disinfect the water (Carlsson, 2003). Below are some of the options:

2.6.3.1 Manual dosing

This is usually carried out as a batch dosing procedure at various levels of scale. It is by far the simplest form of dosing, where a volume of sodium hypochlorite is simply hand-poured into a corresponding volume of water whether it is a bucket or a 2.5 kL tank. Thorough mixing and sufficient chlorine contact time (at least 30 minutes) are required for reliable disinfection. The method is labour intensive, but certainly has its place in emergency treatment of drinking water (http://www.cdc.gov/safewater/publications_pages/Safe_Water_for_the_Community.pdf).

2.6.3.2 Non-electrical dosing mechanisms

Two categories of non-electrical mechanisms exist for dosing sodium hypochlorite (or dissolved calcium hypochlorite): (i) gravity powered chlorinators and (ii) water-powered chlorinators. Both have their pros and cons, and are an affordable option when and where they can be used, since they generally do not require expensive parts or a supply of electricity. Such systems can cost less than a few hundred Rand to purchase or build, and are long lived, and in general do not require complex parts so they can be easily repaired on-site.

Gravity driven chlorinators – In the main, these systems provide an adjustable drip feed of sodium hypochlorite into flowing water. They require an open head of water at atmospheric pressure and cannot be used on pressurised pipe lines. They do not self-adjust to variable flow rates of water and must therefore be adjusted manually. However they are an affordable option that can be constructed and maintained cheaply without the need for highly specialised equipment.

Examples include:

- (i) the Mariotte jar,
- (ii) Inverted bottle with floating valve,
- (iii) Constant head tank,
- (iv) Floating draw-off pipe, and
- (v) the Vandos feeder.

A review of these systems is given by Skinner (2001). The Mariotte jar (Fig. 2.8), also known as a ‘constant-head aspirator’, is perhaps the one exception among the above that can be arranged to have a degree of self-regulation. It is a sealed, rigid bottle that provides a constant drip of sodium hypochlorite via the drip’s replacement by a bubble of air from a submerged pipe in the bottle. It can be arranged in such a way that the drip stops when the water flow stops (i.e. when the water demand stops). This is achieved by positioning the outside end of the air pipe at a fixed level in a water flow-through tank, that when full, rises to a level that submerges the pipe and cuts off the air to the Mariotte jar (WRC UK, 1984).

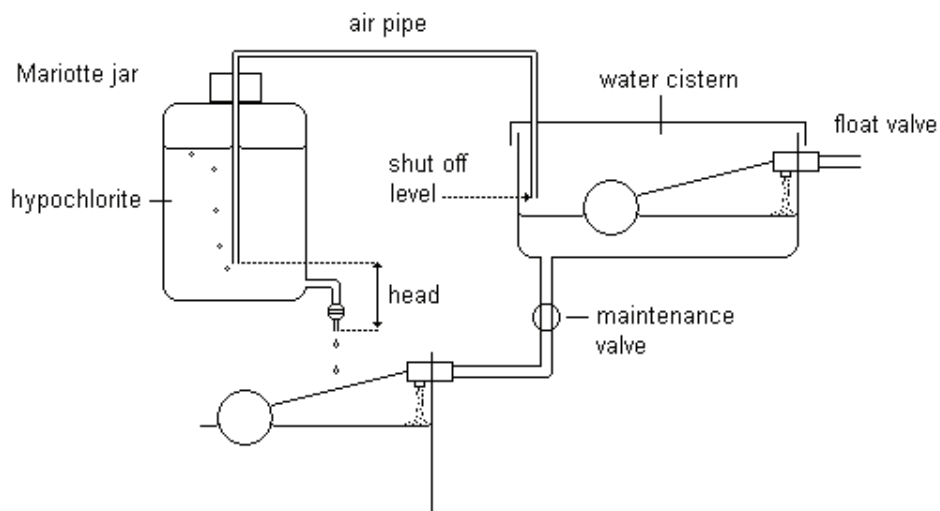


Fig. 2.8 Drip dosing of hypochlorite: Mariotte jar with shut off mechanism.

Water-powered chlorinators – Here, moving water powers a mechanical device, or produces a reduced pressure, which is used to dose the chlorine solution into the water (Skinner, 2001). Unlike the above mentioned drip based systems, most water powered systems self adjust their dose rate to the flow rate of water being dosed.

The mechanical category includes:

- (i) Wheel feeder dosers (hollow-spoke wheel feeder Fig. 2.9, overleaf),
- (ii) Float-powered chemical doser and
- (iv) Hydraulic motor/piston driven dosers (Skinner, 2001).

The mechanical systems, with the exception of (iv) only work at atmospheric pressure.

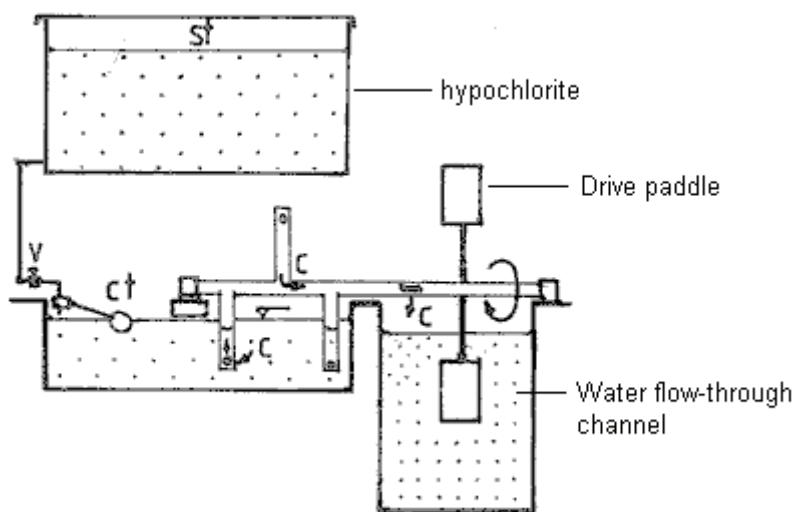


Fig. 2.9 Water-driven hypochlorite dosing: Hollow-spoke wheel feeder.
(adapted from Skinner, 2001)

The pressure driven category includes:

- (i) Venturi-powered dosers (Fig. 2.10),
- (ii) Direct suction dosers, and
- (iii) Displacement-bag doser.

The Venturi (or eductor) requires a minimum pipe flow rate to work reliably, and it and (ii) require a constant head tank feeder (provided by a cistern with a float valve). The Venturi and Displacement-bag doser both require pipe pressure to operate.

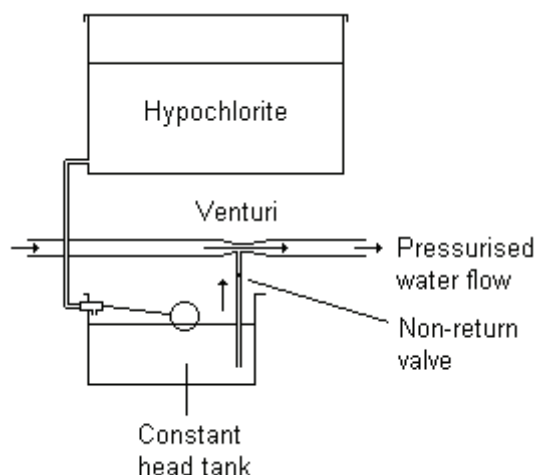


Fig. 2.10 Pressure-driven hypochlorite dosing: Venturi doser (adapted from Skinner, 2001).

2.6.3.3 Hypochlorite dosing Pumps

Hypochlorite dosing pumps provide a versatile but generally expensive option. They can be either electrical or non-electrical. Non-electrical pumps (e.g. hydraulic motor/piston driven dosers made by Dosatron®) require a minimum pressure to operate and are therefore only suitable for systems with a regular high flow rate. Electrical pumps are available in many designs and sizes and can cater for a wide range of dosing rates and pipe pressures. However, for small systems in rural areas the cost of the pump and the corresponding solar panel requirements might exceed the cost of the hypochlorite generator and solar panels required for OSEC. Furthermore, in a small OSEC system, the energy required to run the pump on a continuous basis might exceed that of the energy required to power OSEC.

The use of electrical pumps must be carefully considered in terms of the nature of the application. Where possible the pump should be positioned in the system so that it operates for minimum periods of time rather than continuously. Examples include: (i) pumping the produced hypochlorite as a batch to fill a small tank that feeds a Venturi eductor (Fig. 2.6) and (ii) pumping a batch volume of hypochlorite into a batch volume of water. The system could be regulated by a small level switch located in the tank that turns the pump on and off accordingly. Used correctly, pumps can have long life spans but should be restricted to use in situations where they can be repaired or replaced with

minimum interruption and delay to the site's operation. Table 2.6 gives details of a small electric peristaltic dosing pump:

Table 2.6 A typical small peristaltic dosing pump (For example "Min-E-Wash". Manufacturer: HydroNovaEurope®, distributor in S.A.: Fildos, Cape Town.)	
Capacity	Pump rate = 110 mL / min; Max vol. in 24 h = 158.4 L/day
Electrical	Voltage = AC or DC; Power = 30 W
Maintenance	Replacement of tubing
Price	Between R1 000-R2 000

2.6.4 Maintenance and safety

The running of OSEC, whether using manually operated hypochlorite generators or automated, requires diligent maintenance and safety precautions. Listed below are some of the routine procedures that must be implemented:

2.6.4.1 Maintenance:

- Brine replenishment (either via salt addition or brine preparation): This requires a regular operator.
- Cleaning of electrodes: In areas that have hard alkaline water, lime-scale deposits quickly accumulate on the cathode electrode of the hypochlorite generator. In such cases, routine washing of the electrode either in vinegar or dilute hydrochloric acid must be carried out. The accumulation causes current loss between the electrodes, resulting lower concentration yields of chlorine. This is why some automated systems have water softeners included.
- Overall system checks: Operator awareness to appropriate current readings on display panels is advisable. Low current readings are a definite indicator of reduced production efficiency. Checking for pipe tears and leakage at peristaltic pumps (if present).

2.6.4.2 Safety:

- Ventilation of hydrogen emissions from the cathodic reaction: a well ventilated room sufficiently removes these, but for large plants extraction and capturing devices may be required. (No smoking signs should be present in the housing).
- Rubber gloves and goggles should be available if needed, but routine operations should not necessarily require them.
- Housing kept below 40°C to prevent excessive chlorine emissions and hypochlorite decomposition (toxic by-product formation), (Gordon *et al.*, 1997).
- An effective emergency response protocol for malfunction or breakdown of hypochlorite production and dosing equipment.

CHAPTER III

DEVELOPMENT OF THE MEMBRANE ELECTROLYSER

Project aim (i):

- To establish the most suitable electrolyser design, construction materials and operational parameters to provide a device that is reliable, affordable, energy efficient and durable.

This chapter presents the following areas of research: modifications to electrolyser design (section 3.1); anode evaluation (section 3.2); optimising of running conditions (section 3.3); evaluation of membrane function (section 3.4) and effect of turbidity on membrane function (section 3.5).

3.1 ELECTROLYSER DESIGN

Initial testing of the electrolyser in the laboratory revealed that various modifications were required to improve its function and usability. The modifications included:

- A transparent acrylic cathode chamber to allow cathode observation.
- Wider PVC outlet pipes to prevent gas bubbles interrupting chamber flow.
- Modified PVC top and base caps to facilitate access to the electrodes.
- Membrane attachments changed to silicone tube to prevent breakage of the membrane when servicing the electrolyser.
- A spiral wire anode (VT-1 titanium with various catalytic coatings (section 3.2)).

The modified electrolyser is shown in Fig. 3.1 (overleaf) and described below in detail:

3.1.1 The membrane

The membrane is tubular and made of aluminium-zirconium oxide, which is porous to the migration of aqueous inorganic ions. It divides the cell's anode and cathode chambers. The membranes (supplied by: INMA, Kiev, Ukraine) are 21 cm long with an internal diameter of 1 cm, and a thickness of 1 mm.

3.1.2 The cathode and cathode chamber

The cathode is a 2 mm thick stainless steel spiral that is coiled around the membrane for a length of 17 cm. The spacing pitch of the coils is approximately 3 mm. Stainless steel is commonly used for cathodes because it is corrosion resistant and has a low overpotential for hydrogen evolution (Pletcher, 1982). The cathode does not come into contact with brine or chlorine (as it does in undivided cells), but rather a dilute sodium hydroxide solution formed during electrolysis.

The cathode chamber is 19 cm long with an internal diameter of 4 cm. Water is supplied to the cathode chamber through a 6 mm (outer diameter (OD)) silicone rubber tube, which joins a

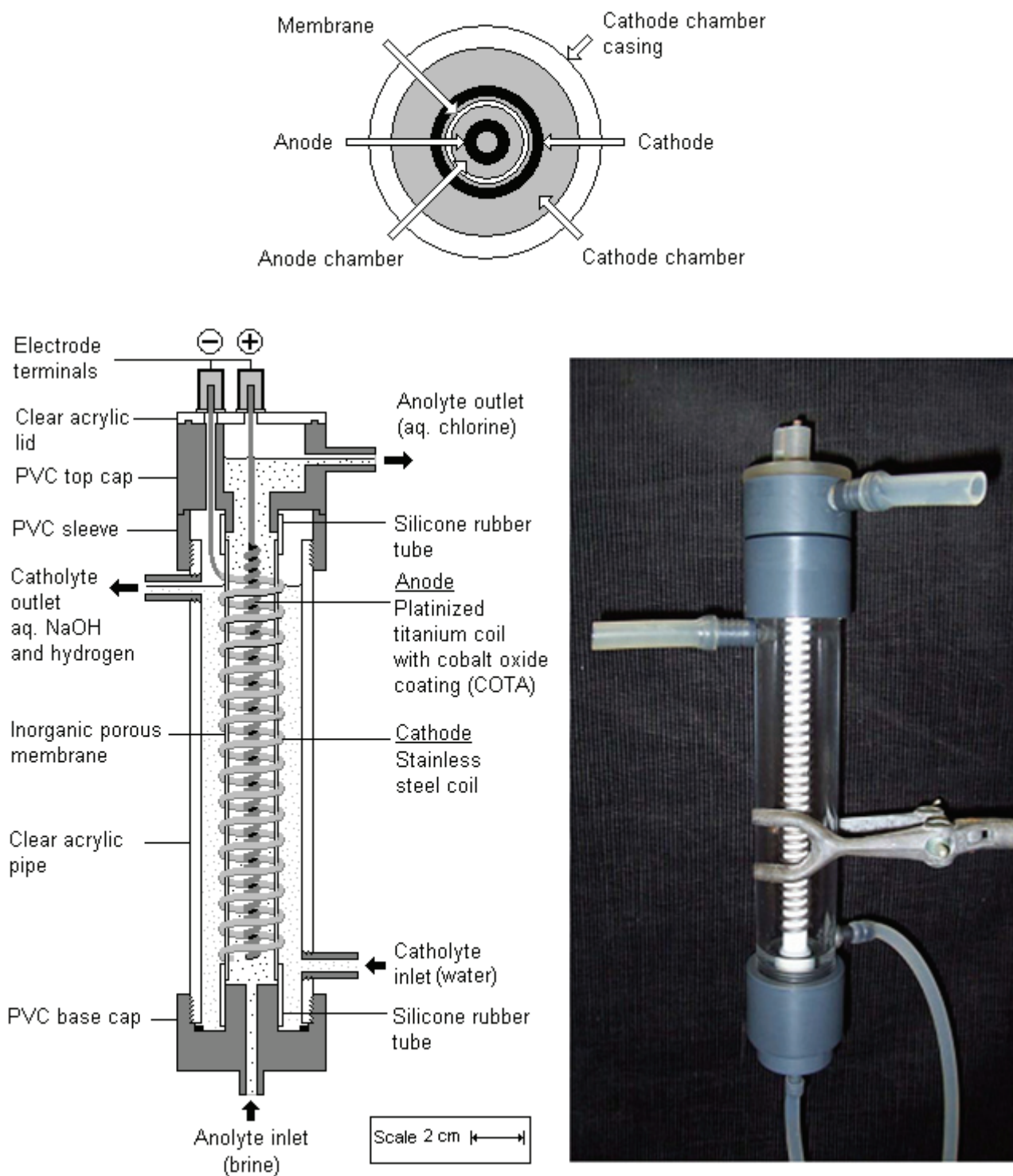


Fig. 3.1 The membrane electrolyser. Top: schematic of horizontal cross section. Left: schematic of longitudinal cross section. Right: photograph showing pipe connections.

screw-in PVC nozzle positioned in the side of the chamber's casing near its base. The outlet pipe at the top of the casing is wider (8 mm OD) silicone tubing, to allow the escape of hydrogen gas with the dilute sodium hydroxide catholyte product. The casing is made from transparent 4 mm thick acrylic pipe to allow observation of possible fouling of the membrane and cathode. For simple assembly and dismantling, the casing screws on to a PVC base cap which is fitted with a silicone rubber seal to prevent leakage. The top of the casing has threading for a PVC sleeve that tightens the anode top cap.

3.1.3 The anode and anode chamber

The anode is made of VT-1 titanium and has an electrocatalytic oxide coating (section 3.2). It forms a spiral wire 20 cm long, 1.5 mm thick, with an outer spiral diameter of 5 mm and a pitch of ~1 mm. The spiral fits down the centre of the diaphragm. The gap between the anode and the membrane is ~2 mm and that between the membrane and the cathode < 1 mm with some points of direct contact. Thus, including the thickness of the membrane (1 mm), the separation between anode and cathode is ~3 mm. The close proximity of the electrodes minimizes ohmic potential drop and increases current density on the electrodes.

3.2 MANUFACTURE AND EVALUATION OF ANODIC MATERIALS

The performance of anodes in brine electrolysis is vital for efficient chlorine production. Two criteria must be met: dimensional stability (i.e. resistance to corrosion), and ability to oxidise chloride to chlorine. In order to select the most suitable anode material for the electrolyser, three catalytic coatings on titanium anodes were investigated. The anodes plus coatings were:

- Dioxide of manganese (MnO_2) / titanium anodes: (DMTA).
- Ruthenium oxide (RuO_2 and TiO_2 double oxide system) / titanium anodes: (ROTA).
- Cobalt oxide (Co_3O_4) / titanium anodes: (COTA).

The selection of the above anodes considered future feasibility of anode manufacture in South Africa, their cost, dimensional stability and performance in chlorine production. Although many different types of anodes are available commercially, their manufacture and properties are covered by patents. Collaboration with the *Dumanski institute of Colloid and Water Chemistry of Ukrainian Academy of Sciences* was established for the preparation and evaluation of suitable Dimensionally Stable Anodes (DSAs) (Appendix 1).

3.2.1 Methodology for anode evaluation

The three anodes (DMTA, ROTA and COTA) were tested in the membrane electrolyser to determine the following:

- (i) Figures of merit (see below),
- (ii) Dimensional stability, and
- (iii) Generation of toxic chlorate.

These criteria were examined under the following operating conditions in the electrolyser:

- Brine concentration = NaCl at 25 and 50 g/L*
- Current density = 8, 12, 24 and 39 mA/cm² *
- Duration of electrolysis = short-term (hours) and long-term (days)
- Anolyte and catholyte flow rates = anolyte 50-90 mL/h, catholyte 140-190 mL/h
- Experimental setup: The electrolyser was fed brine at 50-90 mL/h and water at 140-190 mL/h to its respective chambers using constant head tanks that allowed a steady drip rate to be maintained (Siguba, 2004).
- Chlorine production (FAC: free available chlorine) was measured (Appendix 2) from samples comprising a mixture of the anolyte and catholyte products, i.e. pooled together from their respective outlets at the electrolyser. Mixing the two products converts the hypochlorous acid to hypochlorite at pH 11 (Linkov, 2002), this reduces chlorine reactivity and allowed stable storage of the samples during the course of the experiments
- Chlorate was measured (Appendix 2) directly from anolyte samples to prevent formation of hypochlorite and chlorate (section 2.4.2)
- Figures of merit for electrolysis were calculated as shown below:

$$\text{Current Efficiency (f)} = \frac{\text{Charge used in forming chlorine}}{\text{Total charge consumed}} \times 100 \quad (9)$$

$$\text{Energy Consumption} = \frac{nFV}{3.6 \times 10^4 \times F \times M} = \text{kWh/kg} \quad (10)$$

Where:

n = Number of electrons Transferred

F = Faraday Constant = 96 485.3399(24) Coulombs/mole of electrons

M = Formula Mass (kg)

3.2.2. Results of anode evaluation

The DMTA electrodes rapidly corroded during operation and the anolyte became discoloured. The effects of corrosion can be seen after 1 h of electrolysis (Table 3.1) because the voltage required to maintain the current density had to be significantly increased. The corrosion resulted in extremely low chlorine yields and poor figures of merit. The ROTA electrodes, like DMTA, also corroded

* The choice of these conditions was shown in a previous study (Linkov, 2002) to obtain the best figures of merit using platinised COTA.

during operation, but this only became evident after 24 hours (data not shown). Prior to their corrosion, ROTA displayed good chlorine yields and good figures of merit (Table 3.1).

The COTA electrodes produced very good figures of merit and most importantly did not corrode during electrolysis. COTA was thus chosen to be tested for a longer electrolysis period over 60 h (Table 3.2) at 0.4 A and 25 g/L NaCl because these conditions produced the best figures of merit (Table 3.1). Over the 60 h period COTA maintained stable figures of merit and did not corrode (Table 3.2). The COTA electrodes produced ~0.01 g/L of chlorate in the anolyte (under the operating conditions shown in Table 3.2). The chlorine concentration of the anolyte (average of 6.3 g/L), if dosed into water, would be diluted by a factor of 6,300 to 1,000 for a dose range of 1-6.3 mg/L. Consequently, the chlorate content of the anolyte would also be diluted by this factor, giving a concentration range of 0.002-0.01 mg/L of chlorate. Since the recommended chlorate limit in drinking water is 0.7 mg/L (WHO, GDWQ, 2005), the concentrations from COTA are clearly acceptable.

Table 3.1 Evaluation of anodes: Dmta, Rota & Cota								
Brine(NaCl)	25 g/L				50 g/L			
Current(A)	0.25	0.4	0.8	1.3	0.25	0.4	0.8	1.3
CurrentDensity (mA.cm ⁻²)	8	12	24	39	8	12	24	39
CHLORINE CONCENTRATION OF ANOLYTE (g/L)								
DMTA	0.1	0.2	0.3	1.1	0.3	0.3	2.2	3.4
ROTA	4.1	5.3	8.1	11.3	4.3	6.6	11.4	15.5
COTA	4.3	7.3	12.6	13.9	5.5	8.3	13.1	17.4
CHLORINE / DAY (g/day)								
DMTA	0.2	0.2	0.4	1.3	0.3	0.3	2.6	4
ROTA	4.9	6.4	9.7	13.7	5.2	7.9	13.7	18.6
COTA	5.2	8.8	15.1	16.7	6.6	10.0	15.7	20.8
VOLTAGE (V)								
DMTA	3.9	4.2	4.8	5.4	4.0	4.2	4.8	4.5
ROTA	3.1	3.2	3.5	3.8	2.9	3.0	3.3	3.6
COTA	3.0	3.2	3.3	3.7	2.1	2.6	3.0	3.5
SALT EFFICIENCY (kg NaCl / kg Cl ₂)								
DMTA	172.72	115.14	86.36	23.82	172.71	172.71	22.65	14.69
ROTA	6.01	4.69	3.26	2.21	12.01	7.55	4.40	3.24
COTA	6.28	3.44	2.03	1.79	9.03	6.11	3.83	2.87
ENERGY CONSUMPTION (kWh/ kg Cl ₂)								
DMTA	136.02	154.89	265.99	133.86	68.18	115.61	34.65	41.66
ROTA	3.69	4.77	7.34	8.66	3.51	3.61	4.68	6.12
COTA	3.81	3.49	4.32	6.79	1.93	2.58	5.32	5.15
CURRENT EFFICIENCY (%)								
DMTA	2.19	2.05	1.37	3.05	4.38	2.74	10.43	9.89
ROTA	62.93	50.27	36.25	32.83	62.93	62.58	53.69	44.93
COTA	60.19	68.74	58.31	40.62	83.72	77.29	43.07	50.61
SODIUM CHLORATE (g/L)								
DMTA	0.0028	0.0014	0.0064	0.0236	0.0019	0.0045	0.0083	0.0198
ROTA	0.0055	0.0849	0.1050	0.2125	0.0963	0.0806	0.1138	0.2183
COTA	0.0103	0.0322	0.0211	0.0449	0.0337	0.0402	0.0578	0.1036
Fixed electrolysis conditions: Brine flow rate: 50 mL/h; Water flow rate: 140 mL/h; Electrolysis period: 1 h n = 2-3 (no. of experiments)								

Table 3.2 Cota performance over 60 h.					
	1 h	15 h	30 h	45 h	60 h
CHLORINE CONCENTRATION OF ANOLYTE (g/L)	6.0	6.7	6.1	7.1	5.7
CHLORINE / DAY (g/day)	7.2	8.4	7.3	8.5	6.8
VOLTAGE (V)	3.94	3.95	4.20	4.19	4.82
SALT EFFICIENCY (kg NaCl / kg Cl ₂)	3.36	2.83	3.38	3.73	3.72
ENERGY CONSUMPTION (kWh/ kg Cl ₂)	4.83	4.48	4.81	3.70	5.24
CURRENT EFFICIENCY (%)	49.20	53.54	50.33	63.32	46.30
SODIUM CHLORATE (g/L)	0.0119	0.0126	0.0127	0.0131	0.0102
Fixed electrolysis conditions: Brine flow rate: 50 mL/h; Water flow rate: 140 mL/h (current density 12 mA.cm ⁻² ; current 0.4 A; brine 25 mg/L) n = 2					

3.2.3 Conclusions and selection of anode material

Of the three anodes tested, the obvious choice for use in the electrolyser was the COTA electrode. It produced steady chlorine yields, it was dimensionally stable over long-term tests, and it had good figures of merit and produced very low chlorate levels. These results are comparable to those reported by Bashtan *et al.*, 1999, Linkov, 2002. Furthermore, initial concerns over the cost of COTA production were solved by the development of a cheaper production method by the Dumanski institute team (Appendix 1).

3.3. OPTIMISING RUNNING CONDITIONS

During the course of the above experiments (section 3.2) the slow 50 mL/h flow rate of brine supply to the anolyte chamber had proved difficult to accurately maintain and was highly prone to stoppages. The flow constitutes a very slow drip rate (of 1 drop every ~2 seconds) that requires a very small pipe orifice. Faster rates yielded less chlorine (data not shown) and this had previously been reported by Bashtan *et al.*, 1999. The small orifice was prone to blockage by the formation of gas bubbles leaving solution (particularly with temperature change), and by any small debris in the brine (e.g. settled dust deposits). Efforts were made to solve this problem, and even a medical drip unit was investigated in one interim report. However, a solution eventually came by substituting the continuous flow system for a batch supply system (see below).

3.3.1. Methodology (a batch supply)

The batch supply system entailed controlling the delivery of batches of brine and water to the electrolyser's respective chambers. Here, each incoming batch displaces the previous batch in the electrolyser. The frequency of the batch supply thus formed the flow rate of production, and the maximum size batch is limited to that of the respective chambers in the electrolyser, i.e. 15 mL of anolyte (brine) and 45 mL of catholyte (water).

To match the previous continuous flow rates of ~50 mL/h and ~140 mL/h (i.e. the anolyte and catholyte flow rates respectively), the addition of 15 mL and 45 mL batches required ~20 minute

intervals. Smaller batches could have been chosen and dosed at higher frequencies. However, since the control of the batch would require some form of automation it was reasoned that supplying larger batches at a minimum frequency would demand less energy. To study the effect of batch dosing on the electrolyser in the laboratory, batches were first supplied by hand (i.e. simply poured into the electrolyser). The electrolyser was run with the previously used conditions (see above, Table 3.2).

3.3.2 Results

Twenty-minute intervals with chamber-size batches gave comparable chlorine yields and efficiencies to continuous flow (data not shown). However, after testing a range of batch sizes and supply frequencies, it was found that an eight-minute interval with chamber-sized batches produced better chlorine yields than continuous flow. The comparison is shown in Table 3.3.

Table 3.3 Batch supply vs. Continuous supply									
	[Cl ₂] at 8 min. (g/L)	Volume at 8 min. (mL)	Cl ₂ at 8 min. (g)	Cl ₂ (g/day)	Voltage (V)	W.h/day	Salt efficiency (kg NaCl / kg Cl ₂)		Energy consumption (kWh/ kg Cl ₂)
Batch 15 mL/ 8 min.	5.8	15	0.087	15.6	4	48	4.3		3.1
Continuous flow 112 mL/h	5.1	15	0.077	13.9	4.1	49.2	4.9		3.5
Continuous flow 50 mL/h	6.3	6.7	0.042	7.5	4.2		50.4	4	6.7
Fixed conditions: Brine concentration = 25 g/L; Brine volume = 15 mL; Current: 0.5 A; Catholyte flow 140 mL/h; Catholyte batch 45 mL/8 min n = 2									

The equivalent continuous flow output of 112 mL/h yield more chlorine than the 50 mL/h flow but at significantly poorer salt efficiency.

3.3.3 Conclusions

The eight-min batch supply method produced the best overall figures of merit and the highest daily chlorine yield, equalling $\sim 2.1\times$ that of the previously used continuous flow method. This demonstrates that a short static period of fresh brine residence in the electrolyser is more energy and time efficient than a sustained slow flow rate but $\sim 7\%$ less salt efficient. It is important to note that the chlorine product accumulates from 0 g/L to 5.8 g/L over 8 min. Under these conditions the energy efficiency and chlorine production rate are $\sim 2.1 \times$ higher than slow continuous feed. The increased efficiency is probably due to the fact that the method reduces the length of time that the

electrolysis products remain exposed at high concentration to the electrodes. The batch method produced the most energy efficient chlorine yield at 15.6 g/day using 48 W.h of electrical energy. This means that the electrolyser could be run from a 10 W solar panel system providing the panel received 6 h of direct sunlight.

3.4 EVALUATION OF MEMBRANE FUNCTION AND RUNNING CONDITIONS

The function of the membrane has previously been shown to increase the efficiency of brine electrolysis above that of undivided cells (section 2.2.4 and 2.4.6) (Linkov, 2002; Bashtan *et al.*, 1999). However, membranes can get blocked by particulate matter and scale deposits. Therefore, in the event that this became a problem, it was of interest to know how the COTA anodes would perform without the membrane, i.e. in an undivided cell of comparable size to the membrane electrolyser. The benefits of constructing such a cell were twofold:

- (i) It allowed the function of the membrane to be compared more accurately.
- (ii) It provided a possible alternative electrolyser if membrane blockage became a problem.

In addition to the above, the question of how turbidity and poor quality water might affect the membrane was also investigated (section 3.5).

3.4.1 Methodology (an undivided cell option)

An undivided cell needed to be made that maintained as many of the original parameters of the membrane cell as possible. Simply removing the membrane creates a large single chamber of ~100 mL. This would dramatically change the dynamics of the cell particularly concerning salt consumption. Therefore, to maintain the 15 mL volume of the original anolyte chamber, the spiral cathode was substituted for a stainless steel pipe cathode with similar dimensions to the membrane (section 3.1.1). The anode was placed inside the cathode and secured with pipe adaptors at the top and bottom. The pipe thus became the cathode and casing of the electrolyser (Fig. 3.2).

The cell was constructed as shown in the schematic (Fig. 3.2) and run in a side by side experiment with the membrane electrolyser. The experiment was run using the batch supply system described in section 3.3 and below:

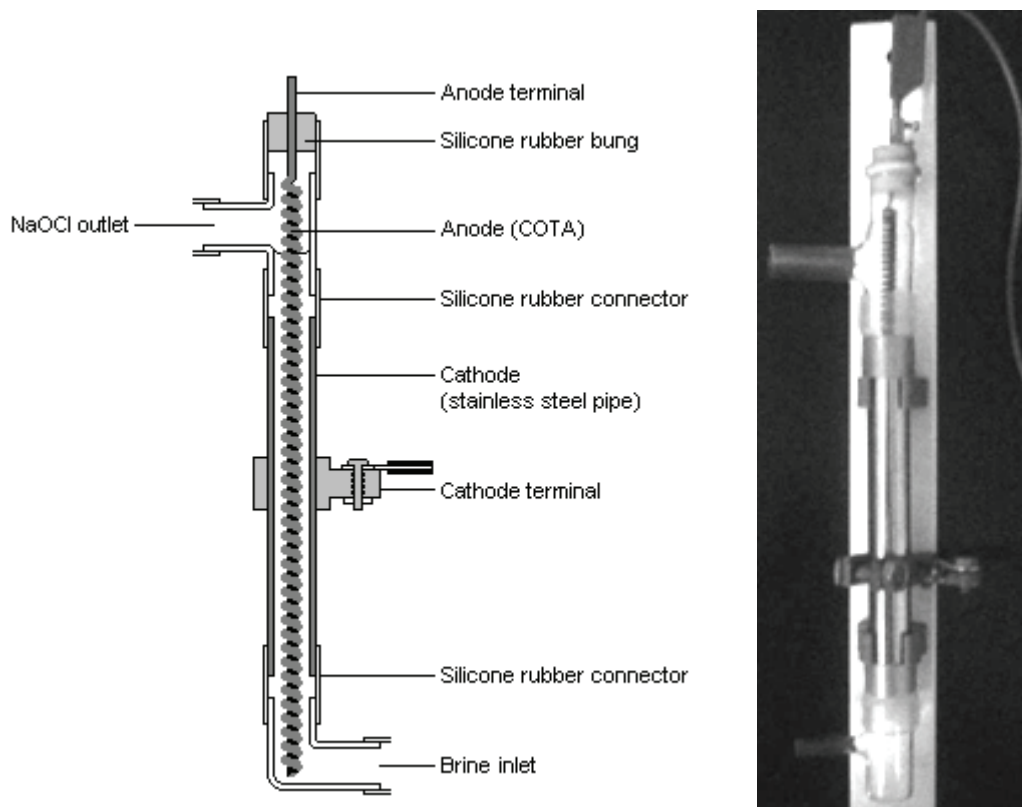


Fig. 3.2 The undivided electrolyser: developed as a possible alternative to the membrane electrolyser.

The running conditions of the experiment were as follows:

- Electrolysis period = 8 minutes;
- Brine concentration = 25 g/L;
- Brine volume = 15 mL;
- Current: 0.5 A

Chlorine (FAC) production was measured (Appendix 2) and the figures of merit were calculated and compared for the two cell types.

3.4.2 Results

During the eight minute electrolysis period (Table 3.4) the membrane cell produced 2.2× more chlorine than the undivided cell, consumed 1.7× less energy and was 2.2× more salt efficient. These results are fairly conclusive, but what of the possibility that the undivided cell could be used in place of the membrane at times of membrane blockage? This question can be answered by looking at the potential daily chlorine output of the undivided cell (see below).

Table 3.4 Comparing membrane and undivided electrolyzers									
Cell type	Voltage (V)	Cl ₂ conc. (g/L)	Cl ₂ / batch (mg)			Cl ₂ (g/day)	W.h/day	Salt efficiency kg NaCl/kg Cl ₂	Energy consumption (kWh/kg Cl ₂)
Membrane electrolyser	4.1	5.7	85.5	15.4	49.2	3.5		3.1	
Undivided electrolyser	3.0	2.6	38.3			7.0	36.0	7.81	5.2
Fixed conditions: Electrolysis period = 8 minutes; Brine concentration = 25 g/L; Brine volume = 15 mL; Current: 0.5 A. n = 3									

3.4.3 Daily chlorine output of the undivided cell

The potential daily chlorine output of the electrolyzers was:

- The membrane electrolyser: 15.4 g Cl₂ /day
- The undivided electrolyser: 7.0 g Cl₂ /day

The undivided cell produced less chlorine than the membrane electrolyser under batch dose conditions, but interestingly it produced a similar amount to the membrane electrolyser run under continuous flow conditions, i.e. 7.6 g Cl₂/day (Table 3.3). Therefore, the answer to whether the undivided cell could substitute for the membrane cell is yes, but 2.2× less water could be chlorinated and salt would be used at low efficiency.

3.4.4 Conclusions

The above results demonstrate that the membrane increases rate and efficiency of chlorine production efficiency. However, it was recognised that the undivided cell did not have the same spiral wire cathode as the membrane electrolyser. Further experiments could be undertaken to determine whether the membrane's effects might be supported by the spiral cathode. However, for practical purposes the pipe cathode represents a simple alternative electrolyser that is considerably cheaper and easier to operate than the membrane electrolyser.

3.5 THE MEMBRANE AND TURBIDITY

Possible blockage (fouling) of the membrane was of major concern to the project. Membrane blockage increases the electrical resistance across the membrane and results in lower chlorine

yields. High levels of turbidity, organic matter, salts (other than NaCl) and water hardness were all considered potential causes of membrane blockage (section 2.4.7).

At the project's chosen pilot site (Chapter 5), problems did arise concerning turbidity. Here, turbidity dramatically increased in summer and autumn, from < 5 FNU to 120 FNU. The high FNU levels revealed that the pre-disinfection sand filter could not remove sufficient turbidity to allow reliable chlorination. It was also noticed that the increased turbidity coincided with a 0.1-0.3 A drop of current within the electrolyser, which due to the design of the dosing system could have been caused by water that flushes through the electrolyser (Chapter 4). Therefore, to determine whether turbidity had caused this effect, the problem was investigated in the UWC laboratory.

3.5.1 Methodology of membrane testing

To investigate the impact of turbidity on the membrane, an appropriate experiment needed to be devised. An exact simulation of the pilot site's batch dosing system would have proved difficult and time consuming to obtain results. Therefore, a continuous flow supply (as used in the anode evaluation experiments in section 3.2.1) was chosen, wherein turbidity could be introduced at controlled levels to both the brine and water supply to the electrolyser. This was carried out using two Mariotte Jars arranged to supply a drip feed of brine and water respectively. A range of turbidity could then be tested over different periods of electrolysis time against a control with low turbidity, and its effects on current and chlorine production be evaluated. The following experimental conditions and methods were used:

- Turbidity in the pilot site's water was used and could be concentrated or diluted using settling.
- Turbidity was measured in FNU (Formazin Nephelometric Units) using a portable turbidity measuring kit (Martini® instruments, see Appendix 2).
- Flow rates of brine and water to the electrolyser were maintained at 50 mL/h and 140 mL/h respectively (as used in section 3.2.1).
- Voltage was set at 4 V over the one-week continuous running period.

3.5.2 Results of membrane testing with turbidity

Table 3.5 shows that turbidity at ~120 FNU (Fig. 3.3) had a dramatic effect on chlorine production. This was most likely caused by the chlorine demand of the turbidity itself and possible additional reactions taking place at the electrodes from the reaction products with turbidity, e.g. THMs. On the other hand the current was far less affected at ~120 FNU, and after 24 h remained on par with that of the low FNU experiment. However, after one week of continuous running at ~120 FNU the current had dropped to 0.33 A, (a 35% current reduction) indicating that there had been a cumulative effect on the membrane or even the electrodes.

Table 3.5 Effect of turbidity on the membrane electrolyser					
		10 min	1 h	24 h	1 week
~120 FNU	Current (A)	0.51	0.56	0.6	0.33
	Chlorine (g/L)	1.2	0.8	1.0	0.2
~10 FNU	Current (A)	0.48	0.56	0.41	0.51
	Chlorine (g/L)	5.9	5.2	5.0	5.3
<1 FNU	Current (A)	0.62	0.58	0.52	0.6
	Chlorine (g/L)	7.4	6.2	5.9	6.1
Fixed conditions: Catholyte feed 140 mL/h; Anolyte feed 50 mL/h; Voltage 4 V. n = 2					



Fig. 3.3 Turbid water from the site. Left: After 5 days standing (~10 FNU). Right: fresh from the tap (~120 FNU).

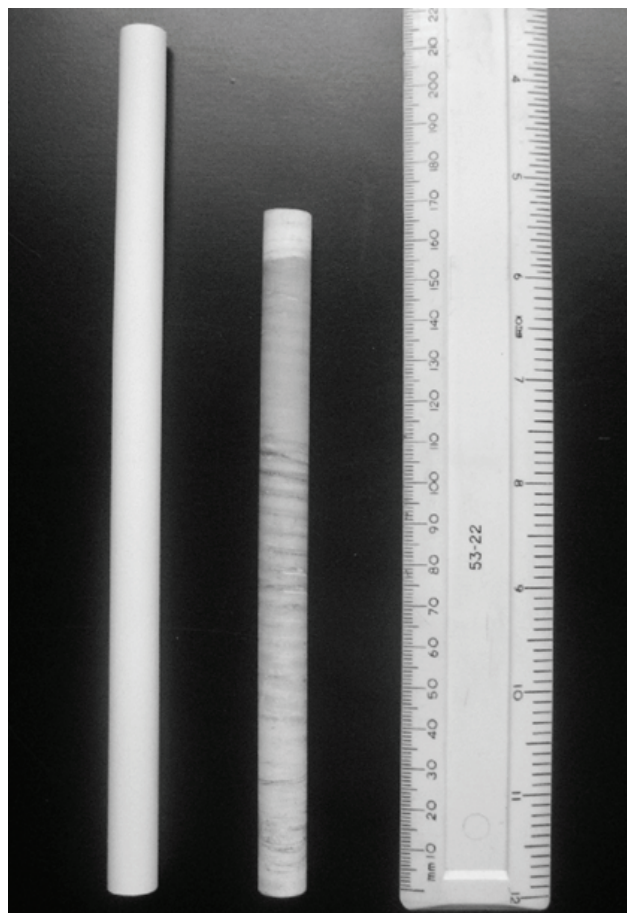


Fig. 3.4 Membrane discolouration: Left: a new membrane as bought from the supplier. Right: a membrane cut to fit the electrolyser, showing staining after six months of use.

3.5.3 Recovery of the membrane

In order to test whether the membrane used at 120 FNU for one week (section 3.5.2) had been permanently blocked by the turbidity, it was removed from the electrolyser and thoroughly washed with tap water. No permanent staining had occurred. It was then installed in an electrolyser with a clean water supply and brine supply of < 1 FNU and run under the same electrolysis conditions as were used in the turbidity experiment.

A current of ~ 0.5 A and a chlorine yield of 6.1 mg/L were obtained from the first run of this experiment. Therefore, the effects of 1-week's running with turbidity at 120 FNU was reversible by washing of the membrane. This suggests that the blockage was colloidal in nature and did not form a tightly bound deposit (i.e. as might be expected from lime scale). However, it is possible that running the membrane for even longer periods at high FNU values could more permanently block its pores.

3.5.4 Conclusions

The high level of turbidity used in the experiment had a definite negative effect on current in the electrolyser, reducing it by 35%. This effect would no doubt worsen over a longer running period. However, at low turbidity of < 5 FNU (suitable for chlorine dosing), the effect was not observed and would probably take much longer to block the membrane than at higher turbidity. This correlates with the successful operation of the electrolyser at the site during periods of low turbidity (Chapter 5). It was also noticed that during the operation of the electrolyser at the site (during a two-month winter period of low turbidity, see Chapter 5) the membrane had become stained by orange coloured deposits (most likely iron) but these had had no notable effect on the current of the electrolyser. The discolouration can be seen in Fig. 3.4 as a banding pattern on the membrane. No such bands developed on the new membrane used in the turbidity experiments. Therefore, the two phenomena are probably unrelated, and the effect observed in the turbidity experiment is likely due to a reversible colloidal adsorption of suspended particles.

3.6 CONCLUSIONS TO THE CHAPTER

The overall conclusions to the research presented in this chapter are as follows:

- COTA proved the best candidate anode for the electrolyser, due to its dimensional stability, good figures of merit, and insignificant chlorate production.
- A short (eight minute) batch supply of fresh brine and water to the electrolyser proved to be a $2.1 \times$ more energy efficient and rapid means of chlorine production than a slow continuous brine feed.
- The batch brine supply method produced a chlorine yield of 15.6 g/day using ~ 50 W.h, which could be supplied by a 10 W solar panel system.
- An undivided electrolyser (based on a stainless steel pipe cathode and COTA anode) provides a slower, less efficient (in both salt and energy consumption) but potentially viable alternative to the membrane electrolyser, which could be used if membrane fouling becomes a problem.
- The membrane can be blocked by turbidity of ~ 120 FNU within its supply feed after one week of running, and to the extent studied here the blockage is reversible by washing the membrane in clean water.

CHAPTER IV

DEVELOPMENT OF THE DISINFECTION SYSTEM

Project aim (ii):

- To develop a disinfection system that incorporates the electrolyser and accurately doses water in a manner that is automatic, low maintenance, solar powered, low cost and sustainable

To successfully implement the electrolyser at a rural site it must be accompanied by an appropriate operating system or disinfection system. The system must take into account the capacity of the electrolyser and the nature of the site where it will operate, and in total comprise: (i) onsite production of hypochlorite, (ii) water disinfection and (iii) community involvement. This chapter presents the laboratory development and testing of the disinfection system in the following sections: integration of the electrolyser (section 4.1); development of a batch dosing system (section 4.2); operation of the batch dosing system (section 4.3) and considerations for rural use (section 4.4).

4.1 INTEGRATION OF THE ELECTROLYSER

4.1.1 A novel concept

The project began with an idea that the electrolyser could function in a manner similar to a flow-through disinfection device. That is, that it could operate in-line with a continuous brine feed to produce hypochlorite and simultaneously dose it to water at a corresponding rate. The idea integrates the rate of hypochlorite production directly with the rate of water dosing, and therefore the electrolyser becomes a continuously active device. Moreover, the electrolyser's flow-through design and small size is well suited to such a means of operation.

4.1.2 Advantages of the flow-through concept

The flow-through concept described above has three foreseeable advantages if it can be successfully achieved.

- Firstly, it doses water with freshly produced hypochlorite, which is beneficial considering that hypochlorite is inherently unstable in storage and subject to concentration change in active chlorine content and toxic by-product formation (Gordon, 1997).
- Secondly, it allows a smaller, less expensive device to be used in a continuous fashion in place of a larger more expensive device operating intermittently.
- Thirdly, in considering its parallel operation to water flow rate and dosing it presents the interesting possibility that its operation could be controlled automatically by water flow rate.

4.1.3 Implementation challenges facing the flow-through concept

Testing of the electrolyser carried out in chapter 2 revealed some immediate challenges to the flow-through concept. The first came in the form of difficulties in controlling the slow required flow rate

of brine to the electrolyser. This was solved by using a batch dose in place of a slow flow (section 3.3). However, the question of how to control a batch dose had yet to be answered. Furthermore, the effects of continuous electrolysis activity might have on the cell were uncertain.

4.2 DEVELOPMENT OF A BATCH DOSING SYSTEM

The possibility that the electrolyser could be controlled by the flow rate of water that it dosed was particularly attractive because it could minimise the role of a human operator. Various non-electrical devices that operate on a similar basis exist, such as the water-powered hypochlorite dosing systems mentioned in the literature review of this report (section 2.6.3). Furthermore, the use of water-power in place of electrical energy (particularly electrical pumps) limits the requirement for solar panels and therefore reduces the cost of the system (section 2.6.2).

4.2.1 A water-powered brine batch

A water-powered means of batch dosing brine to the electrolyser was devised (Fig. 4.1). Here, the brine batch supply system is powered by the filling of the water tank beneath it. As the tank fills, the volume of brine in tube 3 is forced into tube 4 by air pressure generated in the inverted tube 5. The brine dose falls into tube 4 and displaces the contents of the electrolyser. When the water tank empties, brine in the constant head tank 2 feeds into tube 3 and the system is re-set.

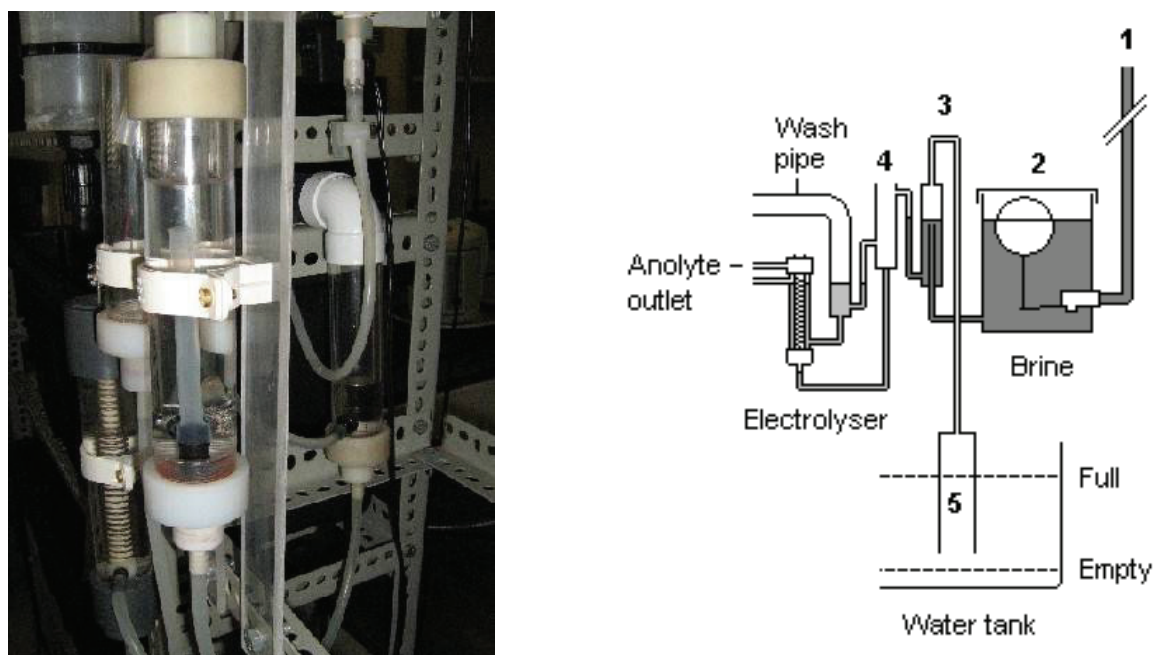


Fig. 4.1 A water-powered brine batch supply system. Left: photograph showing tube 3. Right: schematic diagram of the entire unit.

The wash pipe (Fig. 4.1) forms part of the electrolyser's flush system, which flushes both the cathode chamber and the anode chamber. These components must be understood in context of the complete water dosing system described below.

4.2.2 A complete batch dosing system

The system shown below (Fig. 4.2) was developed to continuously dose 30 L batches of water. It comprises a mixture of electrical and water-powered control. The electrical components consist of two small solenoid valves V1 and V2, a timer, three float switches (S1-3) and a circuit box. Valves V1 and V2 control the release of air from the bells above the U-bend siphons, which causes them to flush water into the tank below. The system chlorinates water through the following sequence:

1. When tank 1 is full (detected by S1) and tank 3 is empty (detected by S3), V2 is opened and tank 2 flushes into tank 3.
2. The filling of tank 3 forces a fixed volume of brine into the electrolyser and starts an 8-min electrolysis period of brine residence in the electrolyser
3. The 8 min period is timed by the “delay on” timer activated by S2 when tank 2 is empty
4. After 8 min of electrolysis, the timer opens V1 and flushes tank 1 into tank 2 (note: some water is diverted to flush out the electrolyser and displace hypochlorite into tank 2)
5. Once tank 2 is full it will only flush again if tank 1 is refilled and tank 3 has emptied

Note: the valves automatically close after flushing due to circuit breaking by the float switches.

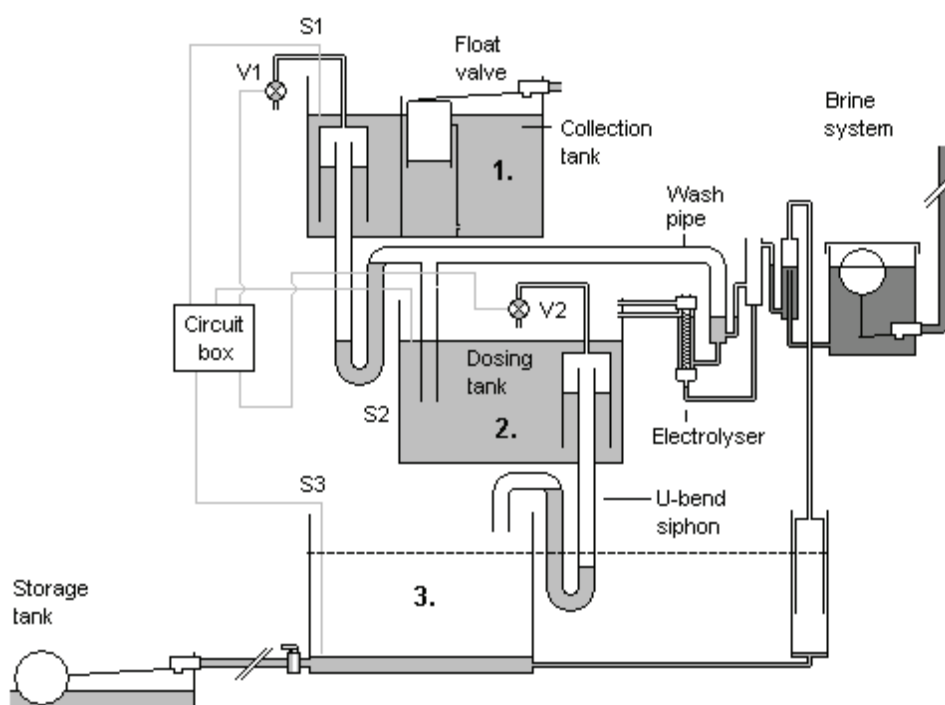


Fig. 4.2 A three-tank batch dosing system.

Control of brine electrolysis and hypochlorite dosing – The batch dosing system initiates electrolysis by supplying the electrolyser with brine (Fig. 4.1 above), and stops electrolysis by flushing it with water (Fig. 4.3 below). Due to the low conductivity of water, electrolysis is effectively stopped and the electrolyser remains inactive until another batch of brine is delivered. The system therefore controls both hypochlorite production and dosing by the availability of water in tank 1 and the requirement for water in tank 3. The concentration of hypochlorite (i.e. the combined anolyte and catholyte) is controlled at three levels: (i) the electrolysis period; (ii) the

voltage on the electrodes and; (iii) the volume of brine delivered to the electrolyser. All three parameters can be adjusted independently.

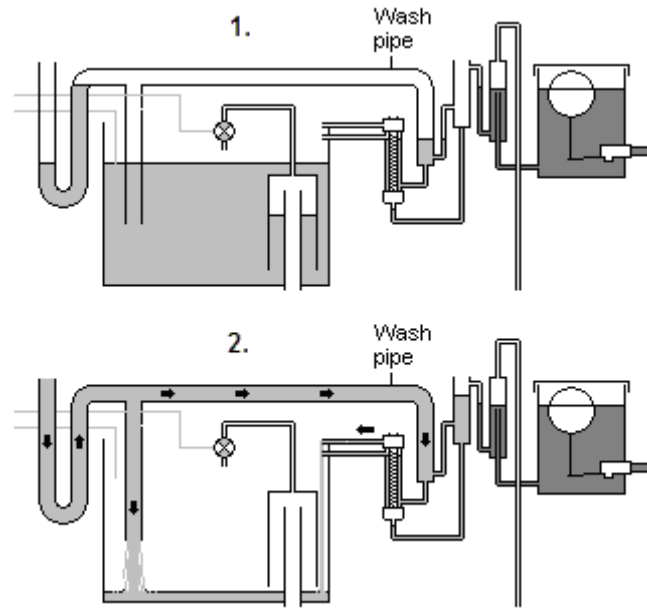


Fig. 4.3 The electrolyser's flush system. 1. Prior to flush. 2. Flushing.

Control of water flow rate – The movement of water through the system is controlled by the float switch / timer / solenoid valve circuit. The system responds to the availability of water in tank 1 and the requirement for water in tank 3 which connects to the chlorinated water storage tank via a float valve (Fig. 4.2 above). Tank 3 thus allows the level of water in the storage tank to be detected.

Tank 1 contains a float valve to control incoming water. The valve arm rests on a detached float that moves up and down in a pipe (Fig. 4.4). The pipe has a small hole at its base that allows water to escape at a slower rate than the flush of the tank. This arrangement serves to delay the opening of the float valve until the tank has completely flushed. The delay is important because it allows the flush siphon to properly break, and it also ensures that a fixed volume of water (30 L) passes through the system on each cycle.

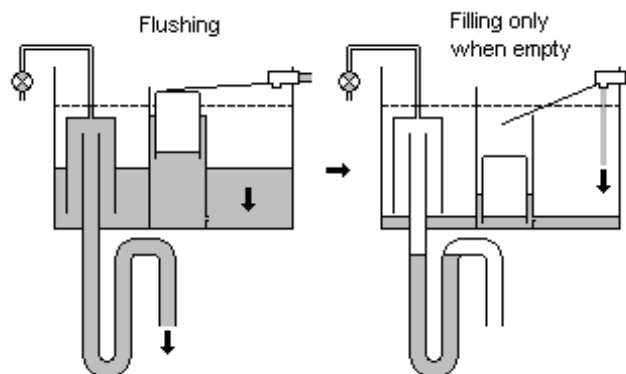


Fig. 4.4 Float valve delay mechanism.

Chlorine contact time – Chlorine contact time occurs between the dosing tank and the storage tank. Here, the minimum time period for water to travel between the two tanks must be 20 minutes.

This allows sufficient chlorine contact time (CCT) (Carlsson, 2003) before the water reaches a storage tank, where dilution may occur particularly if the water is not being used. The easiest way for this to be achieved is by choosing an appropriate pipe length between the dosing tank and the storage tank (Chapter 5, section 5.2.3).

4.2.3 Solenoid valve specifications

The solenoid valves (Fig. 4.5) were purchased from Hydraelectric© (UK) and have the model specification name of “Hot water dispense valves”. The model was recommended by the supplier because of its durability, which was preferable for prolonged usage. The valve seat is made of silicone rubber and heat resistant ceramic material. The valves operate on 24 V DC at 10 W and are opened on activation and closed on deactivation (standing).

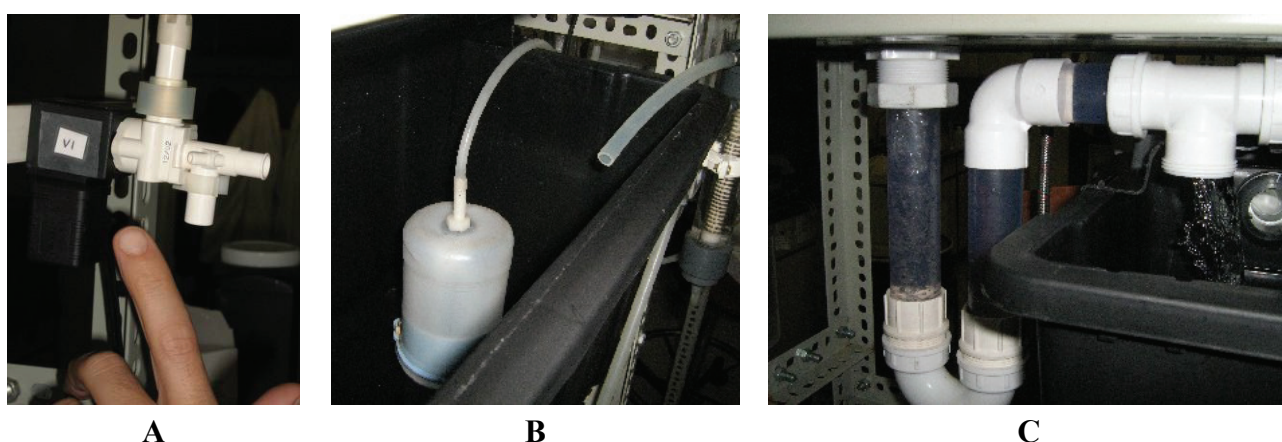


Fig. 4.5. Tank flushing mechanism: A. solenoid valve V1. B. Air bell of a U-bend flush. C. U-bend flush in action.

4.2.4 Conclusions

The batch dosing system presented above uses minimal electrical power and was constructed from commonly available materials, thus fulfilling the aims of minimising construction and running costs. The novel components of the system are: the U-bend flush control mechanism; the brine supply system; and the concept of continuous small batch supply for flow-through hypochlorite dosing and electrolyser flushing. The system therefore required a thorough testing period in the laboratory to determine the reliability of its components and its ability to provide a reliable hypochlorite dose to water (see below 4.3).

4.3 OPERATION OF THE BATCH DOSING SYSTEM IN THE LABORATORY

4.3.1 Control of water

In order to test the reliability of the system's water control, it was connected to the mains water in the laboratory via the top tank's float valve. Simulation of water use from a storage tank was achieved by placing a tap on the outlet of the bottom tank (tank 3) and setting it to slowly drain. This way the system could be left running over night in the laboratory and stopped and started by

opening and closing the tap. The system was left “on” in this manner for more than 6 months, proving that it could control water reliably on demand.

4.3.2 Electrical current readings

Current readings came as spikes corresponding to the presence of brine in the electrolyser and consequent electrolysis. On receiving brine the electrolyser’s current quickly spiked to a mean reading of ~0.5-0.6 A. Following the flushing of the electrolyser with water after 8 min, the current sharply dropped to an average resting state of 0.005-0.01 A, reflecting the poor conductivity of water.

4.3.3 Chlorine dosing

The chlorine (FAC) concentration of the dosed water was measured from samples taken from the dosing tank (tank 2). Because the water already had a chlorine residual of 0.1 mg/L from the tap, its demand was very low. Each dose of chlorine gave an immediate reading of between ~3.5-4.0 mg/L upon mixing with the 30 L batch of water. Therefore, given that tap water has a very low chlorine demand, the concentration of the chlorine from the electrolyser was calculated to be ~7.0-8.0 g/L.

Different dosing concentrations of chlorine could be achieved by changing the setting of the timer. For example, using a 5 min time setting in place of 8 min, the electrolyser produced chlorine at ~2.0-4.0 g/L giving a ~1.0-2.0 mg/L after dosing to the 30 L batch of water. This however, was wasteful regarding salt efficiency, i.e. unconverted brine was wasted. Therefore, to improve salt efficiency for low chlorine dosing concentrations, the volume of brine entering the electrolyser was reduced and electrolysis time maintained at 8 min. This was achieved by slightly raising tube 4 (Fig. 4.1) so that it delivered less brine to the electrolyser.

4.3.4 Electrical energy consumption

The two components in the system that consumed the most energy were the electrolyser and the solenoid valves. With a constant demand for water and constant water availability, the system consumed ~50 Wh of energy over 24 h (Table 4.1). Therefore, a 20 W solar panel producing 120 Wh /6 h could easily power the entire system run at maximum demand.

Table 4.1 Electrical energy consumption of the batch dosing system (dosing at ~4 mg/l, run continuously)					
Component	Time ON	Current (A)	Volts (V)	Power (W)	Energy (Wh)
Electrolyser	8 min	0.5	4	2	0.267
Solenoid valve V1	5 sec	0.42	24	10	0.014
Solenoid valve V2	5 sec	0.42	24	10	0.014
Total energy/batch (1× batch = 30 L of water)					0.291
Total energy/h (7.5× batches = 225 L of water)					2.183
Total energy/day (180× batches = 5400 L of water)					52.38

4.3.5 Inputs and outputs

Continuous operation of the system at a ~4 mg/L chlorine dose on an eight minute batch cycle with a maximum rate of water use (e.g. with the outlet tap left open), had the following inputs and outputs (Table 4.2).

Table 4.2 Inputs and outputs of the batch dosing system					
Inputs					
	8 min	1 h	24 h	1 week	1 month
Brine (L)	0.02	0.11	2.70	18.90	75.60
Salt (g)	0.38	2.81	67.44	472.08	1,888.32
Electrical energy (Wh)	0.3	2.3	54	378	1,512
Outputs					
	8 min	1 h	24 h	1 week	1 month
Water (L)	30	225	5,400	37,800	151,200
Anolyte (L)	0.02	0.11	2.70	18.90	75.60
Chlorine (g)	0.15	0.79	16.53	115.80	463.05

4.3.6 Conclusions

The disinfection system reliably responded to demand and availability of water, and provided a reliable hypochlorite dose that was both reproducible and adjustable. Importantly, the electrolyser had maintained its ability to produce hypochlorite consistently over the test period indicating that the anodic material was stable under the conditions of batch dosing. The tests were however conducted with mains water and therefore the real test of the electrolyser's reliability would be its operation at a rural water source of predictably poorer quality.

4.4 CONSIDERATIONS FOR RURAL USE: SCOPE AND LIMITATIONS

The main aim behind the design of the disinfection system was to achieve automation on a small affordable scale for both the brine supply to the electrolyser and control of chlorine dosing to water. The scope and limitations of the final design are discussed below regarding both its mechanical operation and potential for community management:

4.4.1 Water pressure limitations

The system operates at “open pressure”, i.e. where chlorine is dosed to an open head of water at atmospheric pressure. While this facilitated designing water-powered mechanisms, it also removes the potential energy (in the form of pressure) from the water that could be needed for post chlorination supply purposes. Therefore a trade off between the cost of electrical equipment (which could be used for dosing into a pressurised water pipe) and water pressure was made. The net result was an affordable disinfection system that supplies water to a storage tank at ground level and atmospheric pressure.

The obvious limitation caused by the pressure loss is that the water level in the storage tank at ground level must be higher than the level of the taps it supplies. Therefore, the installation site of the disinfection system should either be on ground located higher than that of the taps it supplies, or, where this cannot be achieved (e.g. on flat ground), a raised horizontal-style storage tank could be used at a position between the level of the dosing tank and the taps. Alternatively, on flat ground, the disinfection system and supply tank could be artificially raised (using blocks, low wooden platforms or a mound of earth) to achieve the necessary elevation above the taps.

The operation of the disinfection system also requires sufficient water pressure to reach the inlet pipe of the batch dosing system (at a height of 1.90 m above floor level). How this is achieved at a rural site will depend on the nature of the water supply and its abstraction method, i.e. either by gravity from water sources at higher levels, or by externally supplied energy (e.g. pumping mechanisms).

4.4.2 Chlorination level and dosing rate

The dosing of freshly produced hypochlorous acid with no storage period is a unique feature of the system. This has advantages over stored hypochlorite (section 4.1.2), but also has a limiting effect on the dosing rate of the system. This is because the electrolysis period required for chlorine production determines the rate at which water can be dosed, i.e. a higher chlorine dose will require more electrolysis time and a longer retention time for each batch of water through the system. If a very high chlorine dose (e.g. $> 7 \text{ mg/L Cl}_2$) is required at a site, this could be achieved by an increase in voltage and a higher concentration of brine; both adjustments would serve to maintain a reasonable dosing rate but at a loss of salt and current efficiency.

4.4.3 Potential for community operation

The disinfection system is automated in chlorine production and dosing, but still requires diligent maintenance and an effective emergency protocol in the event that it breaks down or ceases to function properly. The ability of the community to manage these aspects of the disinfection system's operation is vital (see below).

4.4.3.1 Maintenance

An operator is required to prepare brine and top up the brine supply tank. The task can be standardised (e.g. using a bucket of water and a measuring cup of salt) and placed in a general weekly checklist for the system's operation, which would also include checking the current reading of the electrolyser and cathode de-scaling if necessary (i.e. cathode cleaning in vinegar to remove scale). A detailed user's manual with operation, maintenance and emergency protocol guidelines would be needed, including contact numbers for further advice and help. The means of purchasing salt would need to be determined by the community. Determination of changes in chlorine demand of the water and dosing adjustment is potentially a task manageable by the community, but it would require training and a chlorine measurement kit (these tasks are therefore perhaps best suited to a local water authority). The local authority might also need to facilitate the purchase of spare and

replacement parts for the disinfection system. Finally a log book for recording system operation and purchasing would also be advisable.

4.4.3.2 Emergency protocol

An effective protocol for responding to system malfunction is vital. System malfunction could expose the community to waterborne disease, and therefore should be dealt with in a swift and efficient manner. The first step in the procedure would be to close both the inlet and outlet taps of the disinfection system. The user's manual would then assist in problem identification and response. A local authority (e.g. a plumber with knowledge of the system) might need to facilitate fixing the problem but it would also be of benefit if the community owned an appropriate tool kit and set of spare parts for fixing basic problems.

4.5 CONCLUSIONS TO THE CHAPTER

The development and operation of the disinfection system in the laboratory had proved successful regarding the aims of its design and function. The operational characteristics of the disinfection system are as follows:

- The disinfection system operates automatically in response to water demand (i.e. consumption) and water availability.
- The disinfection system has water-powered components and is designed for chlorine dosing to water at atmospheric pressure.
- The chlorine dose constitutes freshly produced hypochlorous acid of negligible chlorate content.
- Chlorine dosing can be controlled at three levels: (i) adjustment of electrolysis time (ii) adjustment of brine supply volume and (iii) adjustment of current supply.
- Both the brine supply to the electrolyser and chlorine dose to the water are powered by water moving through the system.
- Timing of brine electrolysis and water flushing control are powered electrically by components that use $\sim 1/10^{\text{th}}$ of the power required by the electrolyser. This reduces the solar panel requirements that otherwise would considerably raise the capital cost if electric pumps were to be included.
- A 10-20 W solar panel system is sufficient to supply the entire system's electrical energy requirements.
- Community maintenance and emergency response protocols are required.

CHAPTER V

OPERATION OF THE DISINFECTION SYSTEM AT A RURAL SITE (A PILOT STUDY)

Project aim (iii):

- To establish and operate the disinfection system at a rural water site following the necessary laboratory testing, authorization from the relevant water authority, and the rural community's consent.

This chapter of the report presents the pilot study of the disinfection system in operation at a rural site in the Western Cape. An overview of the project site and test period is given below as a quick reference (Table 5.1).

Table 5.1 Overview of project site & project period	
Rural site	
Location:	Worcester, Western Cape
Location's name:	Oude Wagon Drift farm
Location's type:	Fruit and dairy farm
Community occupation:	Farm workers
Community size:	18 households (~110 people)
Pre-existing water supply	
Reticulation:	Household taps
Storage:	3×2,000 L raised storage tanks
Supply to tanks:	Farm irrigation pipeline (at 3-bar pressure)
Pre-treatment:	Pressurized disc filtration
Water origin:	Breede River
Water catchment area:	Breede River Valley
Local water authority:	WEWUSA
Project period	
Initiation:	January 2008
Installation period:	4 months
Test period:	13 months (May 2008-June 2009)
Total running period estimated:	7 months
Longest uninterrupted running period:	2 months (July-August 2008)
Stoppage time:	6 months

5.1 SITE SELECTION

To reduce travelling costs and to facilitate regular visits by the project team to project site, it was decided that a site in the Western Cape close to the University of the Western Cape (UWC) must be found. However, the Western Cape, particularly within a day's drive from Cape Town, has relatively few communities dependent on untreated water. This problem was eventually solved by

contacting the Worcester East Water Users Association (WEWUSA) manager, Mr Frikkie Joubert. Prior to the selection of the chosen site, potential sites in the Eastern Cape had been investigated (Appendix 3).

The WEWUSA pump water from the Breede River for farm irrigation and this water is also used by the communities of farm workers for all domestic purposes including drinking. With the help of Mr Joubert a farm was selected on which a community of approximately 20 families lives. To reach the farm (a fruit and livestock enterprise owned by the Naude family, headed by Mr Willie Naude) one travels 6 km from Worcester (two hours' drive from Cape Town) on the N15 (R60) to Robertson turning left at Over Hex crossing for a further 3 km (Fig. 5.1). This farm was therefore chosen as the site for the project as it satisfied the requirements for testing the disinfection system in a rural situation.

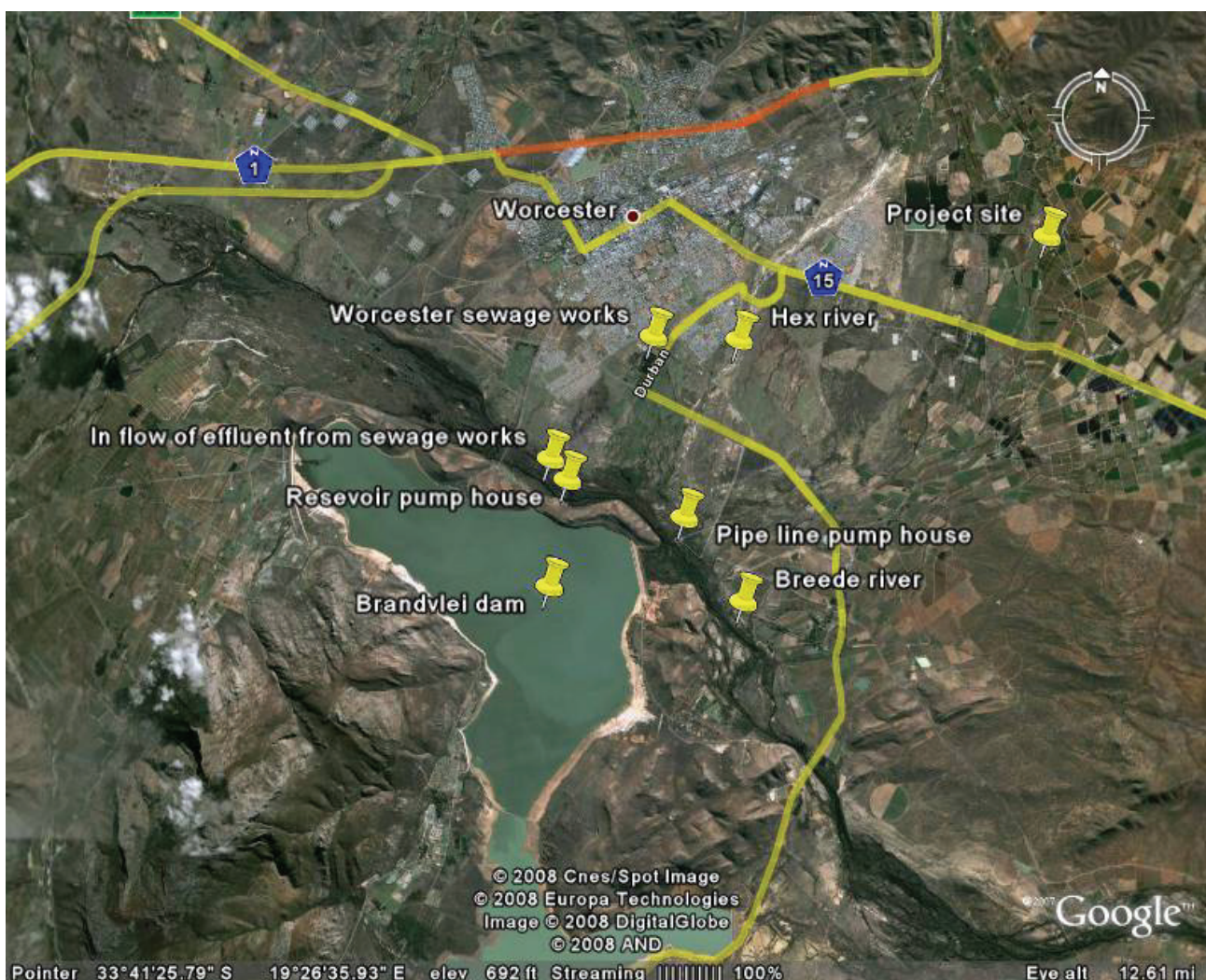


Fig. 5.1 Satellite image (~20.3 km altitude) showing the WEWUSA water supply system and project site.

5.1.1 The existing water source

The water source at Oude Wagon Drift farm supplies a farm worker community of ~100 people. The water is pumped directly from the Breede River and on the farm it passes through a series of

high pressure ~200 micron disc filters (Fig. 5.2). This supplies 3×2,000 L tanks that are elevated above the community houses. The tanks are fed at ~3 bar pressure and each supplies six households (Fig. 5.3) with water for domestic use.



Fig. 5.2 Existing disc filtration system on the farm.



Fig. 5.3 Community households on the farm.

The water is pumped from the Breede River at a site 2 km downstream from an inlet of the Brandvlei dam (Fig. 5.1). The inlet is 2.2 km downstream from a seepage area that receives treated effluent from the Worcester sewage works. Although there was continuous monitoring of the water quality in the river by the Winelands District Municipality, the Worcester East Water Users Association (WEWUSA) had obvious concerns as to the quality of water being supplied to the farm workers. The water is pumped from the river and supplies many farms in that part of the Breede River valley. The pump house is about 15 km from Oude Wagon Drift farm.

During the winter rains and in spring time, there was adequate water in the Breede River to allow pumping for irrigation, however, in summer and early autumn water was added to the river from the Brandvlei dam (Fig.5.1). In those periods the water was much darker in appearance due to suspended solids and it also has an unpleasant odour. This was due to the presence of disturbed sediments from the dam. Clearly there was a need for filtration and disinfection for the water supply to be used as drinking water.

5.2 INSTALLATION OF THE DISINFECTION SYSTEM

For the purpose of the pilot study the disinfection system was intended to operate adjacently to the community's existing water supply. The water from the disinfection system was not intended as a substitute for their existing water but once established and proven reliable and safe it could offer a source of chlorinated drinking water on the site.

5.2.1 The Installation site

The project was allocated a site next to an existing water tank positioned on top of a 3 m hill 45 m away from the community housing (Fig 5.4 A and B).

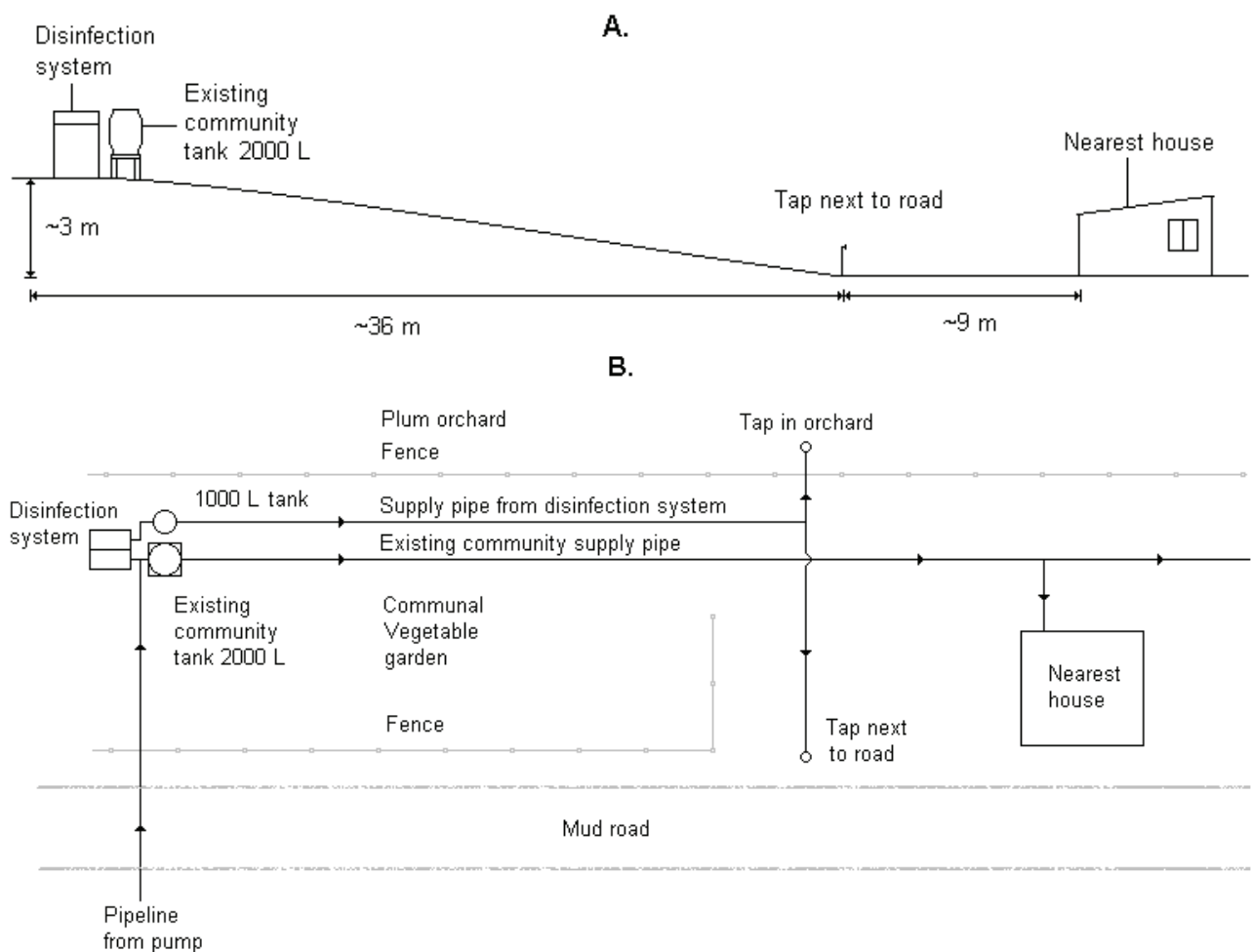


Fig. 5.4 Schematic plan views of site. A. Eye level view. B. Overhead view showing existing pipelines and those of the disinfection system with two taps.

5.2.2 Housing

Construction of the disinfection system began with the installation of a wooden shed with a 4 m² floor space, 2 m wall-height, and corrugated metal roof (Fig. 5.5A, overleaf). The shed provided sufficient floor space and height to house the batch dosing system, sand filter (Fig. 5.6A, overleaf) and a security cage for the electrical equipment. The sloping roof of the shed faced due north at an angle of 30°, appropriate for positioning solar panels (Fig. 5.5A).

5.2.3 Water supply and chlorine contact time (CCT) system

The existing water supply was connected to the disinfection system via a T junction on the inlet pipe of the community water tank (Fig. 5.7, overleaf). This arrangement allowed the inlet pipe to supply both the existing water tank and the disinfection system simultaneously leaving the existing supply to the households unaffected.

The output pipe from the disinfection system was joined to 60 m of 4 cm diameter pipe with a total volume of ~75 L that was coiled around a 1,000 L plastic “JoJo” tank positioned outside the shed behind the community tank (Fig. 5.5A and B). The coil provided a 20 minute chlorine contact time (CCT) for each batch of water before it reaches the storage tank. The necessary volume and length of the pipe coil were calculated as follows:

- Flow rate of chlorinated water from dosing tank = 30 L/8 min batch (or 3.75 L/min)
- Pipe volume required for a 20 min retention time = $3.75 \times 20 = 75$ L
- Volume of 1 m of a 4 cm diameter pipe ($\pi \times r^2 \times 100/1000$) = 1.257 L
- Therefore, pipe length containing 75 L = $75 \text{ L} / 1.257 \text{ L} = \sim 60$ m

The outlet of the tank was joined to a 2 cm diameter pipe which led down the hill toward the housing and split 36 m from the shed to feed two taps: one positioned by the orchard (for use by the fruit pickers in autumn) and one next to the road ~10 m from nearest house (Fig. 5.4). The taps remained locked during the initial testing period of the disinfection system.

5.2.4 Batch dosing system and brine supply

The batch dosing system was set up as shown Fig 5.6B and Fig. 5.7. The brine supply tank was filled with a 25 g/L table salt solution mixed onsite in a 30 L bucket using a 750 g measuring cup. The brine tank is a 40 L semi transparent plastic tank to allow observation of the brine level inside (Fig. 5.6B).



A



B

Fig. 5.5 Outside the shed. A: Housing of the disinfection system and existing community water tank. B: Chlorine contact time coil (75 L) and the chlorinated water storage tank (1000 L).



A



B

Fig. 5.6 Inside the shed. A: Sand filter. B: Dosing system (left: showing tanks 1 and 2) and brine supply and electrolyser (right).

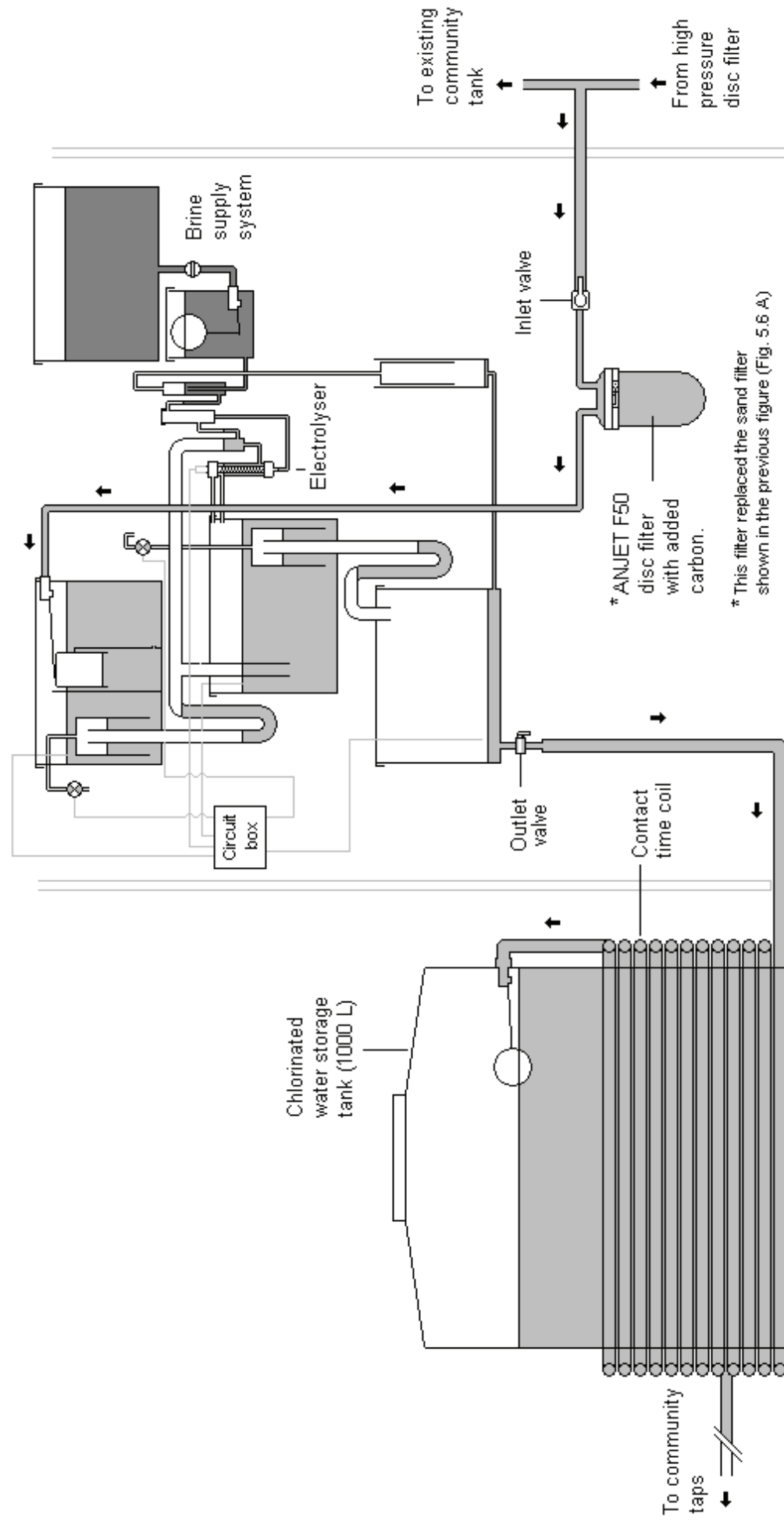


Fig. 5.7 Schematic layout of the disinfection system

5.2.5 Power supply

Three 55 W solar panels were fixed to the roof of the shed to power the disinfection system and the remote monitoring equipment. The panels were linked to a regulator (load max. 10 A) and a 12 V deep cycle battery, which fed a 300 W inverter with a 220 V AC output. The battery, regulator and inverter were housed inside a lockable security cage inside the shed.

5.2.6 Electrical equipment and remote monitoring

The electrical equipment housed in the shed, in addition to the power supply, included the circuit box, SSE® remote monitoring box (for current monitoring of the electrolyser), and a 3-6 V AC to DC adjustable power supply for the electrolyser (Fig. 5.8).

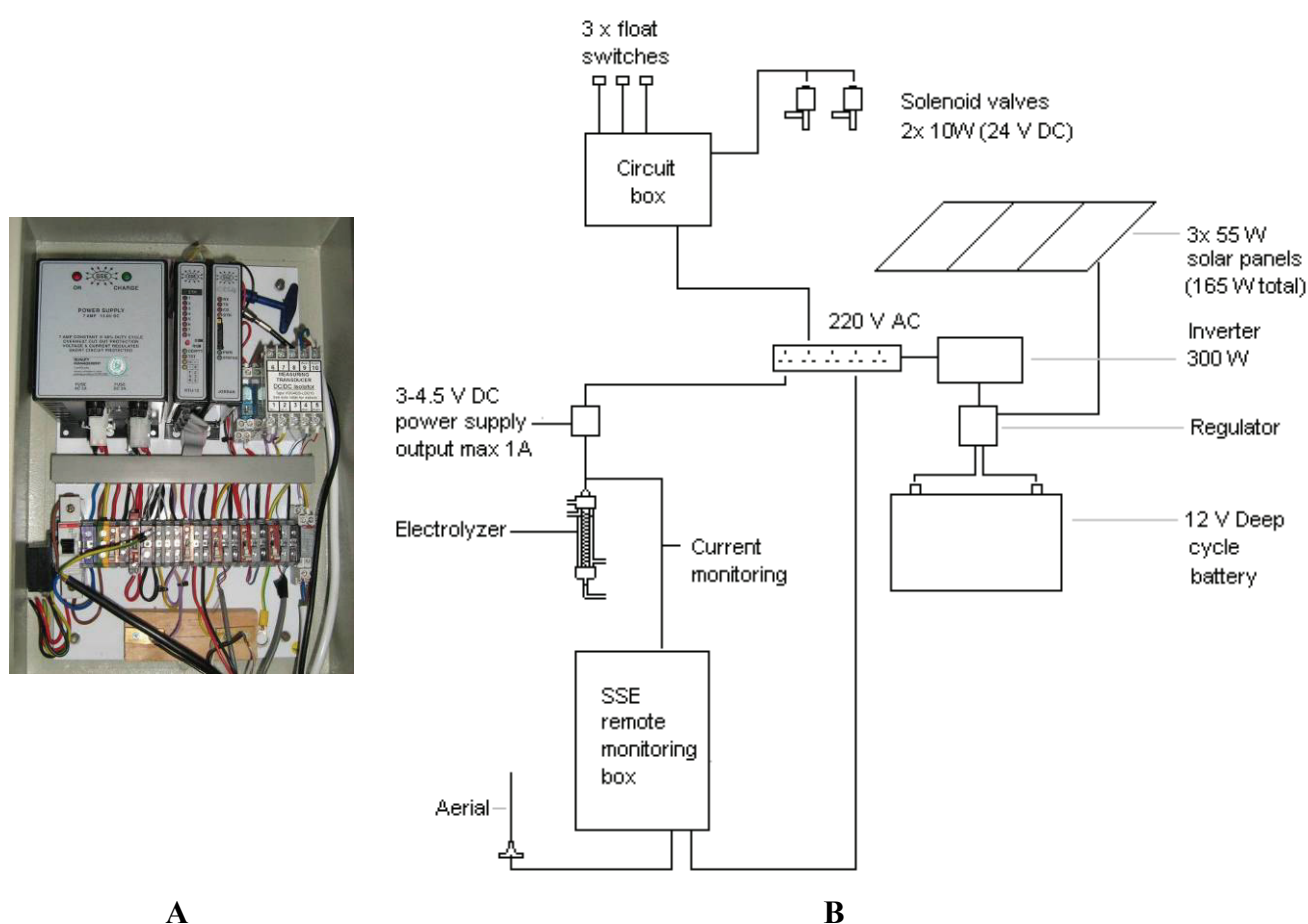


Fig. 5.8. Electrical equipment. A: SSE® remote monitoring box. B: Schematic of components

5.3 CONSIDERATION OF THE EXISTING WATER QUALITY

At the beginning of May 2008 the water from the irrigation pipeline had low turbidity of less than ~5 FNU, and was low pH (pH 6-6.5), which was a promising prospect for both chlorination and brine electrolysis. WEWUSA also kindly provided a printout of water analysis conducted at the irrigation pump station inlet the on the Breede River. The data covered the months of February and March that same year (Table 5.2).

Table 5.2 Water quality supplied to the farmland irrigation system.		
Sampling location: Breede River, Worcester East pump station. Sampling date: February to March 2008. (Data supplied by WEWUSA)		
	6, 19 th February and 19 th March 2008	SANS 241 drinking water: plant operational limit
Microbiological (CFU/100 mL)		
<i>Escherichia coli</i>	19, 3, 4	0
Faecal coliform bacteria	23, 14, 4	—
Total coliforms	300	—
Faecal streptococci	18	—
Physical and organoleptic		
Conductivity at 25°C(Ms/m)	6.3, 7.6, 7	< 150
Total dissolved solids (mg/L)	50	< 1000
pH at 25°C (pH units)	6.81, 6.56, 6.69	< 5.0-9.5
Turbidity (NTU)	20.3	< 1
Chemical (mg/L)		
Ammonia as N	< 0.15, 0.46, 0.17	< 1
Calcium as Ca	2, 2.5, 2.4	< 150
Chloride as Cl	14.6, 49.2, 12.4	< 200
Fluoride as F	< 0.10, < 0.10, < 0.10	< 1
Magnesium as Mg	2.4, 2.2, 1.3	< 70
Nitrate and nitrite as N	< 0.2, 0.27, 0.2	< 10
Potassium as K	1.2	< 50
Sodium as Na	7.3, 8.3	< 200
Sulphate as SO ₄	5.0, < 4.0, 4	< 400
Zinc as Zn	< 0.012	< 5
Chemical micro-determinants (µg/L)		
Aluminium as Al	850, 220, 880	< 300
Antimony as Sb	< 10.0	< 10
Arsenic as As	< 10.0	< 10
Cadmium Cd	< 1.0	< 5
Total Chromium as Cr	20.0	< 100
Cobalt Co	< 7.0	< 500
Copper Cu	< 22.0	< 1000
Cyanide (recoverable) as Cn	< 50	50
Iron as Fe	840, 300, 400	< 200
Lead as Pb	< 20.0	< 20
Manganese as Mn	< 40.0	< 100
Mercury as Hg	< 10.0	< 1
Nickel as Ni	< 8.0	< 150
Selenium as Se	< 10.0	< 20
Vanadium as V	< 50.0	< 200
Chemical organic-determinants (mg/L)		
Dissolved organic carbon as C	1.6	<10
Additional samples (mg/L)		
Chemical oxygen demand	< 8.0, 32.9, 12.0	—
Ortho phosphorus as phosphorus P	0.6, 0.3, 1.0	—
Organochlorides	non detectable	—
Organophosphates	non detectable	—
Boron as B	< 0.10	—
Soap, oil and grease	< 1.0	—
Total suspended solids	23	—
Grey highlighted = exceeds the SANS 241 drinking water limit for plant operation		

The turbidity of the water at the site, < 5 FNU (on May 2008), was considerably less than that of the water described in Table 5.2, 20.3 NTU (or FNU), that had been tested two months earlier. This suggested that either the water quality in the river had dramatically improved over two months and/or that the high pressure sand filters in the irrigation system network and the pre-existing disc filters on the farm had collectively removed at least 90% of the turbidity.

5.4 ESTABLISHING THE DISINFECTION SYSTEM AND REMOTE MONITORING

5.4.1 Determination of chlorine demand and filling the storage tank

The chlorine demand of the water needed to be determined before the system could be operated. This was done by letting water into the system and allowing the electrolyser to run and dose the water on a 4 V, eight-min batch cycle (as established in Chapter 4). The chlorine (FAC) concentration of the water was measured immediately after the dose and then again after a 30 min standing period to determine the chlorine demand.

Using a 2.0-2.5 mg/L dose, the chlorine demand was found to be ~0.5-1.0 mg/L after 30 min to obtain a residual of 1.0-1.5 mg/L. The water was ~pH 5.5-6 (acidic) and ~4.5 FNU (low turbidity). To achieve the above dose, the electrolyser's brine supply needed adjusting to deliver ~10 mL of brine at 25 g/L.

After establishing the chlorine dose requirement, the disinfection system was allowed to fill up the 1,000 L storage tank. Owing to the position of the storage tank and the inclusion of the float valve, the maximum water volume in the tank was only 850 L. The filling of the tank from empty took ~5 hrs. Once full, the chlorine residual in the tank water was measured and found to be ~0.1 mg/L. The loss of residual in the tank probably did not result from malfunction of the electrolyser, owing to the maintenance of stable current readings (~0.3-0.45 A) throughout the procedure. The loss probably reflects the demand of the tank itself and the dilution effect of mixing incoming water with standing water over the 5 h period. Regardless of the cause it was reasoned that this problem could be overcome by increasing the chlorine dose accordingly.

5.4.2 Maintaining an acceptable chlorine residual in the storage tank

This procedure was more difficult than expected. The initial goal was to ensure that a residual between 0.2 and 0.5 mg/L could be maintained at the tap. However, this would be highly dependent on the level of consumption at the tap. For example, a starting residual of 0.2 mg/L in the tank was completely depleted at both the tap and the tank after 48 h of no water consumption. Considering that as an optional water source the consumption levels could be highly variable from day to day and thus input of volumes of chlorinated water to the tank would vary accordingly, this was a difficult problem to solve. It was therefore decided that the tank should receive much higher doses of chlorine to ensure the water leaving the system was disinfected prior to its dilution in the larger volume of the tank. Therefore, unless consumption was very high, an overdose of chlorine in the tank was not possible. At the time of this decision the chlorine dose was increased to ~4.5 mg/L to ensure its disinfection prior to dilution. This corresponded to a 15 mL brine dose to the electrolyser

ran at 4 V for 15 min. The outcome of this method was that an increase in consumption would be accompanied by an increase in chlorine residual.

5.4.3 Current monitoring

Having established the disinfection system with a dosing regime, a system for managing remote monitoring was developed. In order to simulate water use, an arrangement with a community member was made to run water from the road tap on a daily basis during the farm's lunch period. The water was fed via a pipe into the vegetable garden (Fig. 5.7 B) and the tap was closed when the community member heard the flushing of the dosing system inside the shed. This allowed the response of the disinfection system to water demand to be monitored remotely from the UWC laboratory, by recording the electrolyser's activity as a current reading. Table 5.3 shows the current readings obtained for a two-week operation of this procedure.

Table 5.3 Current monitoring over a two week test period														
Day	1	2	3		4	5		6	7	8	9	10	11	12
Current peak	0.48	0.51	0.55	0.46	-	0.58	0.6	0.55	-	-	0.61	0.52	0.58	-
Current resting	0.03	0.01	0.02	0.02	0.01	0.01	0.02	0.01	0.0	0.01	0.01	0.03	0.0	0.0
Days 3 and 5 the system flushed two batches (i.e. 60 L).														
Days 4, 7, 8 and 12 the operator was unavailable.														

Table 5.3 above shows that the system reliably responded to the level drop of water in the storage tank. Current peaks caused by electrolyser activity corresponded to times of water consumption and maintained a reliable level over the two-week period. The resting current corresponding to the presence of water in the electrolyser remained low in periods no activity. The project team concluded that the system had worked successfully and its activity could be monitored remotely.

5.5 CONSIDERATION OF THE COMMUNITY

Community participation and acceptance of the project was essential for it to commence. In order to learn about the community and understand their feelings toward their existing water supply and their feelings toward the project, a baseline household survey was designed to gather the following information:

- Average household population and age distribution of the community.
- Nature of the existing household water supply system and the community's feelings toward it.
- Recent health history (incidence of diarrhoea).
- Community knowledge and understanding of water chlorination.
- Community feelings towards the project and willingness to participate and use the chlorinated water from the disinfection system.

5.5.1 Approach

Three project team members visited each of the 18 households as a group and interviewed (in Afrikaans) one willing adult participant from each household using the baseline survey questionnaire (see Appendix 4) and explained the purpose and intentions of the project. The survey was conducted on Saturday 12.07.2008 between 12:00 and 14:00. This date and time was determined as most suitable, since most community members would be present (the survey coincided with a televised Springbok Rugby match). The survey included the presentation of a glass of water from the disinfection system, and a demonstration by the project team that the chlorinated water was safe to drink.

5.5.2 Summary of findings from questionnaire

- *Average household population:*

Three adults

Three children

Total community population = ~110 people.

- *Average household access to water:*

Four taps

One toilet

One shower

One kitchen sink

One bathroom sink.

- *Pre-existing water source:*

Three overhead asbestos (2000 L) tanks shared between the 18 households, six households per tank on average.

- *Feelings towards the pre-existing water quantity and quality:*

Quantity:

All interviewed were happy with the quantity.

Quality:

Observations of abnormality were described by 3 households. These participants mentioned that in summer and autumn the water appearance was brown or murky; tastes muddy even brackish; and has a slight musty smell. In winter, the water was reported as being clear and colourless but with frequent mud specks; tastes sweet; and has no smell. The participants were concerned about the summer quality of the water and mentioned that they boiled their water during this period.

- *Recent health history (incidence of diarrhoea):*

Two households reported single incidences of diarrhoea (one adult woman and one 5 year old boy) both within the last two years, but did not suspect the water and attributed the cause to something they may have eaten.

- *Knowledge of water chlorination:*

More than 50% of the participants were not aware that municipal water contains chlorine and smells slightly of “Jik”. The role of chlorination in water disinfection was also largely unknown by the participants.

- *Willingness to drink the chlorinated water:*

All participants were prepared to taste the chlorinated water and most could detect the smell of “Jik” when asked. Some participants detected that the water had a different taste. One participant mentioned that the addition of chlorine to the water seemed strange owing to their familiarity with bleach (Jik®) as a cleaning product.

- *Willingness to use the communal chlorinated water tap:*

The majority of participants said they would be prepared to try using the water from the roadside tap. Some participants mentioned that the tap was too far from their houses, but might try it if they were thirsty walking by.

- *Opinion of the disinfection system project:*

No participants raised objections to the project, and all those interviewed understood that the disinfection system represented an optional source of drinking water. Some considered the project interesting but were not sure whether it was a necessity. In general more concern was expressed about the muddy state of the water in summer and one participant asked if the project would fix the problem.

5.5.3 Discussion and major conclusions from the baseline survey

Information gathered from the baseline survey and site assessment resulted in the following major conclusions concerning the project’s commencement:

- *The disinfection system should supply an optional drinking water source:*

Owing to the well established household plumbing (toilets, taps, sinks, etc.) at the site, the water consumption rate by the community (estimated at a minimum of 10 kL/day), would exceed that of the disinfection system’s output, which as a prototype was established to provide a maximum of ~5 kL/day. Therefore, it was concluded that for the scope of this project, the disinfection system would best serve as an optional source of chlorinated water that could be used for drinking, food preparation and limited bathroom use (e.g. brushing teeth).

- *The water at the site requires both chlorination and pre-treatment:*

The mention of changes in the existing water quality (discoloration, smell, taste, etc.) during summer indicates that water disinfection is required at the site and that ideally the entire water supply to the households should be chlorinated and undergo a more efficient pretreatment stage. The appropriate level and method of pre-treatment would be determined during the course of the project. Case history of diarrhoea was minimal suggesting that even if there was microbial contamination of the water it had not seriously affected the community. However, the continual expansion of Worcester's lower income housing settlements upstream of the WEWUSA pump station may cause the water quality to deteriorate in the near future.

- *Boiling of drinking water reveals community concern*

The fact that the community boils their drinking water in summer demonstrates awareness of the threat of potential illness from water.

- *A community operator for the disinfection system was available and willing to participate:*

During the installation of the disinfection system various members of the community had voluntarily helped in its construction and testing during the lunch periods on the farm. One member of the community showed particular interest and participated in the remote monitoring of current experiments (section 5.4.3 and 5.6). During this period, this member became the elected community operator for the disinfection system and gained a good understanding of how it worked and needed to be maintained. The location of the system (being on a daily used route (near the road) and within 100 m of the elected operator's house) also made it readily accessible to the operator.

- *Households furthest from the tap might not use the roadside tap:*

The distance of the roadside tap from the furthest houses in the community was more than 100 m. Such households were unlikely to readily carry water over this distance given that they already have taps in their houses. Therefore, if the disinfection system was to prove successful more taps and increased pipeline length might be required to make the water more accessible.

- *Community response permitted commencement of the project:*

No objections towards the disinfection system were raised by the interviewed participants, and all interviewed proved willing to drink the chlorinated water. Therefore, it was concluded that the system could be made accessible for use by the community.

5.6 CONTINUOUS OPERATION OF THE DISINFECTION SYSTEM

Having established the disinfection system and potential support of the community to use the water, the disinfection system could be left to run at the site under the supervision of the community operator. During a continuous, uninterrupted, two-month period from the start of July to the end of

August 2008, the disinfection system was monitored remotely and checked on weekly visits by the project team.

The following parameters were monitored:

- Electrolyser current (daily remote monitoring from UWC).
- Water use (via indication of electrolyser current activity).
- Chlorine (FAC) concentration, turbidity and pH (during weekly visits).

On each weekly visit an additional test batch was run, and chlorine concentration, turbidity and pH were measured directly from the freshly dosed batch in the dosing tank. Chlorine concentration was also measured in the storage tank and at the road side tap on each weekly visit (results are presented in section 5.6.2 below).

5.6.1 Role of the community operator

During the two month period the community operator was accessible by cell phone communication and had access to the disinfection system for checking the brine supply. The operator was also given instructions for how to shut down the disinfection system if a problem was detected via remote monitoring at UWC. This was achievable by the operator simply closing the inlet tap to the disinfection system (Fig. 5.7).

5.6.2 Results of continuous operation

The results obtained from both remote monitoring of current (RM current readings from batches) and weekly visits to the site are presented in Table 5.4. The batch number represents the number of times the electrolyser was activated by community use of the tap, and indicates the point at which more than 30 L had been drawn from the storage tank.

Table 5.4 Results of continuous operation				
	July 2008			
	Total amount of water drawn from tank ~60 L (or 2 batches)			
	Week 1	Week 2	Week 3	Week 4
No. of batches	1	1	0	0
<u>RM Current reading</u>				
Batch 1	0.48 A	0.51 A		
<u>Weekly visit</u>				
Chlorine residual in tank	0.1 mg/L	0.0 mg/L	0.0 mg/L	0.0 mg/L
Chlorine residual at the road tap	0.1 mg/L	0.0 mg/L	0.0 mg/L	0.0 mg/L
Chlorine conc. test of dose	4.6 mg/L	3.8 mg/L	4.2 mg/L	4.3 mg/L
Turbidity	3.5 FNU	5.6 FNU	4.9 FNU	5.2 FNU
pH	6.3	6.7	6.3	6.1

Table 5.4 Results of continuous operation (continued)				
	August 2008			
	Total amount of water drawn from tank ~90 L (or 3 batches)			
	Week 3	Week 4	Week 3	Week 4
No. of batches	1	0	1	1
<u>RM Current reading</u>				
Batch 1	0.54 A		0.51 A	0.56 A
<u>Weekly visit</u>		No visit		No visit
Chlorine residual in tank	0.0 mg/L		0.0 mg/L	
Chlorine residual at the road tap	0.0 mg/L		0.0 mg/L	
Chlorine conc. test of dose	4.7 mg/L		4.9 mg/L	
Turbidity	4.7 FNU		4.9 FNU	
pH	6.5		6.1	

Total amount drawn from July and August > 150 L

5.6.3 Discussion and conclusions from the continuous running period

- *The disinfection system proved reliable:*

The results from the continuous running period (Table 5.4) show that the system operated in a reliable manner owing to consistent current yields from the electrolyser and consistent chlorine doses at the dosing tank. During this period the inlet water had minimal fluctuation in turbidity and pH.

- *Limited use of water and loss of chlorine residual in the storage tank:*

The total use of water over the two month period amounted to less than one batch (30 L) per week, or 150 L in total over two months. Consequently, the corresponding rate of incoming chlorinated water to the storage tank was insufficient to maintain a desired chlorine residual of 0.1-0.5 mg/L of water. The water entering the storage tank did however receive sufficient chlorine contact time (20 minutes at ~4-5 mg/L) for disinfection to occur prior to its dilution in the 1000 L tank (see section 5.4 concerning chlorine demand).

- *Probable factors behind the limited use of the water:*

Two factors probably account for the limited use of the water by the community. Firstly, the water supply to the household taps during the test period (i.e. winter) was of low turbidity and perceivably good quality. Secondly, the distance and inconvenience of having to collect water from the roadside tap was likely weighed against the first factor by the community.

- *More taps could help maintain a higher chlorine residual in the storage tank:*

Given that prolonged standing time of water in the storage tank reduced its chlorine residual, easier access to the water (which might result in higher consumption) could increase the chlorine residual in the storage tank. Therefore, installation of taps in the yards of the community households could provide a future answer to this problem (see section 5.8.2).

5.7 PROBLEMS ARISING FROM INCREASED TURBIDITY

Fluctuations in the turbidity of the water supply began in September 2008. The water became increasingly more turbid through spring, and by late summer (February to the end of April 2009) it had risen to 120 FNU. Communication with WEWUSA revealed that the phenomenon was caused by the release of water from the Brandvlei Dam into the Breede River, which is done to increase the water level in the river to maintain pumping of irrigation water to the farm network.

5.7.1 Adjustments to the filtration system

The sand filter (Fig. 5.6 A) installed in the shed failed to remove the increased turbidity of the water. There was also concern that the intermittent nature of the water flow (i.e. as 30 L batches) through the filter disturbed its optimal function. Furthermore, the filter proved difficult to clean because of insufficient backpressure for backwashing the sand (thorough washing of the sand by hand would have proved extremely inconvenient on a regular basis). Therefore, the sand filter was replaced by an easily cleanable disc filter (the ANJET F50) with a 115 micron filtration pore size (Fig. 5.9 and Fig. 5.7). The filter canister provided a convenient housing to include granular carbon in the form of graphite or charcoal chips for removing odours and unwanted chemical contaminants in the water. The filter could be easily dismantled *in-situ* via a spring clip mechanism and the discs loosened for cleaning.



Fig. 5.9 The ANJET F50 disc filter that replaced the sand filter.

Fig. 5.9 shows the disassembled filter in two parts: the left hand side part contains the disc stack which fits into the casing on its right hand side. Water enters the casing from the right hand side pipe and then passes through the channels in the disc to leave via the left hand side pipe.

5.7.2 Effects of turbidity increase on the operation of the disinfection system

While the disc filter had made filter cleaning easier it did not improve the removal of the turbidity from the water. Consequently, the high turbidity of the water made chlorination unsuitable due to following reasons:

- (i) The masking effect of high turbidity (i.e. > 10 FNU) on disinfection.
- (ii) The increased risk of toxic THM formation from the organic content of the turbidity.
- (iii) Turbidity at 120 FNU also directly affected the function of the electrolyser, causing current to drop by ~0.1 A through blockage of the ceramic membrane. The effect was detected via the remote monitoring system, and the disinfection system was subsequently shut down by the community operator following a phone call from the project team at UWC. The effect of high turbidity on the electrolyser was confirmed by tests conducted at the UWC laboratory (Chapter 3, section 3.5). The tests also found that membrane function could be restored by washing in clean water.

Owing to the above reasons, the disinfection system had to be shut down during the summer and autumn periods of high turbidity.

5.7.3 Impact of the summer and autumn shutdown of the disinfection system

The shutdown was particularly unfortunate because during this period the community was likely to drink more water due to the heat and be inconvenienced by having to boil their household water. Collection of water from the disinfection system would have offered an easier alternative. Furthermore, this period contains the autumn fruit harvest on the farm where an additional 100 part-time workers are employed: hence the inclusion of the orchard tap by the project team (Fig. 5.4 B). The community operator conveyed that the community had voiced their disappointment that the system had been shut down, and that he had explained to them that turbidity had caused the problem.

In conclusion, there was a clear need for a more effective form of pre-treatment at the site, which would permit chlorination and provide drinking water when it is most needed. This was beyond the means and scope of the pilot study but has been listed as a recommendation point for future action. This in itself represents a much needed future project, i.e. a small-scale water clarification system that could operate in line with the disinfection system for surface water treatment (see section 5.8.2).

5.8 FUTURE OF THE DISINFECTION SYSTEM AND THE PILOT SITE

Considering a successful operation period had been achieved, and that the site proved ideal (regarding its locality, potential for community involvement, and requirement for water treatment), both the site and the disinfection system had potential for further use and development. In particular, the following areas of development needed to be carried out to establish the viability of the disinfection system:

5.8.1 Facilitating future community management of the disinfection system

For the system's future viability it must be manageable purely by the community. Furthermore, the high cost of remote monitoring equipment was only appropriate for experimental work and tests. Therefore, the following adaptations were considered for future community management:

- Inclusion of a small voltage control box with current and voltage displays. This would allow the performance of the electrolyser to be viewed on site.
- A detailed user's manual for maintenance and emergency protocol should be compiled.
- Inclusion of an inexpensive chlorine measurement kit that could be used by the community or by an appropriate local authority.
- A contactable local authority that also has knowledge of the system in case the designated community operator is unavailable. WEWUSA are ideal candidates and have a constant presence in the farmland community.
- Ability to acquire spare parts and replacement components. At present this could be managed by project team members at UWC.
- A method and schedule for cleaning the cathode. The need for cleaning the cathode did not arise at the site during the pilot study but might in time, and certainly could at sites that have hard water.

5.8.2 Required modifications at the site

Upon the completion of this report the pilot site needed two urgent modifications for optimal use and operation of the disinfection system. These were:

- The installation of an appropriate pre-treatment method for removing turbidity to permit disinfection in summer and autumn.
- Extension of the existing chlorinated water pipe to reach the individual yards of the households. This would facilitate access to water and potentially increase the chlorine residual (i.e. by reducing the water's retention time in the tank).

On the submission date of the current report, both the above modifications were being investigated with the possibility of further project funding from various sources.

5.9 CONCLUSIONS TO THE PILOT STUDY

The project successfully completed the first of pilot study's three objectives:

- (i) To establish and operate the disinfection system at a rural water site following the necessary laboratory testing, authorization from the relevant water authority, and the rural community's consent.
- (ii) To determine the viability of the system and its acceptance among the rural community with regard to its operational performance and intended maintenance by the community.
- (iii) To hand over, on the successful outcome of the above, the technology to the community along with training regarding running instructions and maintenance.

However, insight was made to objective (ii) and to the potential viability of objective (iii):

- Considering objective (ii), the system proved mechanically viable under the test conditions and period of operation. A longer test period was needed (owing to the delays caused by turbidity) to fully establish the system's mechanical durability and longevity both in the hands of the project team and in the hands of the community. This would be possible if turbidity removal and an increase in community water use can be achieved at the site (section 5.8.2).
- Potential for the community's acceptance of the system can be gleaned from the baseline survey and from the interest and participation of the community operator. The community showed interest in the system and were aware that the water quality in summer posed a health threat and thus boiled their water. Consequently, disappointment was expressed at the summer shutdown of the system. Various adaptations (section 5.8.1) will be required to establish whether the system is viable for community management.
- Clearly objective (iii) requires the completion of objective (ii), both of which (on the basis of the successful mechanical operation of the system in the pilot study) should be further pursued.

CHAPTER VI

GENERAL CONCLUSIONS AND RECOMMENDATIONS

The main objectives of the project were addressed in three areas of research: (i) the development of the membrane electrolyser; (ii) the development of the disinfection system and; (iii) the operation of the system at a rural site. Collectively, the overall goal was to develop a viable small-scale water disinfection system for rural management, based on the operation of the membrane electrolyser. While the project did not meet the final objective of handing over the disinfection system to a rural community, it successfully developed a low-cost disinfection system that ran in a reliable manner over the test period at the rural site in Worcester (Western Cape).

6.1 Capacity and cost of the disinfection system:

The capacity and costs of the disinfection system are summarised in Table 6.1 below. The costs cited are those applicable to the prototype disinfection system and do not include the remote monitoring system or the various additional components that might be required at different sites (e.g. housing, storage tanks, pipeline supply, pre-treatment equipment, etc.).

Table 6.1 Capacity and operating characteristics of the disinfection system		
Membrane electrolyser	Chlorine production:	Maximum: ~20 g/day (24 h)
	Salt consumption:	Maximum: ~70 g/day
	Brine feed concentration:	25 g/L (table salt in water)
	Brine feed rate:	Adjustable 5-15 ml brine batch and adjustable retention time in the electrolyser
	Operating power:	Ave. ~2 W (using 4 V DC)
Disinfection system	Water chlorination capacity:	< 10 kL/day
	Batch disinfection rate:	30 L of water per 5-20 min cycle
	Chlorine dose range:	1-7 mg/L
	Population served:	100-200 people (no less than 25 L/person/day)
	Energy consumption per day:	Maximum: ~55 W.h (electrolyser + batch dosing)
	Maintenance:	< 30 min /week
Capital costs	Electrolyser:	~R 2 000
	10 W Solar power system:	~R 4 000
	Batch dosing system:	~R 3 000
	Total:	<u>~R 9 000</u>
Running costs	Salt (< 2 kg/month):	~R 15/month
	*Operator (2 h/month):	~R 100/month
	Total:	<u>~R 15-115/month</u>
	*Alternatively, maintenance could be managed for free within the community.	

6.2 Cost saving features of the disinfection system

The disinfection system has two main cost saving features that make it appropriate for small-scale applications:

(i) *Exclusion of electrical pumps:*

The project concluded that the high cost of electrical pumps and their additional solar panel requirements would raise the system's cost out of reach for small rural communities. Therefore, a system combining water power and low powered electrical controls was devised. The prototype electrical control system used in the batch dosing system had a capital cost of ~R1 500 and used ~5 W.h/day, which allows it to be maintained by the single 10 W solar panel system (~R4 000) that could also supply the electrolyser. In contrast, the use of one small peristaltic pump at ~R1 500 operating at 30 W would be able to run for only 10 min/day at the same energy expenditure as the batch dosing system (i.e. ~5 W.h/day), and still require additional controls for its coordination within the system thus requiring more solar panels at greater expense.

(ii) *Role of the membrane:*

The disinfection system was designed to produce and dose freshly made hypochlorous acid to water. In this mode of operation the membrane electrolyser produced chlorine at a fast and highly efficient rate. An equivalent sized electrolyser with the same operating conditions but lacking a membrane was constructed and tested and found to be ~2× less energy efficient and 2× slower at producing chlorine. Therefore, the inclusion of the membrane saves expense on solar panel requirements, i.e. reduces the capital cost of the system. However, the viability of the system does critically depend on the longevity of the membrane; therefore, sites that have hard water may not be suitable for the membrane electrolyser (see below: section 6.4).

6.3 Basic installation and operating requirements

Installation site requirements:

- Sufficient pipe pressure to supply the inlet pipe of the batch dosing system (at 1.9 m from floor level).
- Water quality of turbidity < 10 FNU.
- Ground level either level with, or higher than, that of the community taps (unless an additional form of pump is used to supply the taps or water is fetched by hand).
- Housing that is weather proof and securely lockable. A minimum 2 m ceiling height is also required and if solar panels are used a position receiving at least 6 h/day of full sun exposure is required.
- Water storage tank(s) (at least 1×1000 L), and reticulation (pipes and taps).

Operation requirements:

- A designated maintenance operator to carry out brine preparation, filling of the brine tank and daily system checking.
- Ability to respond to system failure, i.e. to turn the system off and either instigate a repair protocol or contact a relevant body to do so.
- Ability to purchase salt (the system requires a maximum of ~2 kg/month, see above: Table 6.1, “Running costs”).

6.4. Scope and limitations of the disinfection system

An open pressure system:

The scope of the disinfection system is limited by the fact that it is an open pressure system and therefore does not dose chlorine into a pressurised water pipe. It produces chlorinated water from its outlet at ~1 m above ground level. Therefore, as mentioned above (section 6.3) it must be located appropriately for it to supply taps. This may in certain circumstances create the need for a pump or make the system entirely inappropriate for a particular area’s needs.

Hard water:

It is highly likely that the membrane of the electrolyser will block if used in locations that have extremely hard water. The problems caused by lime scale depositing on the electrodes of brine electrolyzers are well known and the effects on the membrane would be predictably bad. In such areas, the membrane electrolyser could be substituted for an undivided electrolyser such as the one also investigated in this study (see below).

An undivided electrolyser option

An “undivided electrolyser” was constructed in a manner that excluded the membrane and retained the same anode and brine volume as the membrane electrolyser. The casing of the undivided electrolyser was its steel pipe cathode. When run under the same operating conditions as the membrane electrolyser, the undivided electrolyser produced 2.2× less chlorine, consumed 1.7× more energy and was 2.2× less salt efficient. However, the undivided electrolyser could be constructed at under R1 000 (i.e. at least half the price of the membrane electrolyser) and is both easier to service and usable at sites with hard water if a regular electrode cleaning protocol is established.

6.5 Conclusions from rural site operation:

- Despite the difficulties experienced with turbidity (section 5.7), the system reliably generated and dosed a reproducible quantity of chlorine in water during periods of acceptable turbidity of < 10 FNU.
- Community involvement in the project shows promise for establishing micromanagement of small-scale water treatment.

- The remote monitoring of current proved a reliable system recording electrolyser activity.

6.6 Overall project conclusions and recommendations:

The initial pilot-scale testing of the brine electrolyser and disinfection system developed in this study indicates that the overall system could be both cost effective and reliable. However, in view of the problems encountered from turbidity, the recommended future installation sites for the system are presented below:

Recommended water sources:

- Groundwater sources (boreholes and protected well points).
- Clarified surface waters (recommended partnership).
- Treated water requiring chlorine residual boosting.

Recommended future installation sites:

- Farms,
- Schools,
- Clinics and
- Villages.

Recommended operational procedure:

The above sites must be no further than 50 km distance of a trained technician with a full knowledge of the system. The technician should make monthly visits to the site and ideally be contactable for problem solving and site management. Therefore very remote rural areas are not suitable unless the above can be satisfied.

Future of the pilot plant in Worcester:

The project is indebted to the farm community for providing a venue for the pilot plant and giving their time and support. While the project was run under the clear auspices of a research programme, the pilot plant remains a functional entity that has shown all promise to be a reliable chlorination system of potential value to the community. However, since the existing system's function will be limited to winter periods of low turbidity, it will not address the community's most urgent need for clean water in summer. Therefore, the need for water clarification provides an excellent opportunity for projects in this field, and it is recommended (upon the community's consent) that the pilot plant remains as a venue for continued studies on small-scale micro-manageable water treatment.

Commercialisation

The results from the pilot plant suggest that both the electrolyser design and dosing system could be suitable candidates for commercialisation either separately or in a combined package. However, in

view of the factors that limited the test period in this report, it is recommended that an uninterrupted running time of at least 6 months is needed to fully confirm the consistency of the system and allow the identification of potential any future running problems (see below: Recommendations for Future Research).

6.7 Recommendations for future research

- The disinfection system should receive at least six months of further testing prior to commercialisation, either at the existing pilot plant (if clarification measures are installed) or at any of the above-mentioned recommended installation sites.
- Collaborative research with an equivalent low cost, low tech, rural water clarification project would form an ideal partnership, which would address the larger problem of small-scale surface water treatment. The clarification project could be installed with immediate effect at the existing pilot plant, which would also benefit the community.
- Continued running of the project at the existing site will allow further experience to be gained in community management issues, such as the drafting of running instructions, routines, maintenance and emergency procedures.

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APPENDIX 1: ANODE MANUFACTURE AND EVALUATION

(Research by Dr. R. D. Chebotareva and co-workers at the Dumanski institute, Ukraine)

METHODS OF MANUFACTURE

Titanium metal sheet (purity standard VT-1) was used as the bulk substrate material for the anode in view of its well known stability in terms of conductivity and corrosion resistance.

Degreasing – Degreasing was carried out first by dipping the metal in acetone followed by boiling in concentrated sodium carbonate solution (30 g/L) for 30 minutes.

Etching – In order to remove surface oxide and to roughen the surface, the titanium substrate was etched in sulphuric acid (850 g/L) at 80°C for 20 minutes, followed by washing with distilled water.

Platinisation – In some cases platinisation of the anode surface was used to prevent oxide accumulation at the interface between the titanium metal and the electrocatalytic coating. This was normally carried out electrolytically to produce a 0.5 micron thick layer of platinum metal (determined gravimetrically). The electrolytic solution comprised: H_2PtCl_6 (10 g/L); NaNO_2 (200 g/L); NH_3 (5%, 2 g/L). The titanium acted as the cathode with a platinum anode (3.8 cm² working surface area) at a current of 5 A/dm² operating at 60°C.

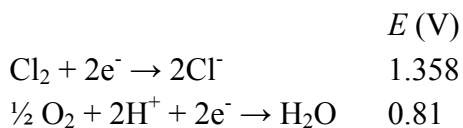
EVALUATION OF THREE ANODIC CATALYTIC COATINGS

The following experiments were carried out in a two-chambered cell with a dividing ceramic membrane for studying the effect of NaCl concentration on current density and current efficiency. The anodes had a working surface area of 0.5 cm² and the cathode was titanium metal. Determination of chlorine production was carried out by radiometric titration. Polarization curves were obtained on a P5829 potentiostat using: a silver/silver chlorine electrode; a 1 cm² platinum monitoring electrode; and the COTA, ROTA or DMTA as the working electrode.

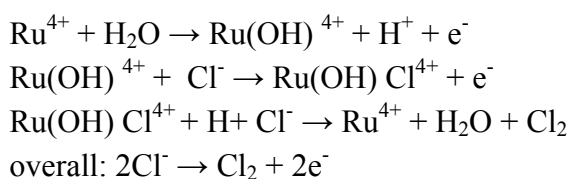
(i) Ruthenium oxide/titanium anodes (ROTA)

RuO_2 and TiO_2 are isomorphous with the rutile structure. Mixtures of the two-oxide system remain metallic conductors down to 30 mol % RuO_2 . This allows dilution of the expensive ruthenium compound. TiO_2 also enhances binding of the oxide layer to the titanium metal substrate (providing a platinised coating is not used). Coatings were applied by dip coating the anode substrate in dilute (1% with respect to ruthenium) butanolic solutions of RuCl_3 and TiCl_4 (in mol ratio of 30% Ru to 70% Ti) and pyrolysis in oxygen at 400°C. The process is repeated four times giving a mixed oxide layer 3-5 microns thick. Two different types of ROTA were evaluated, one with a sub-layer of platinum and one without.

General properties of ROTA – Although the equilibrium redox potential for oxygen release at pH 7 is greater for Cl₂ evolution than for O₂ evolution, the overpotential for O₂ evolution on RuO₂ is much greater than for Cl₂ evolution, causing Cl₂ to be evolved preferentially in aqueous solution.



Also in general, RuO₂ is highly corrosion resistant, and its electrocatalytic action is thought to occur through the following reaction sequence:

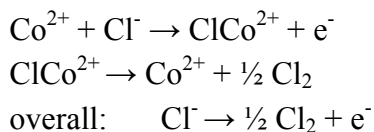


Results – The polarization curves in Figures A.1 (A) and (B) indicate the onset of chlorine evolution at about 1.40 V. Lower electrocatalytic activity is observed at lower NaCl concentrations on ROTA with a sub-layer of platinum than without the sub-layer. However, Figs. A.1 (C) and (D) show little difference in the current efficiency of chlorine evolution on the two electrodes. Current efficiencies of above 75% are obtained with current densities below 0.03 A/cm² with 15-50 g/L NaCl. The Tafel plots in Figs. A.1 (E) and (F) indicate greater deviation from a single mechanism of charge transfer for the non-platinum coated electrode. This can be explained in terms of greater oxidation of RuO₂ to RuO₄ without the protective Pt layer. As the Pourbaix diagram Fig. A.1 (G) indicates this will lead to more corrosion of the electrode coating. Therefore although corrosion occurs with both electrodes it is less for the platinised electrode and thus to be preferred in situations of prolonged polarization.

(ii) Cobalt oxide/ titanium anodes (COTA)

Co₃O₄ is an electrically conducting spinel-type oxide, which has high electrocatalytic activity for chlorine evolution. It has a much lower overpotential for chlorine evolution than does RuO₂. Coating of electrodes can be carried out by thermal decomposition of cobalt (II) nitrate or by electrodeposition of cobalt (II) hydroxide from cobalt (II) sulphate solutions followed by pyrolysis in oxygen. However, in this work the more reliable (in terms of constant composition) method of plasma spraying was used. Pure Co₃O₄ powder was vaporised in an A440 plasmatron at 900°C using tungsten electrodes (10-40 V with a current of 100-150 A). Co₃O₄ thermally dissociates to CoO, which is deposited on the titanium (or platinised titanium substrate to a thickness of about 40 microns). However, CoO is non-conducting. Activation of the electrode is carried out in a brine solution using the CoO coated electrode as an anode for 15 hours at a current density of 0.6 A/dm². The colour of the electrode changes from blue to black corresponding to a conversion of CoO to Co₃O₄.

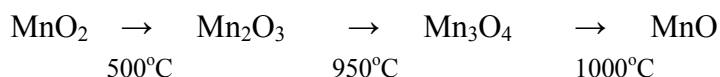
General properties of COTA – Electrocatalytic activity of these electrodes is thought to be via the following process:



Results – The polarization curves of COTA (prepared by plasma spraying of Co_3O_4 marked “pure”) in Figs. A.2 (A) and (B) (see below) indicate higher electrocatalytic activity on COTA, followed by activation with a Pt sub-layer and higher than ROTA. Current efficiencies for chlorine evolution are above 90% for current densities below 0.03 A/cm² for non-polarized COTA (Fig. A.2 (C) using 14-50 g/L NaCl. Current efficiencies are around 80% (see Fig. A.2 (D) for equivalent conditions with COTA on a Pt sub-layer. However, at higher current densities both have current efficiencies around 80%. Both these are better than on ROTA. The Tafel slopes (Figs. A.2 (E) and (F)) vary uniformly with changing electrolyte concentration indicating a single mechanism. Thus it may be concluded that the COTA layer did not undergo corrosion. From the Pourbaix diagram, corrosion is most likely to occur (see Fig. A.2 (G)) under conditions of low pH and positive potentials. Reversal of polarity is to be avoided as it will lead to the reformation of CoO which is non-conducting. Thus platinised COTA is the best option.

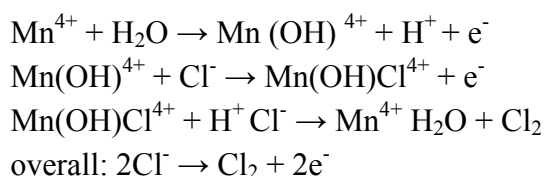
(iii) Dioxide of manganese/ titanium anodes (DMTA)

Electrocatalytic coatings of MnO_2 are attractive because they are cheap and easy to prepare. Although there are electrolytic and plasma deposition methods available, the simplest and most reliable method is via the thermal decomposition of manganese (II) nitrate. In this study, the $\text{Mn}(\text{NO}_3)_2$ solution was boiled to a density of 1.8 g/cm³ and then subjected to a heat treatment of between 180-370°C for one hour during which time a black deposit formed on the titanium substrate. After brushing with a soft brush, the process was repeated 4-5 times achieving a thickness of 100-200 microns of $\beta\text{-MnO}_2$. Higher temperatures lead to the following changes with a loss of electrochemical activity:



There is a slight increase in the current efficiency of electrodes prepared at 180°C as opposed to those at 250-370°C, thus electrodes prepared at that temperature were thoroughly investigated.

General properties of DMTA – $\beta\text{-MnO}_2$ is an n-type semiconductor hence an increase in charge carriers and conductivity occurs with loss of oxygen content. Prolonged polarization as an anode increases the degree of oxidation of manganese and hence conductivity decreases. The overpotential of chlorine evolution on DMTA is higher than that of ROTA or COTA and much closer to that of oxygen evolution. The electrocatalytic behaviour of DMTA is considered to occur via a similar mechanism to that on RuO_2 namely:



Results – The polarization curve (Fig. A.3 (A)) shows that electrochemical activity of DMTA is less than that of ROTA and COTA; also the onset of chlorine evolution is at a higher potential than that of ROTA and COTA. The current efficiency of chlorine evolution is at a maximum of 40% and clearly this is due to the co-evolution of oxygen (Fig. A.3 (B)). The Tafel plots (Fig. A.3 (C)) confirm this behaviour and also the dissolution of the MnO_2 over a range of pH and polarization potential. Thus in spite of their cheapness the use of DMTA in the electrolysis of aqueous sodium chloride is problematic especially due to the reaction $\text{MnO}_2 + 4\text{HCl} \rightarrow \text{MnCl}_2 + \text{Cl}_2 + 2\text{H}_2\text{O}$ at the anode.

CONCLUSIONS

It is clear that the electrocatalytic current efficiency and corrosion resistance for chlorine evolution in solutions of NaCl between 3-50 g/L is in the order: COTA>ROTA>DMTA. Although platinised COTA electrodes have slightly decreased current efficiencies for chlorine evolution compared with those with non-platinised they have increased corrosion resistance. Optimum current densities on COTA are in the range 0.01-0.05 A/cm². Hence, platinised COTA electrodes appear to be the optimum choice. However, their method of preparation requires further study as plasma deposition is not easily adapted for large-scale manufacture. Also platinisation is very costly thus an alternative method of preparing COTA was investigated.

ALTERNATIVE METHOD OF MANUFACTURE OF COTA

The titanium substance was firstly degreased and etched by the methods described earlier in this report. Coating with Co_3O_4 was carried out by electrolysis of CoSO_4 solution (20 g/L) at pH 5. The titanium substrate was initially held at a cathodic potential of -0.3 V, which was slowly increased (2-4 mV/sec) to 1.8 V. The final potential reached was maintained as an activation potential for 1-2 minutes. The electrode was then washed with water, air-dried then heated at 300°C in oxygen for one hour.

Results – Figs. 19, 20 and 21 are very comparable to those of platinised COTA (prepared by plasma deposition) in terms of polarization curves, current efficiency and Tafel plots (Figs. 8-13). Although the optimum current efficiency for 15-50 g/L is lower than for platinised COTA, a figure of around 75% is very acceptable. Preliminary studies of service life stability showed that at a current density of 0.1 A/cm² the voltage required remained stable for 12 months only deviating by 0.1 V.

Conclusion – The alternative cheaper method of COTA manufacture is satisfactory and could be carried out in South Africa.

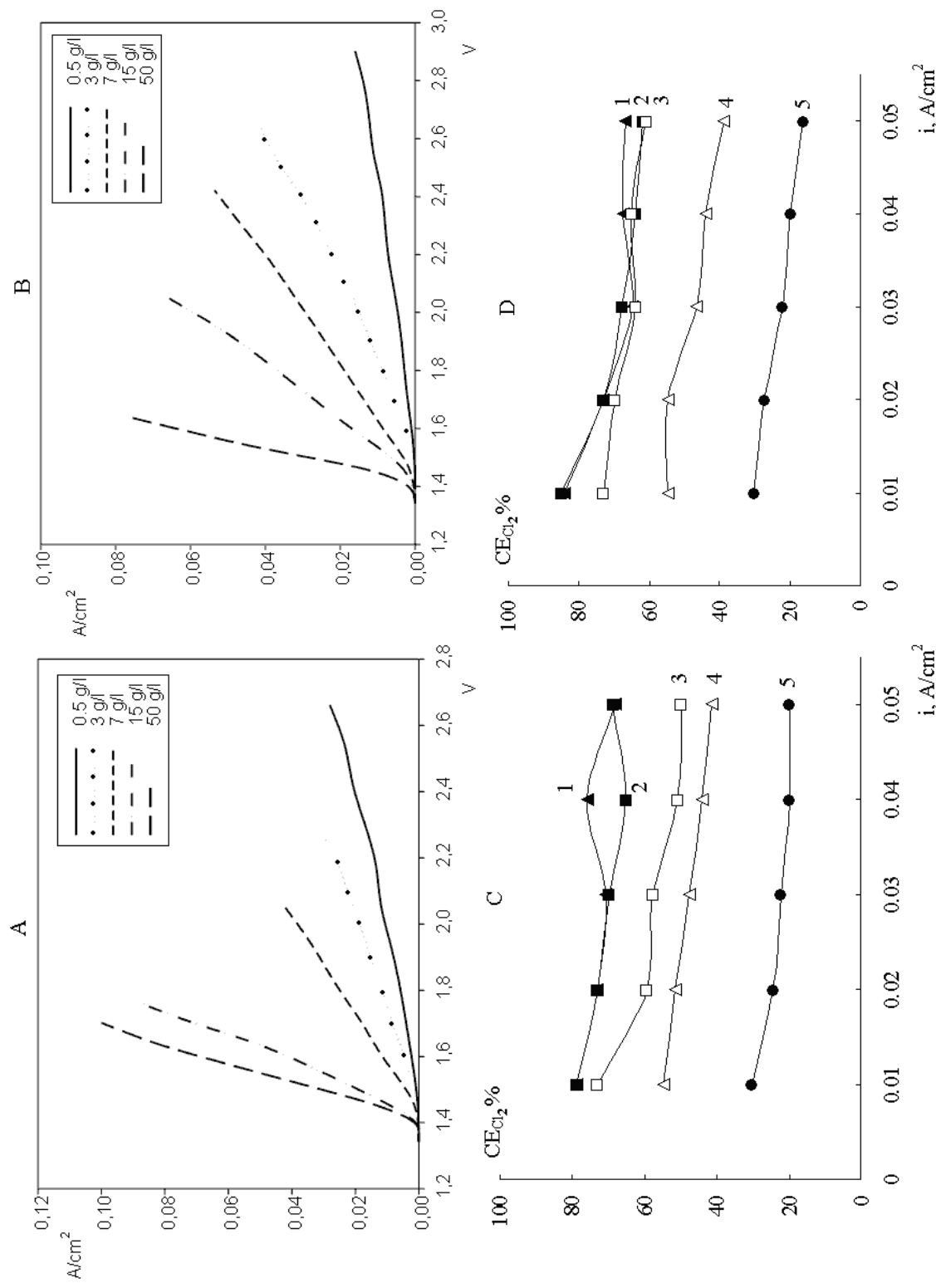


Fig. A.1 ROTa performance. (A): Anode polarization curves on ROTa in solutions of NaCl. (B): Anode polarization curves on ROTa with a Pt sublayer in solutions of NaCl. (C): Function of current efficiency of chlorine with current density on ROTa in solutions of NaCl with concentration (g/l): 1 – 50; 2 – 15; 3 – 7; 4 – 3; 5 – 0.5. (D): Function of current yield of chlorine on density of current on ROTa with a Pt sublayer in solution of NaCl of concentration (g/l): 1 – 50; 2 – 15; 3 – 7; 4 – 3; 5 – 0.5.

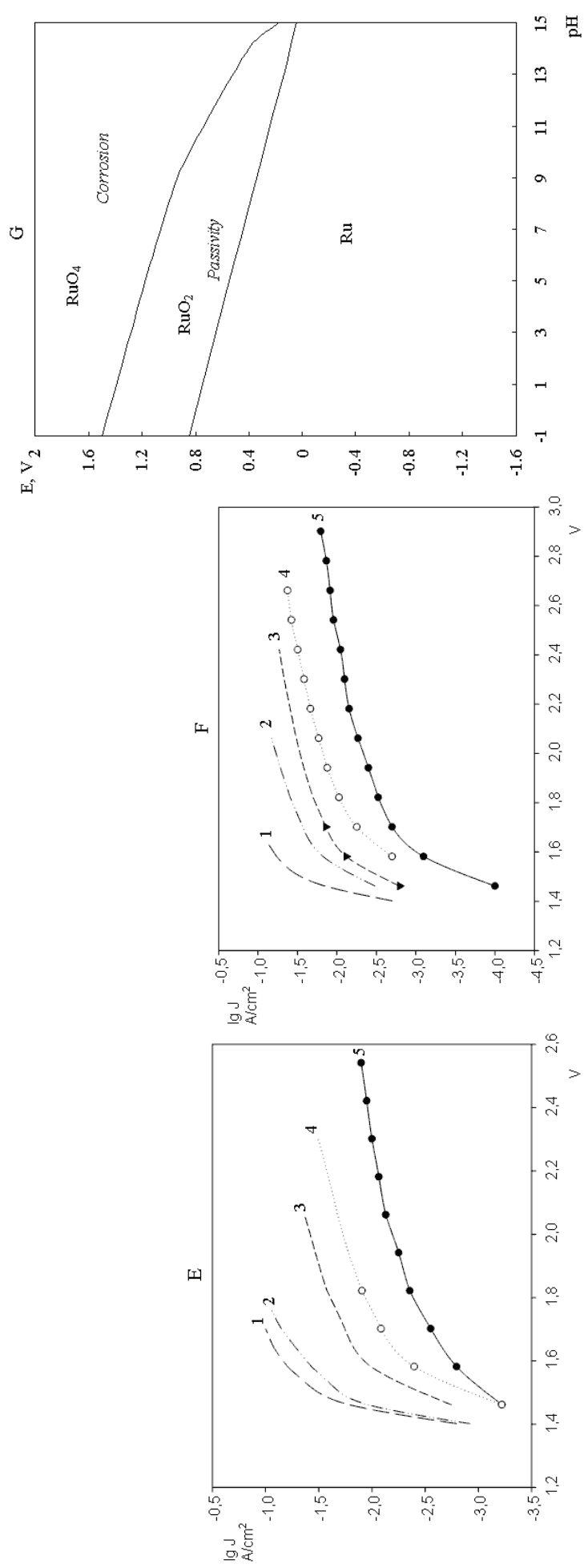


Fig. A.1 ROTA performance (continued). (E): Function of $\lg J - V$ for ROTA in solutions of NaCl (g/l): 1 – 50; 2 – 15; 3 – 7; 4 – 3; 5 – 0.5. (F): Function of $\lg J - V$ for ROTA with a Pt sublayer in solutions of NaCl (g/l): 1 – 50; 2 – 15; 3 – 7; 4 – 3; 5 – 0.5. (G): Areas of corrosion and passivity in the system of ruthenium-water in accordance with the Pourbaix diagram of above.

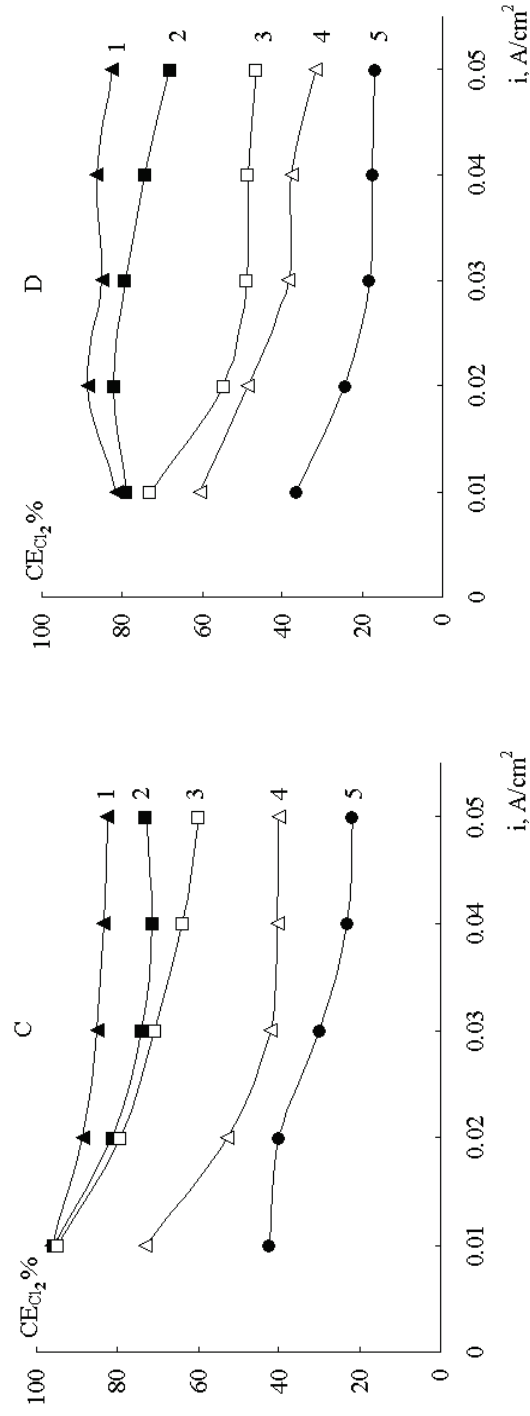


Fig. A.2 COTA performance. (A): Anode polarization curves on COTA in solutions of NaCl. (B): Anode polarization curves on COTA with a Pt sublayer in solutions of NaCl. (C): Function of current efficiency of chlorine with current density on COTA in solutions of NaCl (g/l): 1 – 50; 2 – 15; 3 – 7; 4 – 3; 5 – 0.5. (D): Function of current efficiency of chlorine with current density on COTA with a Pt sublayer in solutions of NaCl (g/l): 1 – 50; 2 – 15; 3 – 7; 4 – 3; 5 – 0.5. Continued on next page...

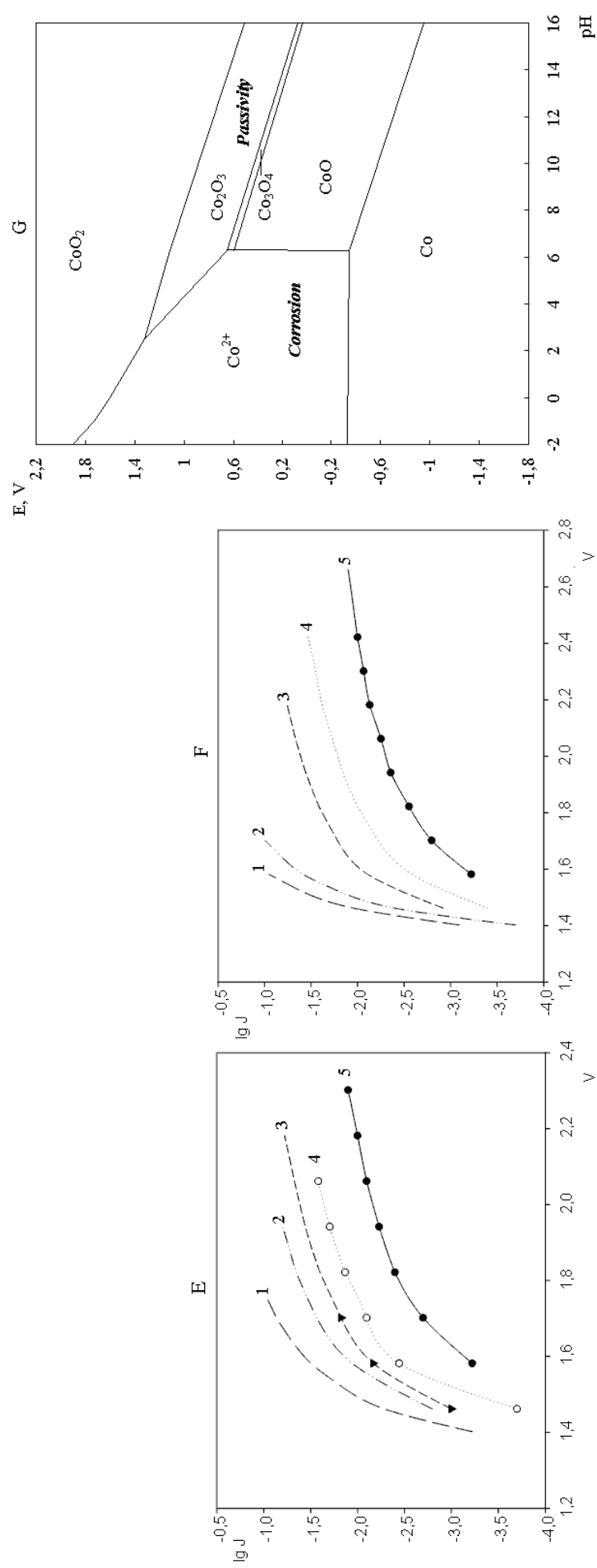


Fig. A.2 COTA performance (continued). (E): Function of $\lg J - V$ on COTA in solutions of NaCl (g/l): 1 – 50; 2 – 15; 3 – 7; 4 – 3; 5 – 0.5. (F): Function of $\lg J - V$ on COTA with a Pt sublayer in solutions of NaCl (g/l): 1 – 50; 2 – 15; 3 – 7; 4 – 3; 5 – 0.5. (G): Areas of corrosion and passivity in system of cobalt-water in accordance with the Pourbaix diagram above.

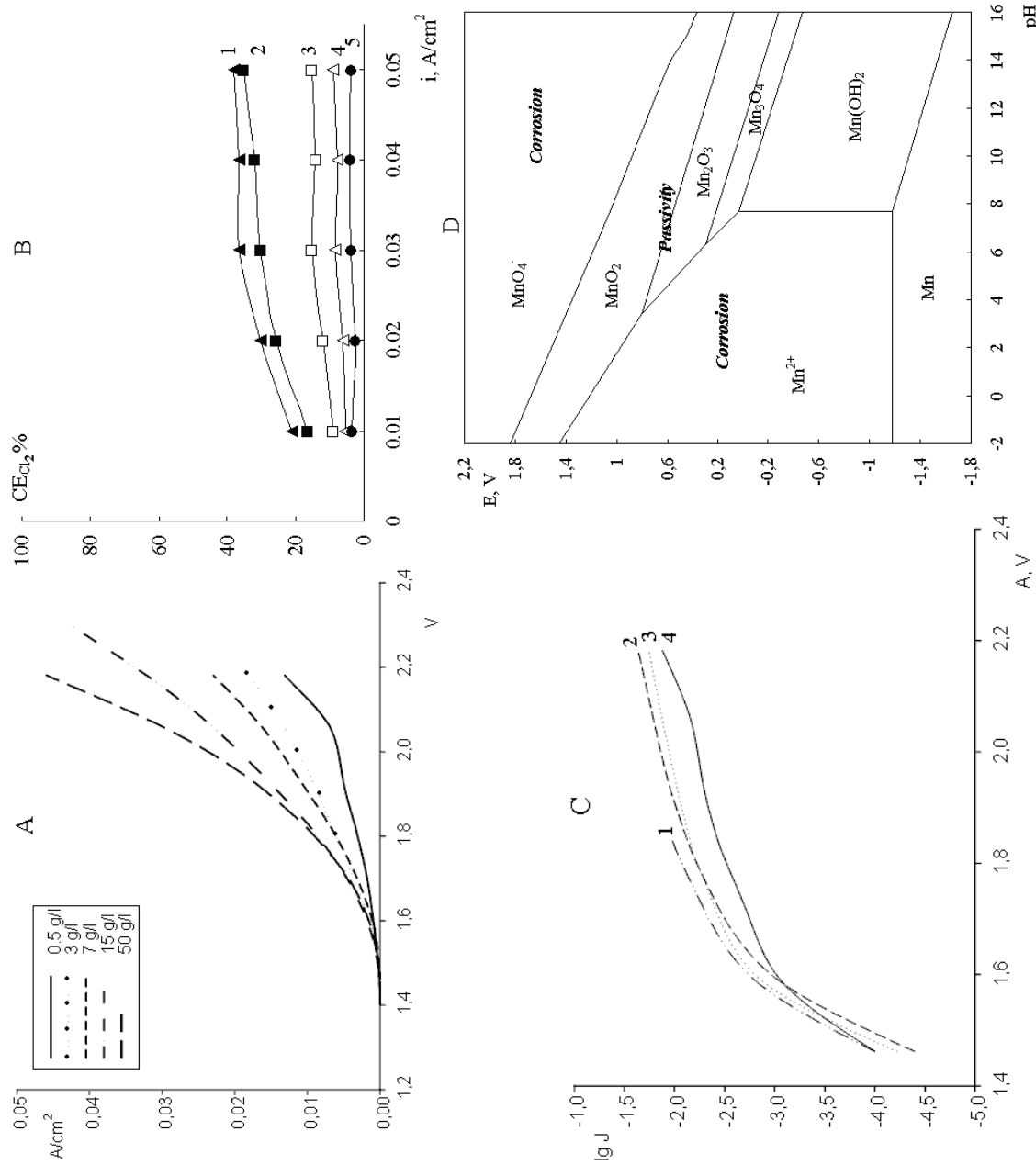


Fig. A.3 DMTA performance. (A): Anode polarization curves on DMTA in solutions of NaCl. (B): Function of current efficiency of chlorine with current density on DMTA in solutions of NaCl. (C): Function of $\lg J - E$ on DMTA in solutions of NaCl. (D): Areas of corrosion and passivity in the system of manganese-water in accordance with the Pourbaix diagram above.

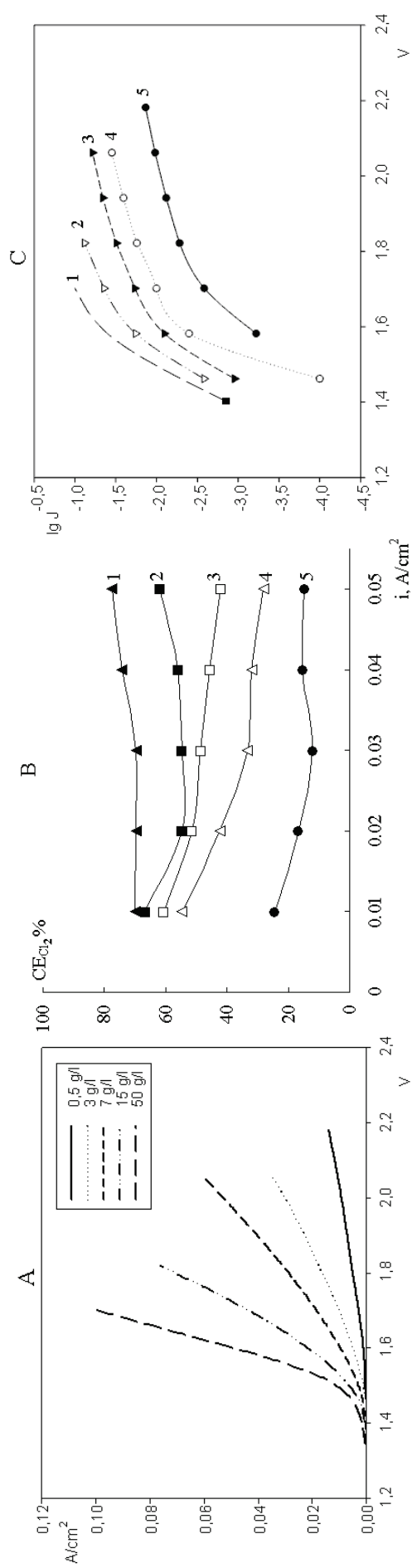


Fig. A.4 COTA performance (prepared by the electrolytic method). (A): Anode polarization curves on COTA in solutions of NaCl. (B): Function of current efficiency of chlorine with current density on COTA in solutions of NaCl (g/l): 1 – 50; 2 – 15; 3 – 7; 4 – 3; 5 – 0.5. (C): Function of $\lg J - E$ on COTA in solutions of NaCl (g/l): 1 – 50; 2 – 15; 3 – 7; 4 – 3; 5 – 0.5.

APPENDIX 2: ANALYTICAL METHODS USED IN THIS PROJECT

- In laboratory work, chlorine was measured using both iodimetric and DPD (N, N-Diethyl-p-Phenylenediamine) titration methods.
- In the field, chlorine was measured using a portable “Free and total chlorine and pH meter” MI411 (Martini® instruments) according to the manufacturers’ instructions.
- The measurement of pH in the field was carried out with the above device.
- Turbidity was measured in FNU using a portable “Turbidity meter” MI415 (Martini® instruments) according to the manufactures instructions.
- Chlorate was measured using a GBC UV/Vis 920 spectrophotometer set at 305 nm at the maximum absorption wavelength of ClO₂ (chlorine dioxide) in the UV/vis range (Chen 1967). The method involves the reduction of chlorate ions to chlorine dioxide by ferrous ammonium sulphate.

APPENDIX 3: OTHER RURAL SITES INVESTIGATED

RURAL SITE 1: GXWEDERA VILLAGE (EASTERN CAPE), MARCH 2005

Gxwadera village is approximately eight kilometres from Alice and is in Ward 4 of the Nkonkobe municipality. In March 2005 it comprised approximately 50 households, each home consisting of 5-8 persons including children. The population fluctuated between 250-400 depending upon social factors. The site was identified via contact with Professors N. Y. Osel Muyima and M. Momba from the departments of microbiology and biochemistry at the University of Fort Hare. Permission for its investigation was obtained from the local authorities and facilitated by Mr. Badi (Manager Community Services), Mr. Z. C. Xolani (Health Inspector) and Mr. N. Landu (Councillor for Ward 7). The following information concerning water use was kindly provided by the village chairperson.

The community used untreated water from a seasonal stream (flowing during the rains between October-April) and a large pond of approximately 1000 m² and about 1 m deep estimated at ~1000 m³ (examined at the end of March). During the rainy season, three other smaller ponds were also used by the village. In the remote parts of the village drinking water was collected and carried by buckets back to the households. The more central part of the village had community taps supplied by a reticulation system consisting of a petrol powered water pump that filled two raised storage tanks from the large pond. The ponds were also used for bathing, laundry, and as a water source for cattle and goats. It was also noticed that the large pond was situated well below the larger portion of households thus placing it at potential risk of faecal contamination from sewerage runoff from pit-latrines in the village. It was unclear whether this had had a direct health impact on the village yet it was noted that the village had recently been supplied with a water tank of delivered treated municipal water. The chosen site for the disinfection system in this village was to be next to the established storage tanks. These would have supplied a sufficient gravitational head of water to

operate the batch dosing system. However, during the course of this project the municipality announced plans that the village would soon receive its own pipeline supply of municipal water, which it now has in 2008. Therefore, the project focused on finding a new site for the disinfection system.

Conclusions – The investigation of Gxwedera village proved a useful exercise in establishing protocol for site visits and investigation. The site was a suitable choice for installing the disinfection system because the water source was at risk from potential faecal contamination and animal usage. Finally, the delivery of mains water to the village was a privilege that the many, more remote, villages are likely never to experience. Therefore, one such village formed the focus of the project's next investigation (see below).

RURAL SITE 2: GABELANA VILLAGE (EASTERN CAPE), MARCH 2006

A second site, Gabelana village in the Mtambalala district was selected with the help of the Mayor and Municipal Manager of Port St Johns. The water source was a perennial spring located 4.5 km from the R61 on T152, and 15 km from the town centre of Port St Johns. The site was chosen because it was in regular use by the local community and had easy access by road and close proximity (500 m) to the house of a Ward councillor who had agreed to guard the equipment if it was installed.

The spring emerged from a hillside depression 3 m below the level of the road. At its source, it formed a shallow (30 cm deep) puddle approximately 5 m², which flowed away as diffuse stream down the hillside at a slope angle of 1:6. The puddle was surrounded by boggy ground trampled by humans and animals leaving the water extremely muddy. Above the spring and the road there were no upstream communities living on the hillside, however the evident use of the spring by cattle did pose a risk of waterborne disease. An accurate determination of flow rate was not possible on the trip, but it was estimated from its usage capacity that with spring box protection it could provide ample water for the disinfection system to operate at a 1.5 L/min rate. The local method of water collection was by women with buckets, who were helped to transport the water to their houses by a daily pickup truck. The spring, among others on the pickup truck route, was thought to service at least 25 households or ~100 people. A site on firm ground 3 m below the spring source was identified for the disinfection system. Thus the hillside would provide sufficient gravitational head for its operation but placed the clean water storage tank considerably further downhill from the road. In this case, to lessen the water carrier's burden on the hill, a hand crank pump could be installed at the level of the road.

Conclusions – The site required considerable spring protection work and protection from cattle. Unfortunately, the cost of spring protection alone was quoted at more than R50 000 and thus beyond the means of this project. However, such sites may be considered in the future depending on the success of the project elsewhere.

APPENDIX 4: QUESTIONNAIRE

PART A (Baseline Household Survey)

1. Household Occupants

2. House Water Supply

3. Drinking water

Adults			Children			No. of	Priv	Share	No. houses sharing	Source	
Number			Number			Taps				Tap	
Age	m/f	Occupation	Age	m/f	Occupation	Sink				Boil	
						Toilet				Other	
						Shower				Comments:	
						Bath					
						Boiler					
						Comments:					
Total number:											

4. Knowledge of current water source

Where it is stored						
Where it comes from						
Water description key: Fine = F; Insufficient = I; Always = A; Often = O; Sometimes = S; Never = N; Very = V; Slightly = sl						
	Spring	Summer	Autumn	Winter	Randomly	All seasons
Quantity						
Clarity (describe) E.g. clear, murky, muddy, milky						
Colour (describe) E.g. none, yellow, orange, brown, grey						
Taste (describe) E.g. normal, sour, bitter, soapy, salty						
Smell (describe) E.g. none, chemical, biological						
Debris (describe) E.g. none, sand, leaves, etc.						

5. Health (history of diarrhoea/vomiting)

Adults				
Age	m/f	When (last 1-2 year period)	Duration	Suspected cause (water?)
Children				
Age	m/f	When (last 1-2 year period)	Duration	Suspected cause (water?)

6. Feelings toward current water supply.

Availability (Quantity):
Quality:
Water related facilities (taps, sinks, toilets, shower, etc.):
As drinking water:

7. Feelings toward the project and communal drinking tap

- Do you know that municipal treated water (e.g. mains water Worcester and Cape Town) is treated with chlorine?
- Do you know why?
- Did you know that municipal water contains a residual amount of chlorine that has a slight smell of JIK®?
- Do you know why?
- How do you feel about the project providing a communal tap for chlorinated drinking water?
- Would you be happy to drink this water?
- Are you happy with the amount of information you have received about the water project so far?

Date:

Interviewer: Miss A. Hess

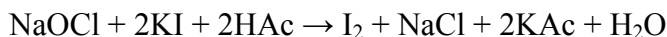
Number of household residents participating in questionnaire:

Notes: *Identity of household and interviewees will remain anonymous.*

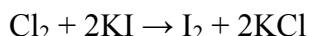
APPENDIX 5: HYPOCHLORITE AND CHLORINE

Relationship between the oxidation strength of chlorine and sodium hypochlorite

To calculate how much sodium hypochlorite (NaOCl) is required to replace the oxidising power of chlorine gas (Cl₂), the reaction of these species with potassium iodide (KI) in a solution of acetic acid (HAc) reveals the following:



And...



Therefore, one molecule of NaOCl will oxidise the same amount of iodide as one molecule of Cl₂.

Trade terms used to define hypochlorite strength

Grams per litre of available chlorine – This measurement must be determined using an analytical method (e.g. see Appendix 2) and represents the mass of Cl₂ of equivalent oxidising strength (see above).

Grams per litre of sodium hypochlorite – i.e. the mass of NaOCl in one litre. It is calculated from the measurement of available chlorine multiplied by the ratio of their respective molecular masses (NaOCl = 74 g and Cl₂ = 71 g). For example 1 g/L Cl₂ × 74/71 = 1.05 g/L NaOCl

Percentage of available chlorine – This is equal to the mass of available chlorine in 100 ml. For example 1 g/L Cl₂ = 0.1% Cl₂ and 0.105% NaOCl.

Weight percent of available chlorine – This is equal to the chlorine concentration (g/L) divided by the specific gravity (actual weight) of one litre multiplied by ten: Cl₂ g/L / (specific gravity × 10).

Weight percent of sodium hypochlorite – This is equal to the weight percentage of chlorine multiplied by 1.05.

(For additional information on hypochlorite handling see: <http://www.powellfab.com/>)

