THE DEVELOPMENT OF SMALL-SCALE ULTRAFILTRATION SYSTEMS FOR POTABLE WATER PRODUCTION

Report to the
WATER RESEARCH COMMISSION

by

V L Pillay and E P Jacobs
Durban Institute of Technology

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EXECUTIVE SUMMARY

INTRODUCTION

This report concerns the development of a small-scale potable water treatment system for rural and peri-urban areas. The major focus of the project was to develop a system that would be sustainable in these applications. In this report, a "small-scale" system is regarded as one serving a very narrow target user group that is geographically concentrated, e.g. a single town, a village, a farm, school, a clinic etc, and the upper production limit would be about 0.5 ML/day. A "sustainable" water treatment technology is regarded as one where the quality of the product consistently meets specified standards, the expertise required for operation and maintenance can be adequately met from locally available resources, and the operating costs can be adequately met from local revenue sources.

Membranes technology is rapidly gaining favour internationally for the production of high quality drinking water, without direct addition of chemicals. In terms of treating non-saline waters, the appropriate membrane processes are UF and MF. Contaminants that are removed by UF include colloids and suspended solids (100 % removal), bacteria and parasites (100 %), some viruses, high molecular mass dissolved organics, oxidized iron (98%), oxidized aluminium (90%) and oxidized manganese (60%). The water produced by UF is of a very high quality and usually exceeds the quality of water produced by conventional water treatment methods (i.e. coagulation and flocculation, clarification and sand filtration).

Internationally, there is a strong swing towards using UF and MF in drinking water production. The advantages include : - very good water quality without any chemical addition; the quality of the product is fixed by the membrane, and does not vary as the raw water quality varies; membrane systems are modular, and the capacity of treatment units can be increased easily; systems can easily be fully automated, avoiding problems due to operator error; the membrane acts as a positive barrier to pathogens (100 % removal of bacteria and parasites, 4 to 6 log removal of viruses)

Despite the international swing towards membrane technology, and its various advantages especially for "developing economies", membranes are not currently employed in drinking water production in SA. Possible reasons for this include :- the high cost of imported membrane systems – this includes the high cost associated with purchasing treatment units, as well as the high cost of obtaining spares for such units; the perceived lack of local membrane expertise in terms of design, construction, operations and troubleshooting; a reticence to use new technology unless it can be proven to be sustainable in the longer term.

The Institute of Polymer Science (IPS), University of Stellenbosch developed capillary ultrafiltration (CUF) membranes in the early 90's. In a project lasting four years, also sponsored by the Water Research Commission, it was shown that the local technology could consistently produce a high quality of potable water. This spurred the next stage of local membrane technology development – to exploit the local CUF membranes and develop complete systems for potable water production in rural and peri-urban areas.

The current project was initiated to exploit the membrane expertise and engineering expertise of the Institute of Polymer Science, University of Stellenbosch, and the Water Technology Group, M L Sultan Technikon. The ultimate aim in this project was to end up with a design for a *sustainable* membrane water treatment system

APPROACH AND ORGANISATION

Based on existing knowledge at the onset of the project, a field unit was constructed. Field trials were then commenced to increase technical knowledge of the process, as well as determine unit performance under various operating scenarios (technical evaluations). Simultaneously, information was gathered from various sources on what criteria would have to be fulfilled for a system to be sustainable. The various sources of information for sustainable water treatment systems in SA included farmers, water authorities, other membrane vendors, funding agencies, e.g. Development Bank, CMIP. Periodically, the information from the technical evaluations was combined with the information of sustainability needs. From this, proposals for the improvement of the unit design were developed. These were implemented either by modifying the existing unit, or by constructing a new unit.

The whole sequence of technical evaluations and information gathering on sustainability was repeated until it was finally felt that the unit design met the requirements for sustainability.

CRITERIA FOR A SUSTAINABLE SMALL WATER TREATMENT SYSTEM

Following various consultations with a wide spectrum of stakeholders, the following were identified as essential criteria for a sustainable small water treatment system.

(i) Water Quality Aspects - the quality of the final product must consistently meet drinking water quality standards, and should not change with raw water quality or operator skills levels.

(ii) Cost factors - Discussions with various stakeholders indicated that, in principle, it has been accepted that the user (community or municipality) may not be able to outlay the initial capital cost, and that there would have to be assistance with the initial capital from central government or development agencies. However, for sustainability, the user must be able to meet all operating costs.

(iii) Control strategy and Operator requirements - it would be preferable to automate the normal operation of the water treatment unit, and hence reduce dependency on operator skills. However it is not feasible, nor desirable, to completely do away with operator input. In terms of monitoring of the unit, as well as to ensure community “buy in”, it is important to define some role for an operator, taking into cognizance the available skills levels in rural and peri-urban areas.

(iv) Reliability and robustness - For a system to be sustainable, it must provide trouble-free operation in the long term. It is not possible to guarantee that a unit would be totally reliable, irrespective of the technology that goes into its development. The guarantee is only as good as the backup service available to correct problems when they develop. In terms of reliability and robustness, therefore, it is necessary to develop an appropriate design as well as provide a sustainable long term plan for maintenance, troubleshooting and repairs.

(v) Local Construction - The unit should be completely locally assembled, and should consist of components that are either locally produced, or alternatively are easily available locally.

(vi) Ongoing Technical Support - For long term sustainability, it is important that there is ongoing technical support to address any unexpected problems that may emerge in particular applications.

CONSIDERATIONS IN THE FINAL DESIGN

At the onset of the project, the approach adopted by the project team was to develop a design for a “high output” CUF unit. In a high output unit, the objective is to maximize the net permeate production. This is achieved by, *inter alia*, operating in the crossflow mode at a high flux. However, as the sustainability criteria were developed, it became apparent that a high output design would not be the preferred design from the point of view of sustainability. Possible problems with the high output design included :- possibly higher capital cost, since the high output design would require extra pumping capacity and automation; a greater sensitivity to feed quality; increased maintenance; frequent chemical cleaning; and higher operator input.

In view of all the above, and in consideration of the sustainability criteria, the design approach was changed during the course of the project. The team subsequently adopted a "median output" approach. The basic principles of this approach were :- operate in the dead-end mode; operate the membranes at a flux well below the maximum obtainable flux; minimize flux enhancement to backflushing only.

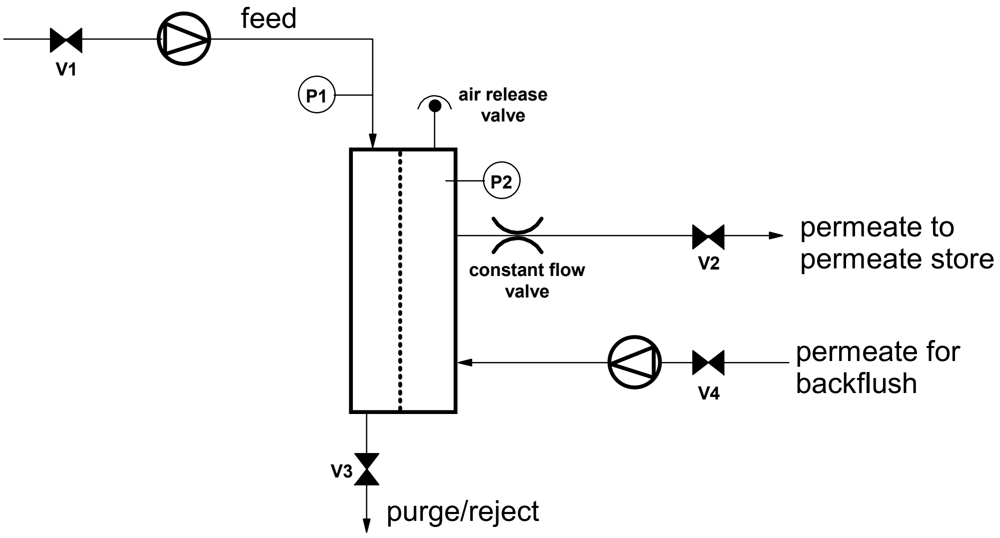
The main disadvantages of this approach are :- increased membrane costs; and a limitation to the maximum feed turbidity that the system may handle. The latter arises from the fact that the crossflow mode of operation can handle very high feed turbidities, while in the dead-end mode, the feed turbidity would have to be limited to a maximum of about 20 NTU. This indicates that for various waters, some form of pretreatment could be necessary. However, these disadvantages are offset by the various advantages, including :- simplified design; less maintenance requirements – due to the unit not being "run hard"; increased period between chemical cleans; and a reduced sensitivity to feed water quality.

THE CUF SYSTEM FOR POTABLE WATER PRODUCTION IN RURAL AND PERI-URBAN AREAS

The basic process and instrumentation diagram for the proposed capillary ultrafiltration system is shown below.

Basis of design	Dead-end operation with periodic backflush
	Constant flux operation, controlled by constant flow valve
Membranes and modules	Type #1713 capillary ultrafiltration membranes OD = 1.2 mm, ID = 1.7 mm, fabricated from polysulphone MW cutoff = approximately 35 000 daltons
	110 mm modules, giving ~ 7 m^2 filtration area
	Module replacement ~ 4 years
Operation and control	Fully automated, controlled by PLC
	Membrane cleaning offsite

Operating pressure	1 bar to 1.5 bar
Design performance	Feed water turbidity < 20 NTU
	Permeate turbidity < 0.2 NTU
	Production per module ~ 5 m^3 / day



Pretreatment and post-treatment

With most raw waters in rural and peri-urban areas, it would be necessary to add some form of pretreatment to the basic CUF system, to reduce turbidities to acceptable levels, reduce fouling of the membranes, and to protect the membranes from turbidity “spikes”. Current pretreatment options include :- cartridge filters; settling in impoundments or tanks in series; roughing filters; sand filters without chemical addition; or sand filters with coagulation/flocculation. The last option would only be applicable in extreme circumstances, in the final analysis, economics will decide whether this option is feasible. There are also various other promising pretreatment technologies which are currently undergoing development and evaluation, and which could emerge as ideal non-chemical pretreatment options for CUF. These are immersed microfilters, and the floating media separator

The CUF produced a very high quality of water, with a low potential for regrowth of biomass. However, it will be necessary to add some form of residual disinfectant, to ensure that there is no subsequent contamination due to the reticulation pipes, or from vessles used to transport water from the water source to homes. The simplest way to provide a residual disinfectant would be to install an inline chlorinator in the product line from the CUF unit. .

Strategy for operation and maintenance

The normal operation of the unit, i.e. filtration and intermittent backflushing, is fully automated, and no direct operator is required. However, operator/maintenance input is required for the following:- daily monitoring of the unit, chemical cleaning of the membranes, and mechanical maintenance.

The strategy proposed for the above is to adopt a "regional" approach to membrane cleaning and maintenance, while still involving the user community in the daily monitoring of the unit. In the "regional" approach, a suitably skilled person is responsible for membrane cleaning and mechanical maintenance for all the units in a small geographic region. The units have been designed so that the membrane modules may be easily removed. The regional technician travels out to each unit once a month to remove fouled membranes and replaced them with cleaned ones. The fouled membranes are taken to a central depot for cleaning. Similarly, mechanical maintenance is performed in rotation on a periodic basis, and mechanical repairs are performed on demand.

The required personnel and skills in terms of operation and maintenance are summarized in the table below :

Task	**Frequency**	**Skills Required**	**Who will do it ?**
Monitoring of unit	Once a day	Literacy	User community Remote sensing
Membrane cleaning	Once a month	Basic technical	Regional technician (SMME, water authority, or farmed out to private person)
Maintenance and upgrading	Once every six months / on demand	Specialist technical	Regional technician (SMME, water authority, or farmed out to private person)

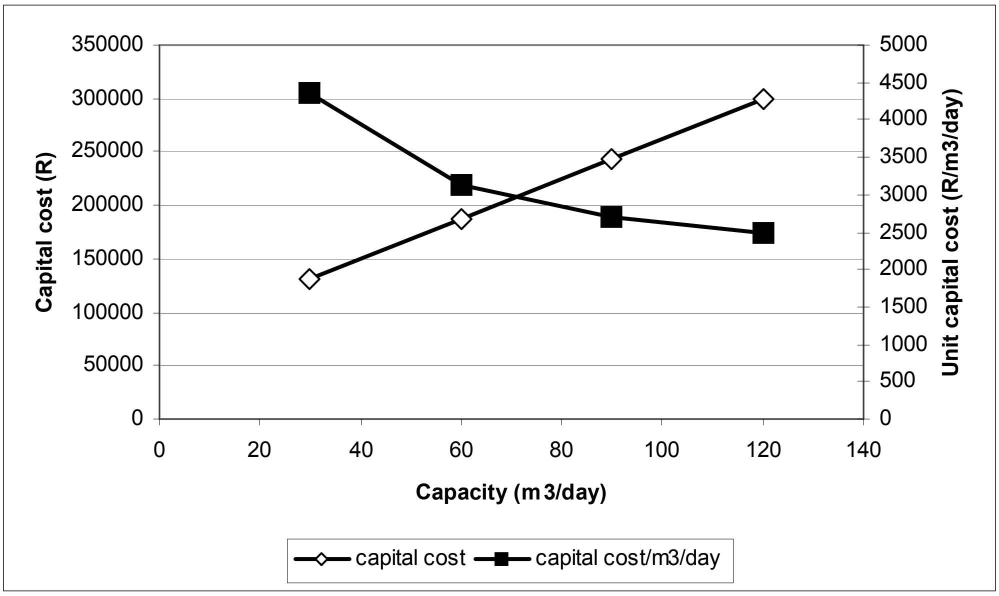
Water Quality

In this, and allied, studies it has been shown that the local CUF membranes produce a high quality of water, characteristically :

- (i) product turbidity << 0.5 NTU, for feeds ranging from 5 NTU to > 50 NTU
- (ii) 99.999 % removal of feacal coliforms
- (iii) significant Fe, Al and Mn removal
- (iv) significant colour removal

Capital and Operating Costs

Only an illustrative, or order of magnitude, capital cost can be stated here. The final capital cost will depend on the pricing policy of the technology vendor, the expected market size etc. The estimated capital costs for units ranging from 20 m^3/day to 120 m^3/day are shown in the figure below. Note that these costs include materials and labour only, and exclude overheads, royalties, profit and vat.



Estimated Capital Cost of CUF Systems (rands in 2002)

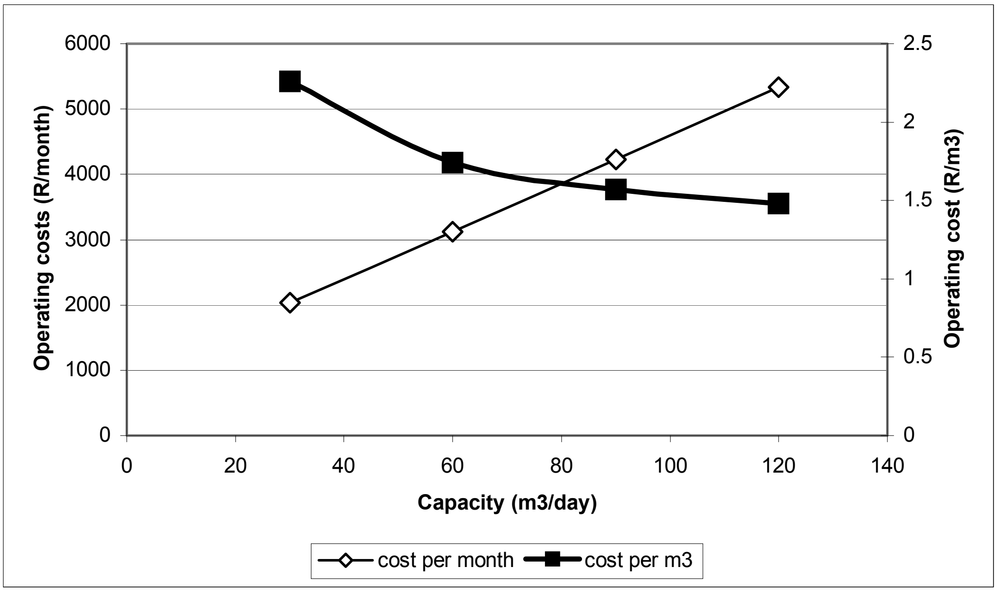
An "economy of scale" applies to the capital cost. As the production capacity increases, the cost per unit production decreases. Conversely, costs do not decrease linearly as production capacity decreases. Hence, it may be found that a single module unit may not be economically cost effective, whereas larger units are.

The above costing structure is based on the prototype design, and cannot be extrapolated to large units. For large units that are to serve a large village or a small municipality, more optimal geometric designs can be obtained, which will result in a lower cost structure.

Operating costs as a function of production capacity are presented below. The assumprions in the determination are shown in the table below :

Operating requirements :

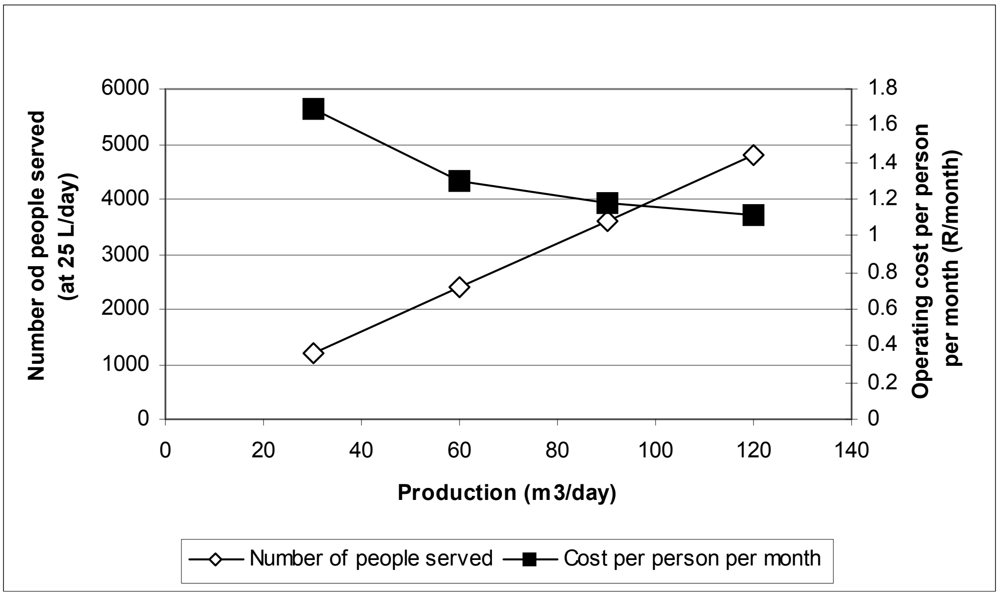
Power consumption	0.13 kW /(m3/h) @ R 0,27 per kWh (based on pump and motor efficiencies of 0.4, and pump discharge pressure of 2.5 bar)
Labour	
Daily monitoring	½ hour per day, at R 150 per month
Chemical cleaning and mechanical maintenance	1 day per month, at R 500 per day
Transport for technician	200 km per visit, at R 1,40 per km
Consumables for chemical cleaning	R 17 per module per month
Membrane replacement	Every four years, at R 7 000 per module



Estimated Operating Costs (rands in 2002)

Once again, scales of economy will apply to the above operating costs. Accordingly, the operating cost per unit production will decrease as higher capacity units are considered.

Currently each citizen in South Africa is entitled to 25 L per day of "free" potable water. The operating costs stated above have been recast to show what it would cost per person per month to provide this "free"water :



Cost per person to provide 25 L/day of potable water

CONCLUSION

The ultimate aim of this project was to develop a design for a membrane water treatment system that would be sustainable in rural and peri-urban applications.

Criteria for sustainability were developed by consultation with various stakeholders in the water field. Based on existing knowledge at the onset of the project, a field unit was constructed. Field trials were then commenced to increase technical knowledge of the process, as well as determine unit performance under various operating scenarios (technical evaluations). Periodically, the information from the technical evaluations was combined with the information of sustainability needs. From this, proposals for the improvement of the unit design were developed. These were implemented either by modifying the existing unit, or by constructing a new unit. The whole sequence of technical evaluations and information gathering on sustainability was repeated until it was finally felt that the unit design met the requirements for sustainability.

A design and a strategy for operation and maintenance have been developed, which go a long way towards meeting the criteria for sustainability. The system design is very simple, and uses locally produced capillary ultrafiltration membranes. The other hardware components are also easily available locally. The strategy for operation and maintenance combines onsite monitoring by the user community with a regional approach to membrane cleaning and mechanical maintenance. This reduces the requirements for high technical skills, while still promoting community ownership of the units.

The capital cost of the system is regarded as quite competitive and economically feasible, and demonstrates economies of scale. The operating costs, which must eventually be met by the user, are regarded as highly attractive, mainly due to the regional approach to operation and maintenance.

In overview, the capillary ultrafiltration system that is the product of this, and allied, projects has demonstrated that "high-tech" water treatment technologies can be made sustainable in developing economy conditions, and is expected to have a major impact on water provision in rural and peri-urban South Africa.

RECOMMENDATIONS

(i) Pretreatment – In view of the fluctuations in turbidity that occur in most rural and peri-urban applications, it would be necessary to have some form of effective pretreatment. Two new technologies, viz. the floating media separator and the immersed membrane microfilter have shown great promise in initial trials, and are ideally suited for integration with the capillary membrane system. These pretreatment technologies should be developed further.

(ii) Alternative energy sources – The use of solar energy, wind energy and natural heads has not be explored by this project team. Consideration should be given to investigating these energy sources, to extend the applicability of the capillary ultrafiltration system.

(iii) Value engineering – The cost of system hardware could be reduced by employing "agricultural" grade valves, actuators and instrumentation. The control system costs could be reduced by using dedicated control circuits rather than PLCs. An exercise in evaluation these alternative hardware choices should be undertaken, ensuring however that reliability is not sacrificed for price.

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The project team wishes to acknowledge the following for their invaluable assistance, guidance and input into the project :

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(ii) Umgeni Water

(iii) Mr Martin Pryor and Mr Raachi Rajgopal, Umgeni water

(iv) The staff of the Department of Chemical Engineering, Durban Institute of Technology

(v) The students of the Water Technology Group, Durban Institute of Technology

(vi) Mr Deon Koen, University of Stellenbosch

(vii) The staff of the Chemical Engineering Workshop, University of Natal

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1 INTRODUCTION

This report concerns the development of a small-scale potable water treatment system for rural and peri-urban areas. The major focus of the project was to develop a system that would be sustainable in these applications.

There appears to be very little consensus on the definition of a “small-scale” water treatment system. Definitions range from “a system that provides water at point source, without reticulation”, to “systems that serve towns with less than 200 000 inhabitants”! In this report, a “large-scale” or “conventional” treatment system is regarded as a centralized treatment facility whose product water is reticulated over a wide geographic area, generally to one or more large cities and surrounding towns and suburbs. A “small-scale”system is regarded as one serving a very narrow target user group that is geographically concentrated and relatively isolated, e.g. a single town, a village, a farm, school, clinic etc. The product may be provided at point source, or may be reticulated over this narrow geographic region. Based on typical South African demographics, the upper limit for “small-scale” systems would be a town of about 10 000 people. Based on a water utilization of 200 L per family per day, the upper limit for small-scale systems would be about 0.5 ML/day.

Similarly, the terms “sustainable development”and “sustainable technologies” are widely used, especially with reference to developing economies, but there is no concise and comprehensive definitions of these terms. For the purpose of this report, a “sustainable” water treatment technology is regarded as one which, as a minimum, meets the following criteria :- the quality of the product consistently meets specified standards and is relatively insensitive to marginal changes in feed water quality; the expertise required for operation and maintenance can be adequately met from locally available resources; the operating costs can be adequately met from local revenue sources.

1.1 The need for small water treatment systems

The supply of potable water to rural and peri-urban areas is a national development priority. It is generally recognized that large-scale water treatment plants whose product is reticulated over a wide geographic region would not be viable in these applications. Hence, there has been a strong leaning towards small, package or preconstructed, water treatment units. Package plants may have various advantages over conventional potable water treatment processes, including,

(i) **Rapid deployment** - Most package plants can be transported, installed and operational within days.

(ii) **Lower capital costs** - In general, reticulation of water from large-scale regional water treatment works to rural and peri-urban communities would be extremely expensive. Package plants which produce potable water at the point of demand would save on reticulation infrastructure and could results in a significant saving in capital. Since a major component of the selling price of water is capital redemption, package plants could lead to a significant reduction in the cost of supplying potable water.

(iii) **Simplified operation** and maintenance procedures in comparison with conventional water treatment processes.

(iv) **Suitable capacity** for small and isolated communities.

(v) **Modularity** - Most package units are modular and the capacity of the plant can be easily upgraded to cater for changing demographics.

There are various package water treatment plants being marketed internationally and locally. A comparative study of some of the units available locally is presented in Water Research Commission Report No. 450/1/97, *Package Water Treatment Plant Selection*

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1.2 Introducing Membrane Technology

Membranes technology is rapidly gaining favour internationally for the production of high quality drinking water. A membrane is a selective barrier that allows certain entities to pass through freely, while restricting the passage of other entities. In terms of water treatment, a membrane may be regarded as an extremely fine filter that allows clean water to pass through, while retaining the undesirable contaminants.

Four pressure driven membrane processes are applicable to drinking water production, i.e. reverse osmosis (RO), nanofiltration (NF), ultrafiltration (UF) and microfiltration (MF). The differences amongst the processes, and the contaminants that each is capable of removing, is shown in Figure 1.

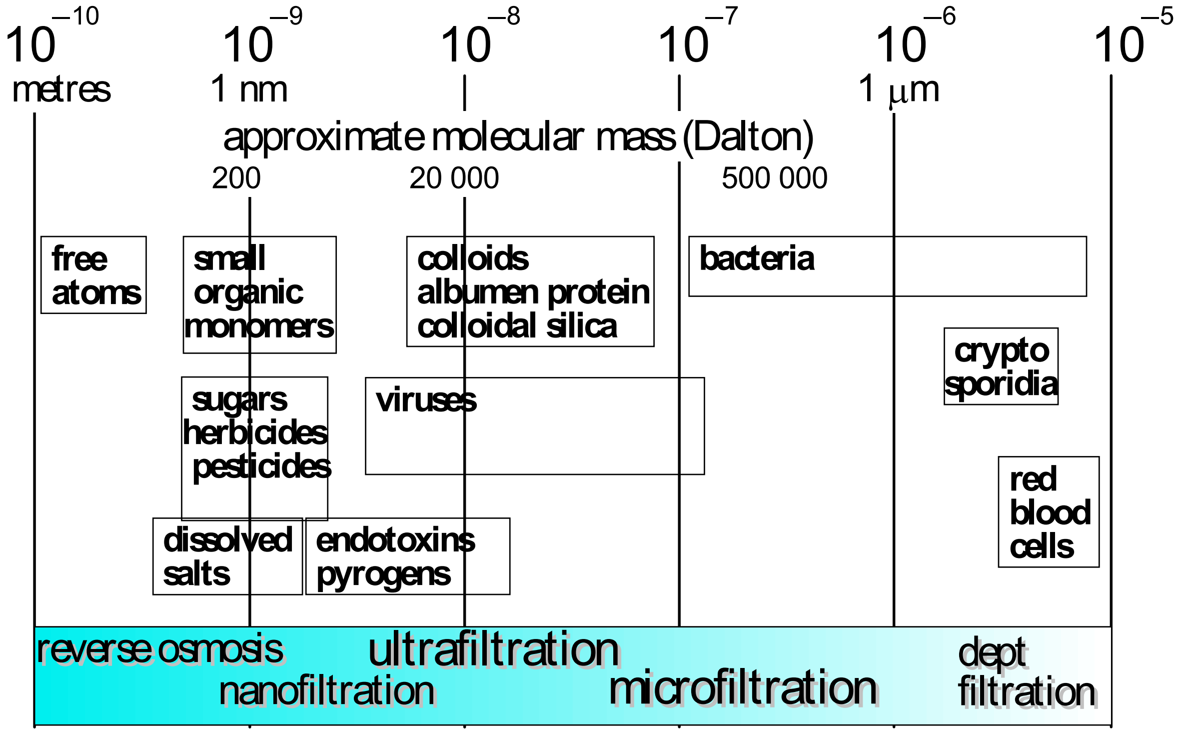


Figure 1 – Pressure Driven Membrane Processes

In terms of treating non-saline waters, the appropriate membrane processes are UF and MF. Contaminants that are removed by UF include colloids and suspended solids (100 % removal), bacteria and parasites (100 %), some viruses, high molecular mass dissolved organics, oxidized iron (98%), oxidized aluminium (90%) and oxidized manganese (60%). The water produced by UF is of a very high quality and usually exceeds the quality of water produced by conventional water treatment methods (i.e. coagulation and flocculation, clarification and sand filtration).

Internationally, there is a strong swing towards using UF and MF in drinking water production. The advantages include :

- Very good water quality without any chemical addition.
- The quality of the product is fixed by the membrane, and does not vary as the raw water quality varies.
- Membrane systems are modular, and the capacity of treatment units can be increased easily.

- Systems can easily be fully automated, avoiding problems due to operator error.
- The membrane acts as a positive barrier to pathogens (100 % removal of bacteria and parasites, 4 to 6 log removal of viruses)

The last point is of particular relevance in South Africa, where water sources may be highly contaminated with pathogens emanating from runoff from informal settlements etc. In the widely used conventional water treatment systems, i.e. coagulation/flocculation and sand filtration, the ability to remove pathogens is very much dependant on how the system is operated. If the system is operated poorly, pathogens will not be removed but water will still be produced. Conversely, a membrane will always remove pathogens irrespective of how it is operated, providing that the membranes are not physically damaged.

Despite the international swing towards membrane technology, and its various advantages especially for "developing economies", membranes are not currently employed in drinking water production in SA. Possible reasons for this include :

- The high cost of imported membrane systems – this includes the high cost associated with purchasing treatment units, as well as the high cost of obtaining spares for such units.
- The perceived lack of local membrane expertise in terms of design, construction, operations and troubleshooting
- The perception that membrane technology is a "high-tech" technology that will not be sustainable in developing economies.

1.3 Local developments in Membrane Technology

Since the early nineties, a small but dedicated group of South African membrane researchers have been very actively involved in developing local technology for drinking water production. The Institute of Polymer Science (IPS), University of Stellenbosch developed capillary ultrafiltration (CUF) membranes in the early 90's. These membranes were initially tested at Mon Villa, a conference centre in Stellenbosch, where they were employed to produce drinking water for the conference centre from raw water from the Theewaterskloof dam. In a project lasting four years, also sponsored by the Water Research Commission, it was shown that the local technology could consistently produce a high quality of potable water.

This spurred the next stage of local membrane technology development – to exploit the local CUF membranes and develop complete systems for potable water production in rural and peri-urban areas.

The current project was initiated to exploit the membrane expertise and engineering expertise of the Institute of Polymer Science, University of Stellenbosch, and the Water Technology Group, M L Sultan Technikon, towards the goal of producing a sustainable CUF based water treatment system, applicable to rural and peri-urban areas in developing countries.

1.4 Objectives of this Project

The overall aims of the project are as follows :

(i) To engineer a reliable, robust, simple to operate and cost effective ultrafiltration process for the provision of potable water to small communities, from eutrophic, brown-coloured and turbid surface waters. The engineering of the process will thus include aspects such as minimising power requirements, capital equipment and maintenance requirements.

(ii) To develop and evaluate appropriate flux enhancement and cleaning strategies

(iii) To evaluate the economics and operating requirements of the process

(iv) To expand the countries skills base in terms of membrane technology and potable water provision

(v) To demonstrate the process to potential users

This project is closely allied with WRC Project No 965, *Ultrafiltration capillary membrane process development for drinking water*. The final report for Project No. 965 concentrated on the technical aspects of the capillary ultrafiltration system, i.e. hardware, software and process development. This report concentrates on the aspects of applicability and sustainability, and is primarily aimed at potential users of the system. It is strongly recommended that this report be read in conjunction with the final report for project No. 965.

2 APPROACH AND ORGANISATION

2.1 Approach

Merely developing a unit that produces a high quality of water is not a solution to the problem of potable water provision. Past experience, both locally and internationally, has shown that many new technologies fail in the field after a short while, i.e. they are not *sustainable* in that environment. The factors that lead to failure include :

- Lack of adequate operational skills
- Difficulties with maintenance
- Lack of spares
- Lack of expertise for troubleshooting and optimization
- Lack of ongoing development to improve the technology
- Increases in operating expenses to the level where the product is too expensive

In view of the above, the ultimate aim in this project is to end up with a design for a *sustainable* membrane water treatment *system*. In this project, *system* is regarded as consisting of two main components :

(i) The water treatment unit, i.e. membranes, pumps, valves, piping and control system

(ii) A strategy for ensuring the long term sustainability of the unit, i.e. operation, maintenance, future improvements etc

This project followed a somewhat unconventional, iterative, approach towards achieving its aims. This is illustrated in Figure 2.

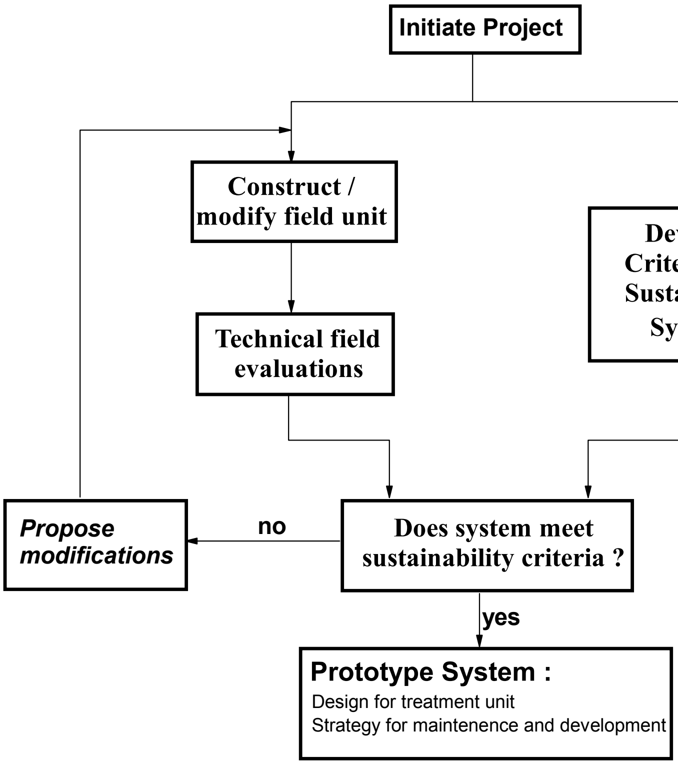


Figure2 – Overview of the approach to this project

Based on existing knowledge at the onset of the project, a field unit was constructed. Field trials were then commenced to increase technical knowledge of the process, as well as determine unit performance under various operating scenarios (technical evaluations). Simultaneously, information was gathered from various sources on what criteria would have to be fulfilled for a system to be sustainable. Periodically, the information from the technical evaluations was combined with the information of sustainability needs. From this, proposals for the improvement of the unit design were developed. These were implemented either by modifying the existing unit, or by constructing a new unit.

The whole sequence of technical evaluations and information gathering on sustainability was repeated until it was finally felt that the unit design met the requirements for sustainability.

The various sources of information for sustainable water treatment systems in SA included :

- Farmers
- Water authorities
- Other membrane vendors
- Funding agencies, e.g. Development Bank, CMIP

In total five field evaluations were performed during this project. There were, in chronological order :

- A farm in Hermanus, Cape
- The Umgeni Water Process Evaluation facility, Wiggens Water Works, Durban
- A farm in George, Cape
- A farm in Crammond, Pietermaritzburg
- A farm in Stanger , Durban

2.2 Organisation of this Report

In Chapter 3 the basic options in terms of membrane unit design are outlined. Chapter 4 states the criteria for a sustainable system that were employed in this project. Chapter 5 discusses the considerations that went into the final design. The prototype design for a CUF system for potable water provision in rural and peri-urban areas is presented in Chapter 6.

3 BASIC DESIGN OPTIONS

The separation ability of the membrane is fixed in its formulation. The membrane module then has to be incorporated into a water treatment unit. There are various design choices which affect the performance, and hence economics, of the treatment unit. These options are highlighted here. In Section 5 the final design choices for the prototype unit are discussed.

3.1.1. Definitions

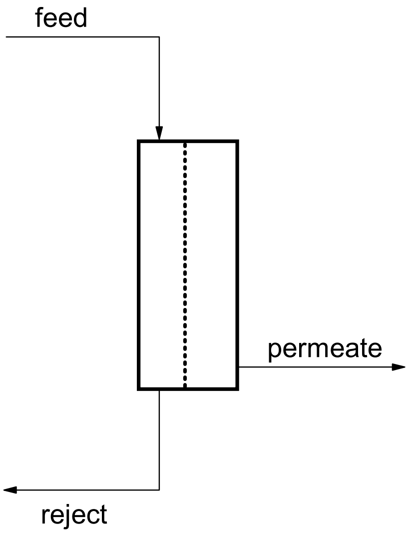


Figure 3 - Definition of Streams in a Membrane Treatment Unit

The raw water, or *feed* is pumped into the membrane module. The pressure difference, or *differential pressure (DP)*, across the membrane causes clear liquid to filter through the membrane. This leaves the module as the product or *permeate*. The contaminants are retained on the feed side of the membrane. The exit stream from the feed side is the *reject*, which has a substantially higher concentration of contaminants than the feed.

The major indicators of membrane performance are *rejection* and *permeate flux*.

Rejection = 1 – (concentration of permeate / concentration of feed)

Flux = permeate flowrate / unit membrane area

= litres/m^2 h (LMH)

The contaminants that do not pass through the membrane accumulate at the membrane surface to form a *fouling layer*. This fouling layer increases the resistance to permeate flow, and hence decreases the performance of the membrane. In general, the fouling layer increase with time. Eventually, when the fouling layer has severely decreased the performance of the membrane, the foulants have to be removed with *chemical cleaning*. A major objective in designing membrane systems is to reduce fouling, and hence reduce the frequency of chemical cleans.

3.1.2. Crossflow vs Dead-end

In dead-end operation, the feed is pumped into the membrane, and the only stream leaving the membrane is the permeate (Figure 4). Dead-end operation is usually alternated with *backflushing* or a periodic purge, to remove the concentrated contaminants.

In crossflow operation, a part of the reject stream is recirculated over the membrane surface at a high velocity, usually by a recirculation pump (Figure 5). This high velocity over the membrane surface serves to reduce the fouling layer, giving higher permeate fluxes. Crossflow operation usually produces high fluxes, but has greater capital and energy requirements. Crossflow operation is usually essential if the feed water has a very high level of contaminants (or turbidity). Dead-end operation requires substantially less capital and operating energy. However the permeate fluxes are usually lower. Dead-end is generally only applicable when the feed stream has a low concentration of contaminants.

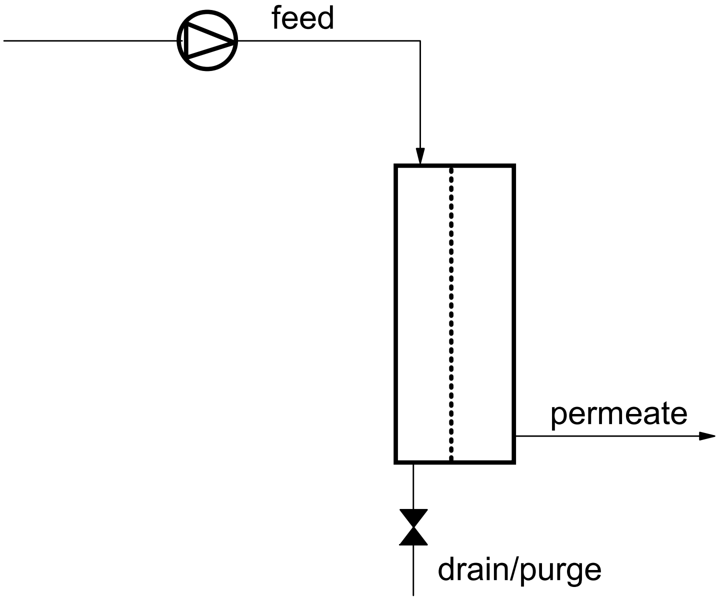


Figure 4 - Dead-end operation with purge

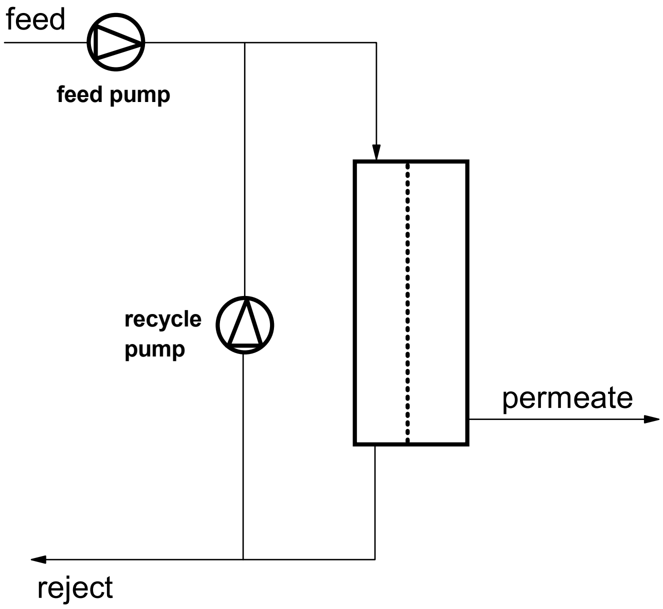


Figure 5 - Crossflow Operation

3.1.3. Constant Flux vs Constant Pressure

In constant pressure operation, the DP across the membrane is maintained at a constant value, either by a pressure control valve on the reject stream, or by pressure control valves just after the feed pump. Membrane fouling causes the permeate flux to decrease with time. Eventually, when the flux reaches an unacceptably low value, the membrane has to be chemically cleaned (Figure 6).

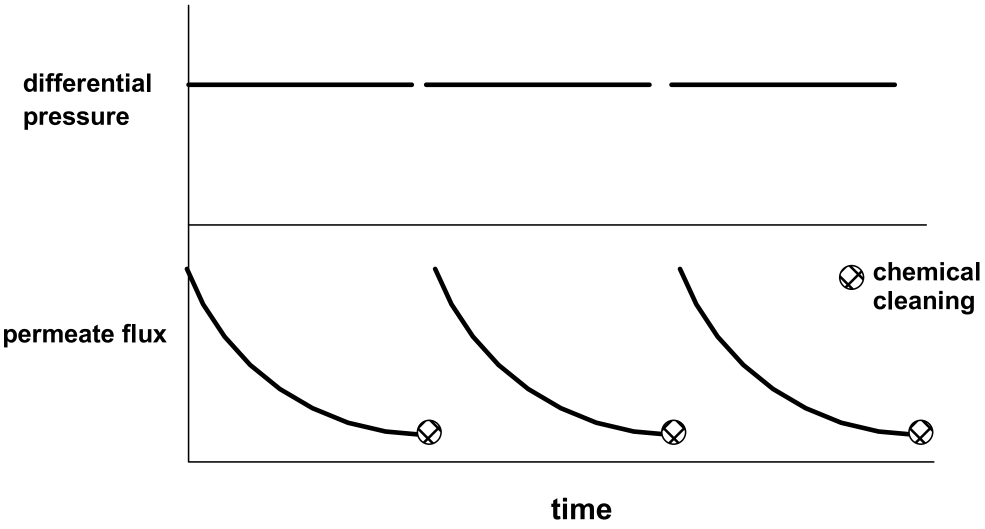


Figure 6 - Constant Pressure Operation

In a constant flux operation, the permeate production rate is controlled, either by a positive displacement pump or by constant flow valves. Fouling of the membrane causes the DP across the membrane to increase. When the DP reaches a specified maximum value, the membrane has to be chemically cleaned (Figure 7).

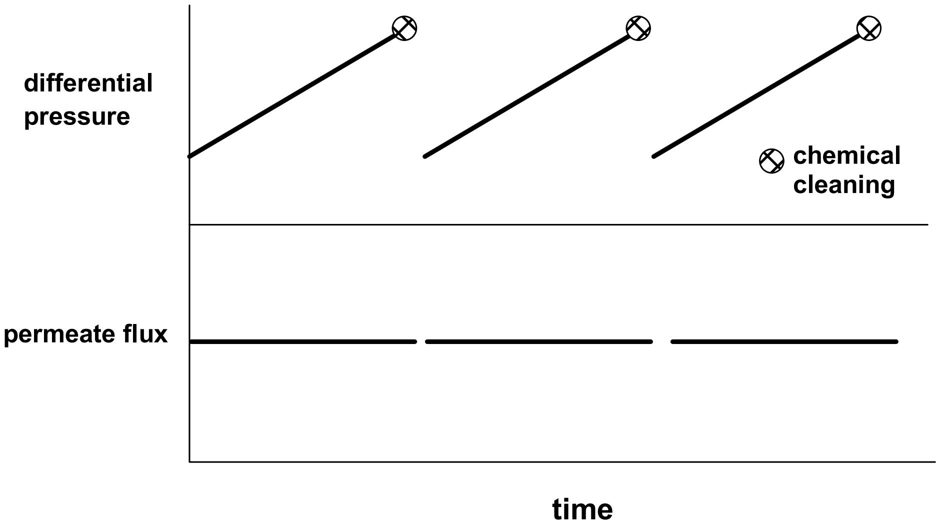


Figure 7 - Constant Flux Operation

3.1.4. Flux enhancement strategies

Fouling is the major negative aspect of membrane technology. The accumulation of foulants on the membrane surface leads to a decrease in performance, in particular a decrease in permeate flux. Periodically the membrane has to be chemically cleaned to remove the adsorbed foulants.

Flux enhancement strategies concern ways to reduce the fouling in the membrane. The objectives are to increase the permeate flux, as well as decrease the frequency of chemical cleans.

Four flux enhancement strategies were evaluated during this project :

(i) Operating at a high crossflow velocity – as noted above, this decreases the growth of the fouling layer

(ii) Flow reversal :- this concerns periodically switching the feed from one end of the module to the other end. For example, the filtration cycle is initiated with the feed being pumped into the top of the module. After a set filtration period, valves are changed so that the feed enters through the bottom of the module. Flow reversal is expected to disturb the fouling layer, once again limiting its growth.

(iii) Backflushing :- this is the most common flux enhancement strategy. Periodically the filtration cycle is stopped, and permeate is pumped through the membrane in the reverse direction to filtration. This reverse flow removes some of the accumulated foulants, which are then purged from the system in the reject stream. The effects of backflushing on both constant pressure and constant flux operations are shown in Figure 8.

(iv) Reverse pulse :- this is a new variation on the backflush. The momentum of the fluid in the recirculation line is used to create an instantaneous high negative pressure on the feed side of the membrane. This causes permeate to be drawn through the membrane in the reverse direction, and hence removes some of the accumulated foulants.

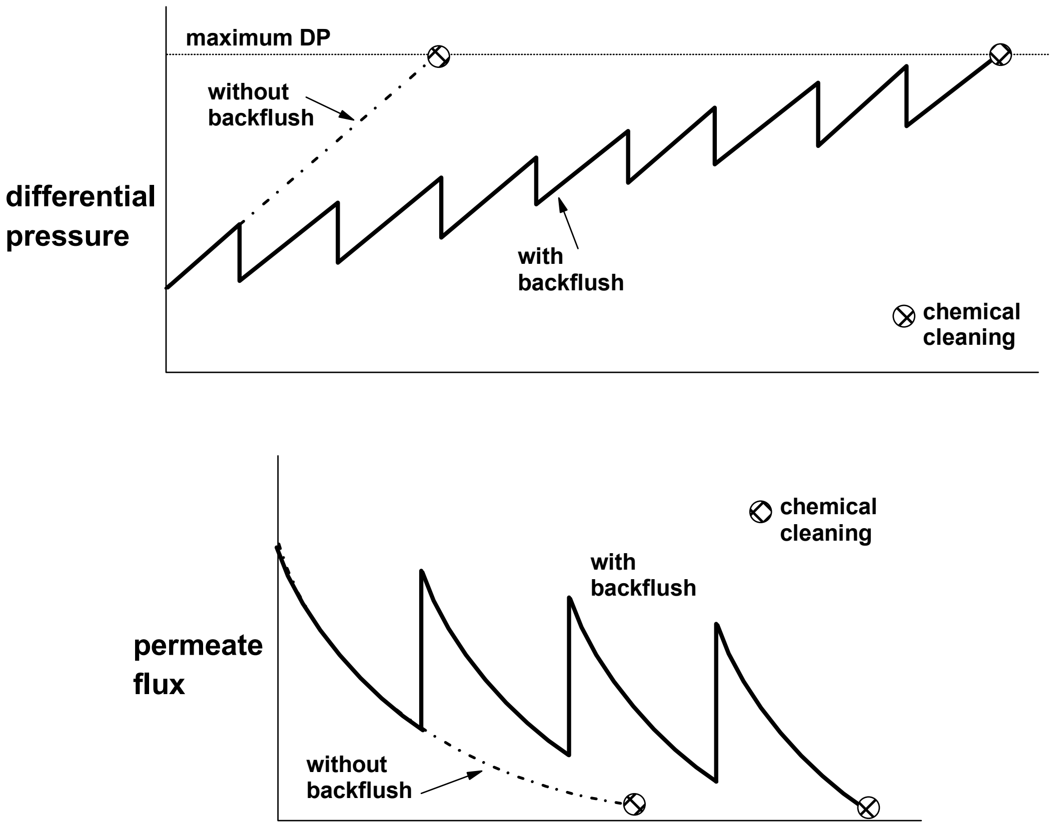


Figure 8 - Effects of Backflushing on Constant Pressure and Constant Flux Operations

4 CRITERIA FOR A SUSTAINABLE SMALL WATER TREATMENT SYSTEM

Following various consultations with a wide spectrum of stakeholders, the following were identified as essential criteria for a sustainable small water treatment system. In Section 5, the way in which these criteria affected design choices is discussed.

4.1 Water Quality Aspects

4.1.1. Compliance with standards

That the quality of the final product must consistently meet drinking water quality standards is obvious. The standards applied in this study are given in Table 1a and 1b.

Table 1a – SABS Physical, organoleptic and chemical requirements for potable water

Determinands	Units	Upper limit and Ranges
Physical and organoleptic Requirements		
Colour	mg/ℓ Pt	20
Conductivity	mS/m	150
Dissolved solids	mg/ℓ	1 000
Odour	TON	5
pH Value	pH units	5,0 – 9,5
Taste	FTN	5
Turbidity	NTU	1
Chemical requirements: Macro –determinands		
Ammonia as N	mg/ℓ	1.0
Calcium as Ca	mg/ℓ	150
Chloride as Cℓ	mg/ℓ	200
Fluoride as F	mg/ℓ	1.0
Magnesium as Mg	mg/ℓ	70
Nitrate and nitrite as N	mg/ℓ	10.0
Potassium as K	mg/ℓ	50
Sodium as Na	mg/ℓ	200
Sulphate as SO_4	mg/ℓ	400
Zinc as Zn	mg/ℓ	5.0
Chemical requirements: Micro-determinands		
Aluminium as Aℓ	µg/ℓ	300
Antimony as Sb	µg/ℓ	10
Arsenic as As	µg/ℓ	50
Cadmium as Cd	µg/ℓ	5
Chromium as Cr	µg/ℓ	100
Cobalt as Co	µg/ℓ	500
Copper as Cu	µg/ℓ	1 000
Cyanide (free) as CN	µg/ℓ	70
Cyanide (recoverable) as CN	µg/ℓ	200
Iron as Fe	µg/ℓ	200
Lead as Pb	µg/ℓ	50
Manganese as Mn	µg/ℓ	100
Mercury as Hg	µg/ℓ	2
Nickel as Ni	µg/ℓ	150
Selenium as Se	µg/ℓ	20
Vanadium as V	µg/ℓ	200
Chemical requirements: Organic determinands		
Dissolved organic carbon as C	mg/ℓ	10
Total trihalomethanes	µg/ℓ	200
Phenols	µg/ℓ	10

Notes: The limits for iron are based on aesthetic aspects.

NS - No standard currently in place.

MBA - Must be acceptable

Table 1b – SABS Microbiological requirements for potable water

1	2	3	4	5
Determinands	Units	**Allowable compliance contribution** [a]		
		95 % min.	**4 % max.**	**1 % max.**
		Upper Limits		
Heterotrophic plate count	count/mℓ	100	1 000	10 000
Total coliform	count/100 mℓ	Not detected	10	100
Faecal coliform	count/100 mℓ	Not detected	1	10
Somatic coliphages	count/10mℓ	Not detected	1	10
Enteric viruses	count/100 ℓ	Not detected	1	10
Protozoan parasites (Giardia/Cryptosporidium)	count/100 ℓ	Not detected	1	10

[a] The allowable compliance contribution shall be at least 95 % to the limits indicated in column 3, with a maximum of 4 % and 1 %, respectively, to the limits indicated in columns 4 and 5.T he objective of disinfection should, nevertheless, be to attain 100 % compliance to the limits indicated in column 3.

4.1.2. Independence of raw water quality

The product quality should be relatively independent of the raw water quality, and should not change substantially, or fall out of the quality standards, as the raw water changes.

4.1.3. Independence of operator skills

The quality of the product should be independent of operator skills levels. This is to avoid the likely scenario that the quality of product would change significantly with time as operators changed.

While it is accepted that operators from rural/peri-urban areas can be trained to an adequate level and dedicated to the operation of a single water treatment unit, it was felt that this was not a sustainable scenario. Possible problems included the high mobility and turnover of skilled personnel, especially in rural/peri-urban areas, as well as the high long term operating cost associated with a dedicated operator.

4.2 Cost factors

Clearly a sustainable system must be economically cost effective. The total cost of the system includes the initial capital cost and the operating costs over the life of the unit. Choices exist in terms of developing a low capital cost unit which will have high operating costs, or a higher capital cost unit which will have lower operating costs. For example, a unit could be totally manually operated. This would decrease the capital costs (no control system, control valves etc), but increase the operating costs (operator requirements). Conversely the system could be highly automated (high capital) with low operator requirements (low operating costs).

Discussions with various stakeholders indicated that the favoured option would be a higher capital cost unit with lower operating costs. In principle it is accepted that the user (community or municipality) may not be able to outlay the initial capital cost, and that there would have to be assistance with the initial capital from central government via its development agencies. However, for sustainability, the user must be able to meet all operating costs.

Accordingly, the economic criteria adopted in this project was that the operating costs must be affordable to the user, whilst external assistance may be necessary with the initial capital costs.

4.3 Control strategy and Operator requirements

Following the discussions in Section 5.1.2 and Section 5.2, it would be preferable to automate the normal operation of the water treatment unit, and hence reduce dependency on operator skills. However it is not feasible, nor desirable, to completely do away with operator input. In terms of monitoring of the unit, as well as to ensure community “buy in”, it is important to define some role for an operator, taking into cogniscance the available skills levels in rural and peri-urban areas.

4.4 Reliability and robustness

For a system to be sustainable, it must provide trouble-free operation in the long term. It is not possible to guarantee that a unit would be totally reliable, irrespective of the technology that goes into its development. The guarantee is only as good as the backup service available to correct problems when they develop.

In terms of reliability and robustness, therefore, it is necessary to develop an appropriate design as well as provide a sustainable long term plan for maintenance, troubleshooting and repairs.

4.5 Local Construction

The unit should be completely locally assembled, and should consist of components that are either locally produced, or alternatively are easily available locally. This is to protect the user from escalating costs associated with unpredictable exchange rates, as well as ensure that repairs can be carried out rapidly without delays due to waiting for parts that have to be imported.

From a broader perspective, local construction is also desirable from the point of view of developing and promoting the local economy, in line with initiatives to reduce Africa's dependance on foreign technology.

4.6 Ongoing Technical Support

For long term sustainability, it is important that there is ongoing technical support to address any unexpected problems that may emerge in particular applications.

5 CONSIDERATIONS IN THE FINAL DESIGN

The separation efficiency is fixed by the membrane. The productivity in terms of permeate flux is determined by how the unit is designed and operated.

At the onset of the project, the approach adopted by the project team was to develop a design for a "high output" CUF unit. In a high output unit, the objective is to maximize the net permeate production. This can be achieved by operating in crossflow mode, operating at a pressure or flux close to the maximum, implementing multiple flux enhancement strategies, and optimizing the filtration-backwash cycle to maximize the net permeate output. The high output design maximizes the production from each membrane module, and hence fewer modules are required for a specified total production.

The experimental unit at Wiggens Water Works formed the basis of this approach. Investigations were performed into the crossflow operating mode, backflushing strategies, reverse flow and the reverse pulse technique. These investigations increased the team's knowledge on the various factors affecting performance in these operating modes. This equipped the team to develop a strategy to maximize permeate production and produce a high output design.

However, as the sustainability criteria were developed, it became apparent that a high output design would not be the preferred design from the point of view of sustainability. Possible problems with the high output design included :

(i) possibly higher capital cost - The high output design minimized the required membrane area. However, the high output design requires a high volume recirculation pump and various extra automated valves and piping to implement the flux enhancement strategies. Hence it could occur that the high output design may be more expensive than alternative designs, despite the reduced membrane area.

(ii) higher operating cost – the energy requirement of a high output design is high, mainly due to the crossflow operation.

(iii) sensitivity to feed quality – A unit designed to maximize the permeate flux would only be applicable to the water on which the optimization was done. If the water quality changes substantially, or the unit is operated on a different water, the entire optimization exercise would have to be repeated. This would require a high level of operator skill or very intelligent automation, either of which would increase the costs of the system.

(iv) increased maintenance – Any piece of apparatus which is "worked hard" requires more frequent maintenance, and this also applies to the membrane system. Operating the unit at its performance limits would require more regular maintenance.

(v) frequent chemical cleaning – As a membrane is operated near its performance limit, the rate of fouling increases. This requires more frequent chemical cleaning.

(vi) higher operator input – A high output design would of necessity require closer monitoring than a lower output design. Combining this with the increased frequency of chemical cleans would necessitate a greater operator input as well as a higher operator skills level.

In view of all the above, and in consideration of the sustainability criteria, the design approach was changed during the course of the project. The team subsequently adopted a "median output" approach. The basic principles of this approach were :

(i) operate in the dead-end mode

(ii) operate the membranes at a flux well below the maximum obtainable flux

(iii) minimize flux enhancement to backflushing only

The main disadvantages of this approach are :

(i) increased membrane costs - the membrane area required for a given permeate production is greater, and hence the capital cost of the modules is greater.

(ii) limitations to feed water quality – The crossflow mode of operation can handle very high feed turbidities. In the dead-end mode, the feed turbidity would have to be limited to a maximum of about 20 NTU. This indicates that for various waters, some form of pretreatment could be necessary. Whilst this may seem to be a major limitation of the system, it must be recognized that this approach uses the CUF membranes for what they are meant to do – remove fine colloids, bacteria, pathogens and some large organics. If larger suspended material is present in the water, there are less expensive processes to remove them.

However, these disadvantages are offset by the various advantages, including :

(i) simplified design - The design and control is vastly simplified, since all excess valves, piping and control circuits for the flux enhancement strategies are obviated. The unit then essentially consists of feed and backflush pumps, modules, and associated piping and valves.

(ii) less maintenance – due to the unit not being "run hard"

(iii) increased period between chemical cleans

(iv) reduced sensitivity to feed water quality – if the operating point is chosen within the broad operating window for the modules, the unit may be operated easily on different feed water qualities, without any necessity for changes to the operating point.

The overall effect of the above design approach is to produce a more reliable, robust and simplified water treatment unit that is more consistent with the criteria for sustainability.

The above design philosophy was implemented on the field units at Craddock and Stanger, where it proved fairly successful. This formed the basis of the design for the prototype unit, described in Section 6.

6 THE CUF SSYSTEM FOR POTABLE WATER PRODUCTION IN RURAL AND PERI-URBAN AREAS

6.1 Membranes and Modules

The membranes and modules utilized throughout this project were the capillary ultrafiltration membranes developed and produced by the Insitiute of Polymer Science, University of Stellenbosch. The capillaries have an outside diameter of approximately 1.7 mm and an inside diameter of about 1.2 mm. The capillaries are cast into a module based on a shell and tube arrangement. The feed stream is pumped into one end of the module. Clear liquid permeates the membrane and collects in the shell side. This is then withdrawn as product. The reject or purge stream leaves through the opposite end of the module (Figure 9).

At the onset of the project the “skinless” polysulphone membranes were used. These were cast into a 90 mm module, giving a filtration area of approximately 4 m^2. During the course of the project there were various new developments in terms of both membranes and modules at the Institute of Polymer Science. This project followed those developments, with new membranes being tested on the field units at that time.

The final “production” membrane was the type #1713 polysulphone capillary. This new membrane was substantially more robust than the early “skinless” capillaries. The final “production” module was the 110 mm module, which has a filtration area of approximately 7 m$^{2.}$

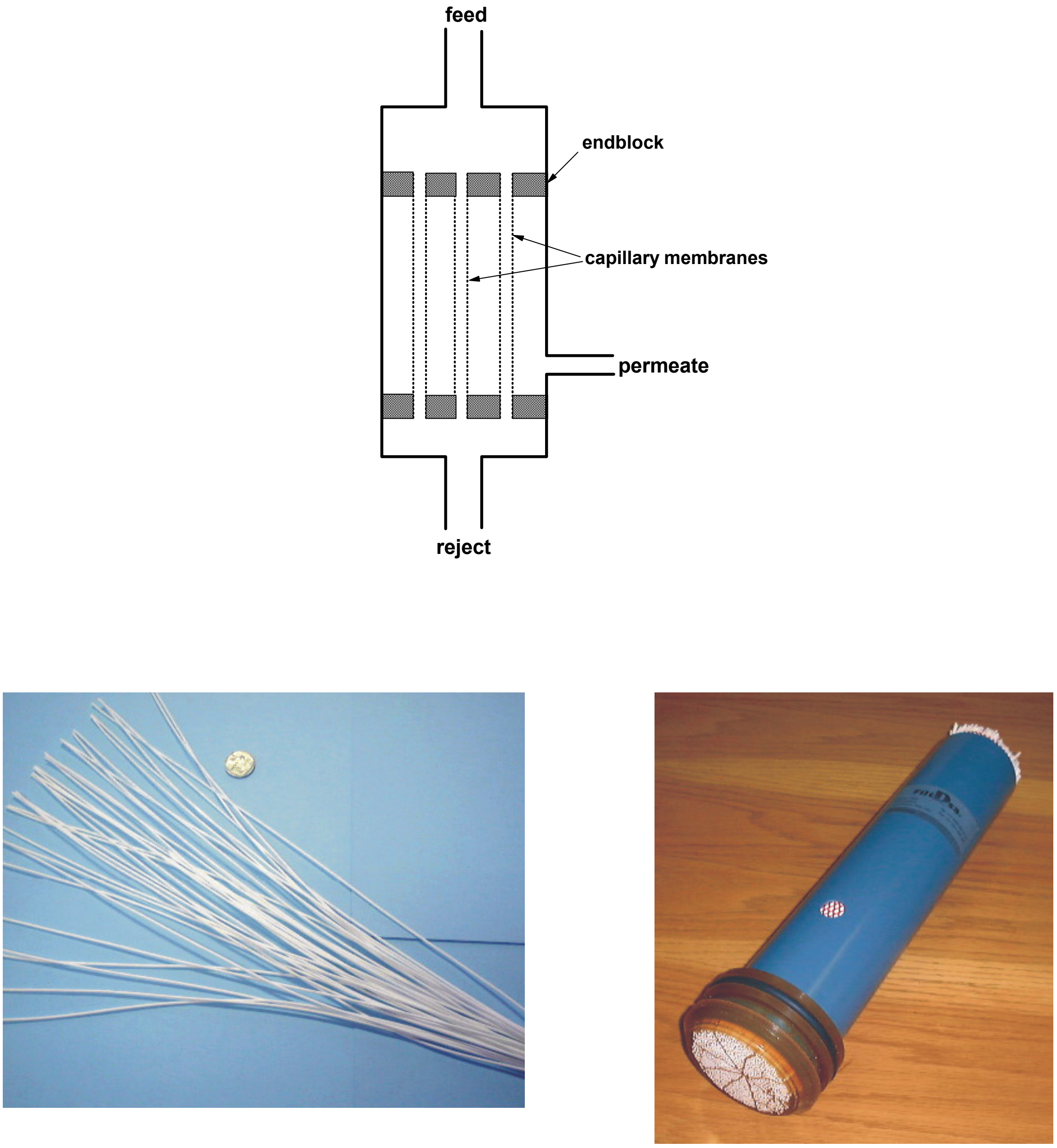


Figure 9 - Capillaries and a shell-and-tube module

6.2 P&I of water treatment unit

The basic process and instrumentation diagram for the proposed capillary ultrafiltration system is shown in Figure 10, and a computer generated geometric design for a six module prototype is shown in Figure 11. Figure 10 excludes pretreatment and post-treatment options, which are discussed in Section 6.3.

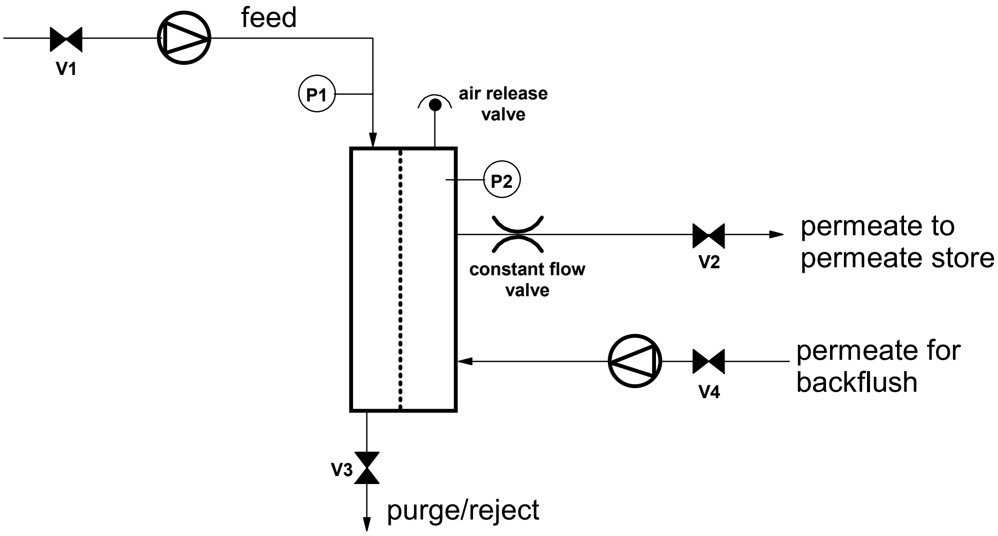


Figure 10 – Basic P&I of Prototype Unit

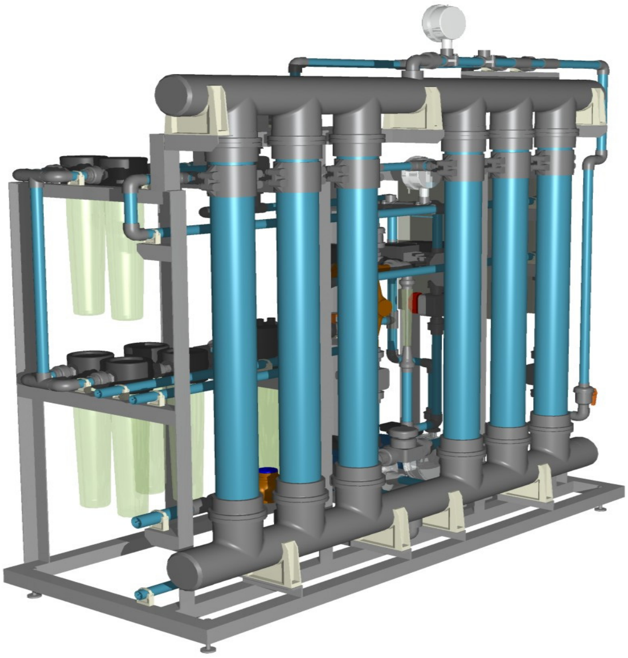


Figure 11 - Computer generated geometric design for prototype

Table 2 – Design specifications for capillary ultrafiltration system

Basis of design	Dead-end operation with periodic backflush
	Constant flux operation, controlled by constant flow valve
Membranes and modules	Type #1713 capillary ultrafiltration membranes OD = 1.2 mm, ID = 1.7 mm, fabricated from polysulphone MW cutoff = approximately 35 000 daltons
	110 mm modules, giving ~ 7 m^2 filtration area
	Module replacement ~ 4 years
Operation and control	Fully automated, controlled by PLC
	Membrane cleaning offsite
Operating pressure	1 bar to 1.5 bar
Design performance	Feed water turbidity < 20 NTU
	Permeate turbidity < 0.2 NTU
	Production per module ~ 5 m^3 / day

6.3 Pretreatment and post-treatment

The basic P&I presented in Section 6.2 does not include pretreatment or post-treatment. The choice of pretreatment will be very dependant on the feed water quality, and variations in quality. The necessity for post-treatment will also be dependant on the particular application. Some of the available options are discussed below.

6.3.1. Pretreatment Options

With most raw waters in rural and peri-urban areas, it would be necessary to add some form of pretreatment to the basic CUF system, to reduce turbidities to acceptable levsls, reduce fouling of the membranes, and to protect the membranes from turbidity “spikes”. Current pretreatment options include :

(i) cartridge filters – a series of cartridge filters ranging from 50 micron down to 5 micron mesh are inserted after the feed pump. This is very effective in protecting the membranes from turbidity spikes. Despite manufacturer's claims to the contrary, cartridge filters can be washed manually and reused. The project team has been doing this quite successfully over the past few years.

(ii) Settling in impoundments – this concerns allowing the raw feed water to undergo some form of settling to reduce turbidity. The impoundment may be a dam, a pond, or a series of settling tanks. This is also effective in reducing turbidity spikes.

(iii) Roughing filters

(iv) Sand filters without chemical addition

(v) Sand filters with coagulation/flocculation – Superficially, it may seem that this option aims to combine conventional chemical water treatment with CUF as a post-treatment. In stand-alone coagulation/sand filtration water treatment systems, it is critical to operate at the correct coagulant dose for that water. Operating at a lower coagulant dose will result in an unacceptable quality of water. If coagulation/sand filtration is used as a pretreatment to CUF, the purpose of the sand filter is merely to reduce the turbidity to, e.g. 5 NTU, and not to produce a final quality water. Hence, the system may be operated at a coagulant dose far below optimal, with the membranes performing the task of bringing the low quality sand filter product up to drinking water standards. Further, if the quality of the raw water varies, resulting in fluctuations in the sand filter product, these variations will be ironed out by the membranes. In the final analysis, economics will decide whether this option is feasible.

There are also various other promising pretreatment technologies which are currently undergoing development and evaluation, and which could emerge as ideal non-chemical pretreatment options for CUF :

(vi) immersed microfilters – here the microfilter is in the form of a flat sheet module which is inserted directly into the raw water. Permeate is withdrawn by suction, leaving the contaminants behind in the raw water vessel. The permeate withdrawal could be performed by the feed pump for the CUF unit, thus requiring no additional pumping capacity.

(vii) Floating media separator – This is a new separation technology in which contaminants are trapped by charged beads during the upflow of the raw water through a floating bed of the beads. Periodically the bed is fluidized downwards, disturbing the bed and removing accumulated foulants, which are then withdrawn through the bottom of the vessel. In preliminary trials by the University of Stellenbosch team, the floating media separator showed great promise as a non-chemical pretreatment. It is also very simple to construct, and can be easily scaled up. This is currently undergoing further trials.

6.3.2. Post-treatment

The CUF produced a very high quality of water, with a low potential for regrowth of biomass. In various trials, the product from CUF showed no regrowth after standing in sunlight for about three years. If the product is to be reticulated, however, it will be necessary to add some form of residual disinfectant, to ensure that there is no subsequent contamination due to the reticulation pipes. Even if water is being provided at point source, e.g. if product is immediately used by villagers, it is highly recommended that post-disinfection occurs. Studies have shown that the vessels used to transport water from the point source to households may themselves be contaminated with pathogens, eventually resulting in contamination of the water.

The simplest way to provide a residual disinfectant would be to install an inline chlorinator in the product line from the CUF unit. The amount of chlorine that would be required to give an effective residual is expected to be quite low, since the CUF system would have removed all suspended material and a large portion of macromolecules. Clearly ozonation or ultraviolet radiation could also be used a post disinfectant, but will not give adequate residual disinfection.

6.4 Operational Guidelines

6.4.1. Normal Operation

Startup

Option 1 (see Figure 10)

(i) V2 , V3 and V4 are closed. V1 is opened

(ii) The product side of the modules are filled with clean water. This is to prevent excessive transmembrane pressures and fluxes on startup.

(iii) The feed pump is switched on.

(iv) After a short delay, V2 is opened

Option 2 (if no clean water is available)

(i) V2 and V4 are closed. V1 and V2 are opened.

(ii) The feed pump is switched on.

(iii) As the product side of the modules fills with permeate, air will be released via the air release valve. When the product side is full of permeate, the air release will cease.

(iv) V2 is opened, permitting permeate flow

(v) V3 is closed

Filtration

The system continues in the final state from above. The constant flow valve limits the flowrate of permeate, thus assisting in reducing fouling. The transmembrane pressure will increase progressively, as the fouling layer on the membranes increases. At periodic intervals, the system is switched into backflush mode. The intervals between backflushes is dependant on the quality of the feed water, and is determined by experiments on the water during commissioning.

Backflush

(i) The feed pump is switched off

(ii) V1 and V2 are closed

(iii) V3 and V4 are opened

(iv) The backflush pump is switched on. Permeate is pumped into the product side of the modules, through the membrane (in the reverse direction) into the feed side. In the process, foulants are dislodged from the inside of the membrane walls and are carried out in the reject stream.

(v) After the backflush period, V3 is closed, and after a short delay the backflush pump is switched off and V4 is closed. This ensures that the shell side of the modules are full of permeate.

(vi) V1 is opened.

(vii) The system jumps to step (iii) of Option 1 in Startup

6.4.2. Membrane Cleaning, Monitoring and Maintenance

Chemical cleaning of the membranes is initiated when the transmembrane pressure drop reaches a preset maximum value (~ 2 bar), or after a specified operating time, whichever occurs first. The protocol for membrane cleaning is discussed in Section 6.5. Monitoring of the system and maintenance are also discussed in Section 6.5.

6.5 Strategy for operation and maintenance

The normal operation of the unit, i.e. filtration and intermittent backflushing, is fully automated, and no direct operator input is required. However, operator/maintenance input is required for the following :

- daily monitoring of the unit
- chemical cleaning of the membrane
- servicing of pumps and valves
- upgrading of unit as new technology is developed.

6.5.1. Daily monitoring

This task entails taking daily readings of pressures, flowrates and possibly turbidities. Whilst this is not essential to operate the unit, it ensures that there is daily observation of the unit to ensure that it is operating smoothly. It also ensures that there is some ownership or "buy in" from the user.

It is estimated that this task would take approximately 30 minutes per day. No special skills are required, except for literacy. This task could be performed by e.g. a school teacher, a nurse, farm worker, member of the community water committee etc. It is planned that this person would be paid a nominal monthly stipend to ensure that the duty is performed.

An alternative approach would be to use telemetry to link individual units to a central monitoring and control center. Here pressures, flowrates and possibly turbidities would be measured by online sensors, and the values transmitted to the central monitoring unit. It would be fairly easy to develop intelligent software to interpret this data, and issue alarms if the units performance is deteriorating or deviating significantly from design value. This will then be passed onto the regional technician (see Sections 6.5.2 and 6.5.3) for action. The economics and logistics of this option has not been explored by the project team.

In practise it would be highly desirable to have someone onsite who accepts responsibility for, and takes ownership of, the system. Accordingly, even if remote sensing is implemented, it would still be preferable to retain the onsite monitor.

6.5.2. Chemical cleaning of membranes

This is one of the critical tasks in sustaining the system, since inadequate cleaning will result in the system progressively degrading. After reviewing various options, the project team proposes a "regional" approach to chemical cleaning, in contrast to cleaning on site. This operates as follows :

(i) the modules have been redesigned to be easily removable. This can be done by a single person, with the only skills required being the ability to use basic tools.

(ii) the units are designed so that a chemical clean is only required once every month to once every three months.

(iii) Once a month a "regional" technician travels out to each unit in that region. The fouled membranes are removed and replaced by cleaned membranes.

(iv) The fouled membranes are returned to a central cleaning facility for that region, where all the membranes are chemically cleaned, repaired (if necessary), and made ready for the next month.

The regional technician could be :

(i) a technician employed by a water authority or water provider

(ii) a private person, e.g. agricultural sales representative, who does it as a part of his/her broader tasks

(iii) an SMME

(iv) technical students/staff from higher educational institutions in that region, e.g. technikons, technical colleges

The training for the chemical cleaning technician, as well as chemicals and replacement membranes, will be provided by the vendor of the CUF units, who will ensure that quality standards are met.

The “regional” approach is of advantage to the end user as well as the the vendor of the units. This approach is also advantageous from the point of view of environmental protection, since all chemical usage would be restricted to the regional center, rather than being dispersed through the region.

6.5.3. Mechanical servicing

Mechanical equipment with moving parts, e.g. pumps, valves, have to be serviced on a regular basis, to ensure problem free service. Once again, a regional approach is proposed in terms of mechanical servicing.

It is expected that mechanical servicing would be required every six months. However, the mechanical technician needs to be available at short notice at all times, to deal with emergency repairs in the event of breakdown. This task requires specialist technical skills. The options here are :

(i) dedicated roving technician who is an employee of a water service provider

(ii) a private skilled person, to whom the regional task is farmed out

(iii) an SMME responsible for that region

6.5.4. Summary

The required personnel and skills in terms of operation and maintenance are summarized in Table 3.

Table 3 – Requirements for Monitoring and Maintenance

Task	**Frequency**	**Skills Required**	**Who will do it ?**
Monitoring of unit	Once a day	Literacy	User community Remote sensing
Membrane cleaning	Once a month	Basic technical	Regional technician (SMME, water authority, or farmed out to private person)
Maintenance and upgrading	Once every six months / on demand	Specialist technical	Regional technician (SMME, water authority, or farmed out to private person)

6.6 Water Quality

The ability of UF and MF to produce a very high quality of drinking water without any chemical addition has been proven in many publications. There have also been various reports published of the quality produced by the locally produced capillary UF membranes (see Section 9).

In this, and allied, studies it has been shown that the local CUF membranes produce a high quality of water, characteristically :

(v) product turbidity < 0.3 NTU, for feeds ranging from 5 NTU to > 50 NTU

(vi) 99.999 % removal of feacal coliforms

(vii) significant Fe, Al and Mn removal

(viii) significant colour removal

6.7 Ongoing technical support and training from tertiary institutions

Ongoing technical support and skills development in membrane technology (at all levels) is regarded by the project team as an important pillar for long term sustainability of the technology. One of the aims of this project has been to establish an expertise base in membrane technology in this country. This aim has been very successfully met. The Institutue of Polymer Science, University of Stellenbosch, and the Water Technology Group, M L Sultan Technikon have developed a very close partnership on membrane technology development, with the university researchers focusing on membrane and module development and conceptual design, and the Technikon researchers focusing on design, construction and field evaluations. Within the partnership exists all the required expertise on the local membrane technology.

It is planned that this partnership will form the basis of future tertiary institutional support in CUF technology, in collaboration with vendors of CUF units and research funding agencies. This will ensure that vendors and users of CUF technology will have easy access to technical support and traning from the academic sector in South Africa, should that need arise.

6.8 Economics

6.8.1. Capital Costs

Only an illustrative, or order of magnitude, capital cost can be stated here. The final capital cost will depend on the pricing policy of the technology vendor, the expected market size etc. Estimated capital costs are presented for a range of unit sizes, to illustrate the economies of scale.

Application	Potable water production from non-saline borehole or surface waters
Unit Description	Capillary ultrafiltration unit consisting of feed and backwash pumps, membrane module banks, actuated valves, PVC piping, backwash and CIP tanks, PLC, on steel structure

Membranes and modules	Capillary Ultrafiltration type # 1713 110 mm modules (7 m^2)
Operation and Control	Mode of operation: Dead-end filtration with intermittent backflushing. Standard operation is fully automated and controlled using an EASY PLC. (Klochner Moeller) Chemical cleaning is performed manually.
Design Specifications	
Feed supply :	Non-saline surface or borehole water, < 10 NTU
Permeate production :	5 m^3 / day per module
Permeate quality :	< 0.2NTU.
Water recovery :	Average of 90%.

The estimated capital costs for units ranging from 20 m^3/day to 120 m^3/day are shown in Figure 12. Note that these costs include materials and labour only, and exclude overheads, royalties, profit and vat.

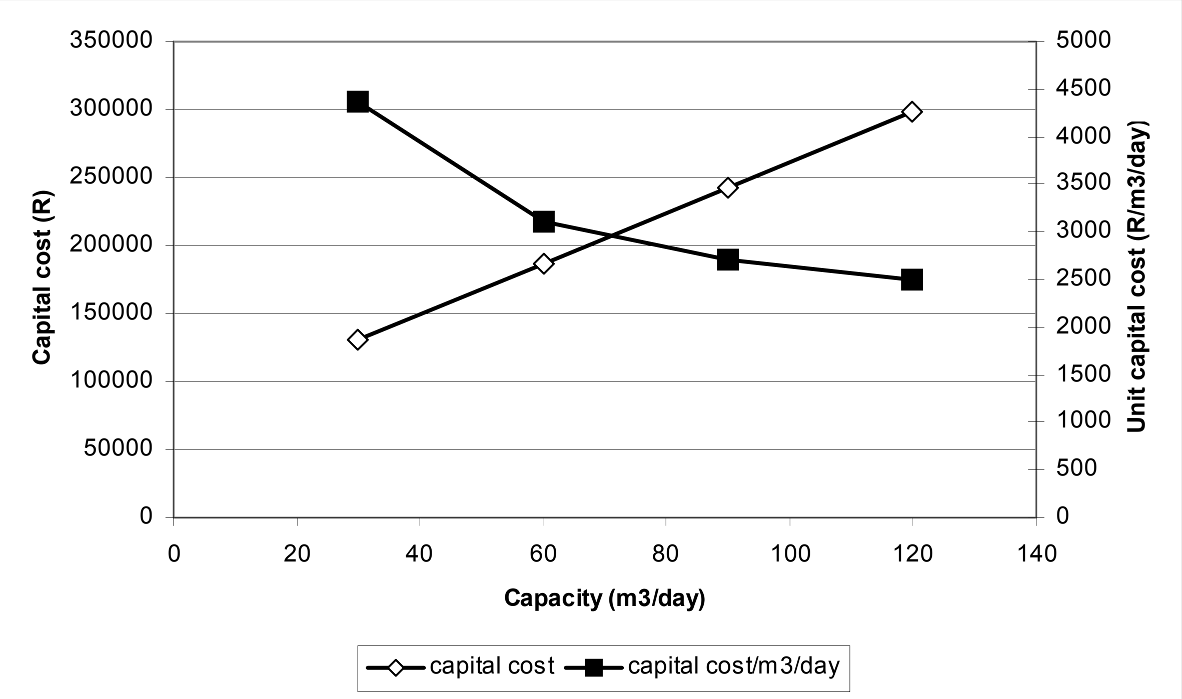


Figure 12 - Estimated capital cost of CUF Systems (rands in 2002)

An “economy of scale” applies to the capital cost. As the production capacity increases, the number of modules required increases, but the cost of the control system, frame and actuated valves does not increase substantially. Hence, the capital cost per unit production decreases. Conversely, costs do not decrease linearly as production capacity decreases. Hence, it may be found that a single module unit may not be economically cost effective, whereas larger units are.

The above costing structure is based on the prototype design, and cannot be extrapolated to large units. For large units that are to serve a large village or a small municipality, more optimal geometric designs can be obtained, which will result in a lower cost structure.

6.9 Operating Costs

Operating costs as a function of production capacity are presented below. The assumptions in the determination are shown in the table below :

Operating requirements :

Power consumption	0.13 kW /(m3/h) @ R0,27 per kWh (based on pump and motor efficiencies of 0.4, pump discharge pressure of 2.5 bar)
Labour	
Daily monitoring	½ hour per day, at R 150 per month
Chemical cleaning and mechanical maintenance	1 day per month, at R 500 per day
Transport for technician	200 km per visit, at R 1,40 per km
Consumables for chemical cleaning	R 17 per module per month
Membrane replacement	Every four years, at R 7 000 per module

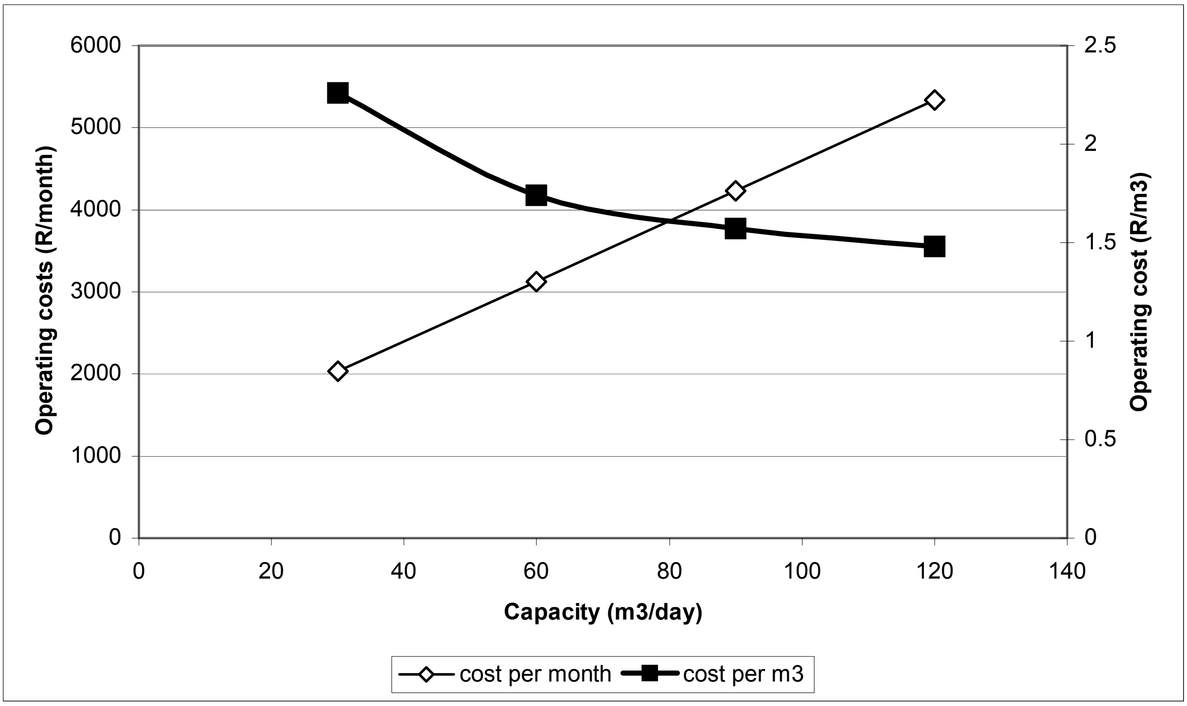


Figure 13 - Estimated Operating Costs (rands in 2002)

Once again, economies of scale apply to the above operating costs. If the size of the unit increases, the power consumption, cleaning consumables and membrane replacement will increase. However, the costs for labour and transport will remain the same. Accordingly, the operating cost per unit production will decrease as higher capacity units are considered.

Currently each citizen in South Africa is entitled to 25 L per day of "free" potable water. The operating costs stated above have been recast to show what it would cost per person per month to provide this "free"water (Figure 14).

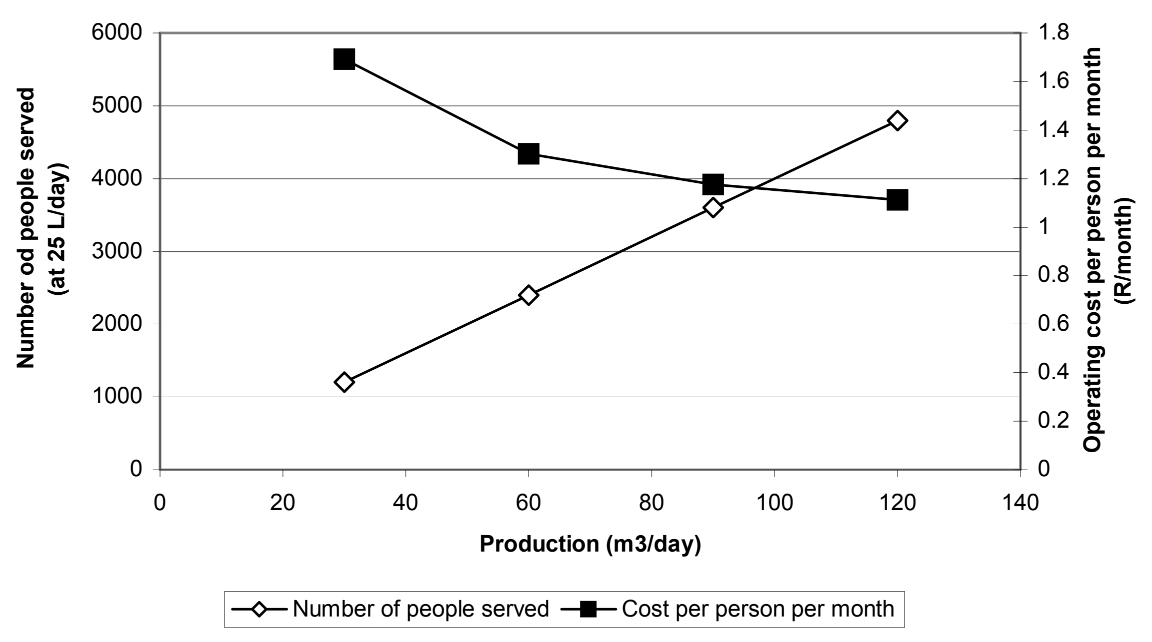


Figure 14 - Cost per person to provide 25 L/day of potable water

6.10 Sensitivity to feed water quality

The CUF unit was designed for a feed water turbidity of < 20 NTU, but should preferably be operated below 10 NTU. If the feed turbidity exceeds this value, it will not affect the quality of the product, i.e. the unit will continue to produce a very high quality of water that meets drinking water standards. However, the fouling of the membranes will be accelerated, necessitating more frequent chemical cleans, and thus increasing the operating costs of the system.

In the worst case scenario, very high input turbidities (> 100 NTU) for an extended period may cause membranes to block up. In this instance, the permeate production rate will decrease drastically and may cease altogether, but the quality of the product will not deteriorate.

If a conventional water treatment system (coagulation, clarification and sand filtration) is operated at turbidities substantially greater than the design value, the product flowrate is likely to remain unchanged, but the quality is likely to have deteriorated drastically. This is due to the optimal coagulant dose being very dependant on the quality of the feed water. This poses a serious health hazard, since consumers would continue to drink this water unaware of the presence of pathogens. Hence, it is a major advantage of the membrane system that if *any* product is obtained, it will be of a high quality. Extended poor operation will cause the product to cease, and hence force the user to take remedial actions.

7 CONCLUSION

The ultimate aim of this project was to develop a design for a membrane water treatment system that would be sustainable in rural and peri-urban applications.

Criteria for sustainability were developed by consultation with various stakeholders in the water field. These included water quality aspects, cost factors, control strategy and operator requirements, reliability and robustness, local construction, ongoing technical support.

Based on existing knowledge at the onset of the project, a field unit was constructed. Field trials were then commenced to increase technical knowledge of the process, as well as determine unit performance under various operating scenarios (technical evaluations). Periodically, the information from the technical evaluations was combined with the information of sustainability needs. From this, proposals for the improvement of the unit design were developed. These were implemented either by modifying the existing unit, or by constructing a new unit. The whole sequence of technical evaluations and information gathering on sustainability was repeated until it was finally felt that the unit design met the requirements for sustainability.

At the onset of the project, the approach adopted by the project team was to develop a design for a "high output" CUF unit, i.e. to maximize the net permeate production by, *inter alia*, operating in the crossflow mode at a high flux. However, as the sustainability criteria were developed, it became apparent that a high output design would not be the preferred design from the point of view of sustainability. Possible problems with the high output design included :- possibly higher capital cost, since the high output design would require extra pumping capacity and automation; a greater sensitivity to feed quality; increased maintenance; frequent chemical cleaning; and higher operator input.

In view of all the above, and in consideration of the sustainability criteria, the design approach was changed during the course of the project. The team subsequently adopted a "median output" approach. The basic principles of this approach were :- operate in the dead-end mode; operate the membranes at a flux well below the maximum obtainable flux; minimize flux enhancement to backflushing only.

The main disadvantages of this approach are :- increased membrane costs; and a limitation to the maximum feed turbidity that the system may handle. This indicates that for various waters, some form of pretreatment could be necessary. However, these disadvantages are offset by the various advantages, including :- simplified design; less maintenance requirements – due to the unit not being “run hard”; increased period between chemical cleans; and a reduced sensitivity to feed water quality.

The final design is shown in Figures 10 and 11, and Table 2. The system design is very simple, and uses locally produced capillary ultrafiltration membranes. The other hardware components are also easily available locally.

The normal operation of the unit, i.e. filtration and intermittent backflushing, is fully automated, and no direct operator is required. However, operator/maintenance input is required for the following:- daily monitoring of the unit, chemical cleaning of the membranes, and mechanical maintenance.

The strategy proposed for the above is to adopt a “regional” approach to membrane cleaning and maintenance, while still involving the user community in the daily monitoring of the unit. In the “regional” approach, a suitably skilled person is responsible for membrane cleaning and mechanical maintenance for all the units in a small geographic region. The units have been designed so that the membrane modules may be easily removed. The regional technician travels out to each unit once a month to remove fouled membranes and replaced them with cleaned ones. The fouled membranes are taken to a central depot for cleaning. Similarly, mechanical maintenance is performed in rotation on a periodic basis, and mechanical repairs are performed on demand.

The capital cost of the system is regarded as quite competitive and economically feasible, and demonstrates economies of scale. The operating costs, which must eventually be met by the user, are regarded as highly attractive, mainly due to the regional approach to operation and maintenance.

In overview, the capillary ultrafiltration system that is the product of this, and allied, projects has demonstrated that “high-tech” water treatment technologies can be made sustainable in developing economy conditions, and is expected to have a major impact on water provision in rural and peri-urban South Africa.

8 RECOMMENDATIONS

8.1 Pretreatment

In the dead-end mode of operation, the design feed turbidities are limited to < 20 NTU, and preferably below 10 NTU. This is to extend the period between chemical cleans to a logistically acceptable period. Operating at higher turbidities will not affect product quality, but will necessitate more frequent cleans.

In rural and peri-urban areas where this system is most applicable, turbidities of raw river water can vary drastically over seasons, and even over a day. Peak value > 100 NTU are not uncommon. Hence, it will be necessary to have some form of pretreatment to reduce turbidity levels and spikes.

Some common pretreatment methods are listed in Section 6.3.1. They were not exhaustively evaluated during this project. Two further new and promising pretreatment technologies are the floating media separator (FMS) and the immersed membrane microfilter (IMM). Preliminary trials on both these technologies were extremely promising, with both reducing high turbidities down to acceptable values for capillary ultrafiltration. These technologies do not require any chemical addition, and can be easily integrated with the ultrafiltration system.

It is strongly recommended that further investigations into effective pretreatment technologies be conducted, with emphasis on FMS and IMM.

8.2 Alternative energy sources

In all investigations conducted in this study, the units were powered from grid electricity. The power consumption for the system is relatively low (about 0.65 kW for a 30 m^3/day unit). With suitable optimizations, this could be decreased to about 0.45 kW. It is entirely feasible, therefore, for the units to be powered by solar or wind energy. This would extend the applicability of the unit greatly, and include remote regions which are not on the electricity grid.

The system operates at a feed pressure of 1 bar to 1.5 bar. This can be provided by a water head of 10 m to 15 m. Indeed, in the Hermanus unit (see Appendix), the feed pressure is provided solely by a natural head.

It is highly recommended that alternative energy sources, and the exploitation of natural heads, be investigated further, to extend the applicability of the system.

8.3 Value engineering

In all units used in this study, “industrial” grade valves, actuators and instrumentation were used, and control was via an off-the-shelf PLC. Various inexpensive “agricultural” grade equipment and instrumentation is available on the local market, but their long term reliability was not known to the project team. The project team is also aware that the PLC could be replaced by a dedicated circuit, at a fraction of the PLC cost.

It is recommended that an exercise in value engineering be performed on the current design, to take advantage of latest technologies and reduce the cost of the system, while ensuring that reliability is not compromised.

9 TECHNOLOGY TRANSFER ACTIONS

9.1 Inter-institutional Technology Transfer

This project arose out of a very close partnership between the Institute of Polymer Science, University of Stellenbosch (US), and the Department of Chemical Engineering, M L Sultan Technikon (now Durban Institute of Technology- DIT). The net result of this partnership is that capillary ultrafiltration technology that was initially developed at the US has been very successfully transferred to students and staff at DIT, to the extent that DIT are now a national center of expertise in this technology. The success of this partnership in technology development has caught the attention of, inter alia, the following :

(i) The National Research Foundation – the partnership was recently featured in the NRF publication Research Files : From Africa For Africa. The relevant pages are attached here.

(ii) The Centre for Interdisciplinary Studies, University of Stellenbosch – the development of the CUF system has been selected as a case study for a research project on Research Utilisation.

9.2 Conferences and Papers

As noted in the introduction, this project was very closely allied with WRC Project No. 965, *Ultrafiltration capillary membrane process development for drinking water*. That project concentrated on the technical aspects of the capillary ultrafiltration system, i.e. hardware, software and process development, while this project concentrated on the aspects of applicability and sustainability. Outputs in the form of presentations at conferences etc were made jointly, and it is difficult to ascribe any particular output to one project or the other. Hence, for completeness, all reports concerning capillary ultrafiltration for drinking water production that emanated from either project are listed here as technology transfer actions.

9.2.1. International conferences

Pillay, V. L., Jacobs, E. P, *Ultrafiltration – A New but Acceptable Technology for Potable Water Production*, International Conference on Membranes 99 (ICOM99), Toronto, Canada, June 1999

Jacobs, E.P., **Pillay, V. L.**, Moodley, N., Bradshaw, S., Goodenough, H. and Prior, M., *Back Flushing In constant flux capillary Ultrafiltration for potable water production,* 21 Century International Symposium on Membrane Technology and Environmental Protection, Beijeng, China, September 2000

Jacobs, E.P., Botes, J.P., **Pillay, V.L**. and Bradshaw, S.M., *Reverse-pulse ultrafiltration in potable water production*, , Engineering with Membranes, Granada, Spain, 3-6 June 2001

9.2.2. Local Conferences

Moodley, N., Naidoo, J. A., **Pillay, V. L**., Jacobs, E. P., and Pryor, M., *Optimisation of backflush strategies in constant flux ultrafiltration for potable water*, 3rd WISA MTD Workshop, Drakensberg, South Africa, September 1999

Botes, J.P., Jacobs, E.P., Bradshaw, S.M., and **Pillay, V.L.**, *4 Years of Capillary UF Membrane Operation : The Mon Villa Case Study*, 3rd WISA MTD Workshop, Drakensberg, South Africa, September 1999

Naidoo, J.A., Moodley, N., and **Pillay, V.L.**, *Application of Capillary Ultrafiltration to Cape Waters*, 3rd WISA MTD Workshop, Drakensberg, South Africa, September 1999

Moodley, N., Gumede, L., **Pillay, V.L.**, Pryor, M.J., and jacobs, E.P., *Application of UF Membranes in Drinking Water Production from KZN Waters*, 4th WISA MTD Symposium, Stellenbosch, March 2001

Pillay, V.L., *What has been achieved in Membrane Technology ?*, WISA MTD Workshop, WISA Biennial Conference, Durban, May 2002

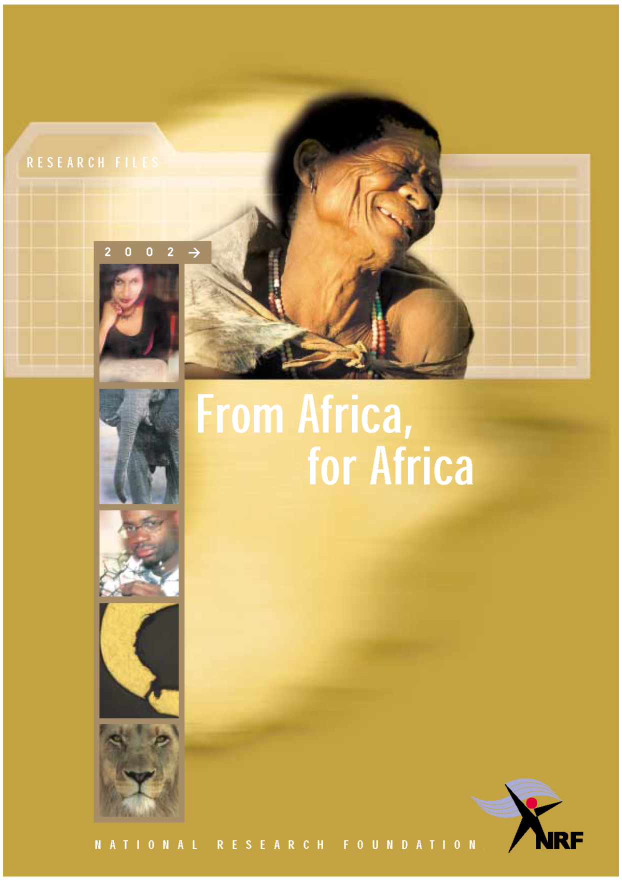
Jacobs, E.P, Botes, J.P, **Pillay, V.L**. and Bradshaw, S.M., *Reverse-pressure pulsed ultrafiltration*, 5th WISA-MTD Symposium, Vereeniging, April, 2003

Pillay, V.L. and Jacobs, E.P., *A sustainable ultrafiltration system for potable water production in developing economies*, 5th WISA-MTD Symposium, Vereeniging, April, 2003

9.3 Lectures/Workshops

Lectures on the CUF system for potable water were given to the following water authorities :

- (i) Amatola Water – Eastern Cape
- (ii) UGU Water – southern KZN



RESEARCH FILES

2002

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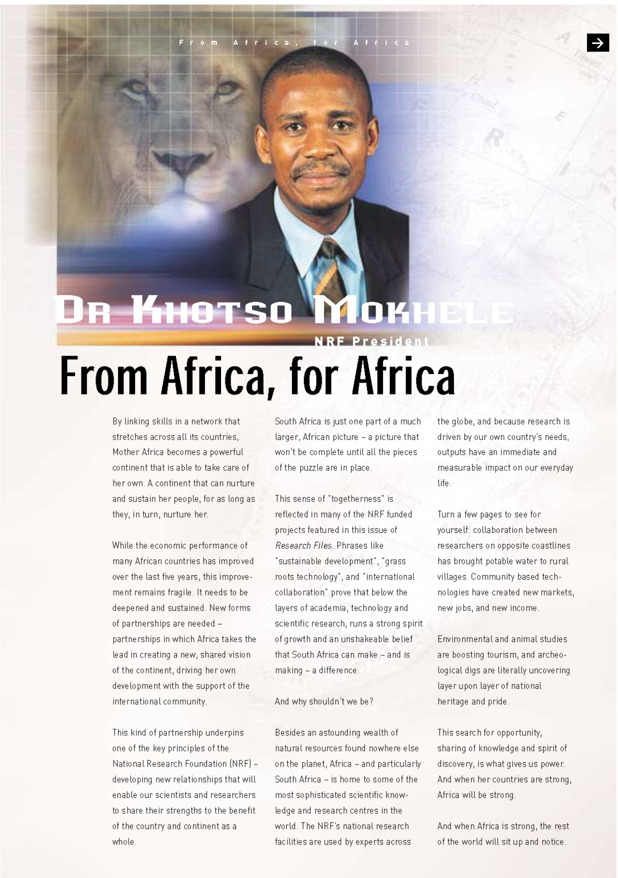


From Africa, for Africa

Dr Khotso Mokhele

NRF President

From Africa, for Africa

By linking skills in a network that stretches across all its countries, Mother Africa becomes a powerful continent that is able to take care of her own. A continent that can nurture and sustain her people, for as long as they, in turn, nurture her.

While the economic performance of many African countries has improved over the last five years, this improvement remains fragile. It needs to be deepened and sustained. New forms of partnerships are needed – partnerships in which Africa takes the lead in creating a new, shared vision of the continent, driving her own development with the support of the international community.

This kind of partnership underpins one of the key principles of the National Research Foundation (NRF) – developing new relationships that will enable our scientists and researchers to share their strengths to the benefit of the country and continent as a whole.

South Africa is just one part of a much larger, African picture – a picture that won't be complete until all the pieces of the puzzle are in place.

This sense of "togetherness" is reflected in many of the NRF funded projects featured in this issue of *Research Files*. Phrases like "sustainable development", "grass roots technology", and "international collaboration" prove that below the layers of academia, technology and scientific research, runs a strong spirit of growth and an unshakeable belief that South Africa can make – and is making – a difference.

And why shouldn't we be?

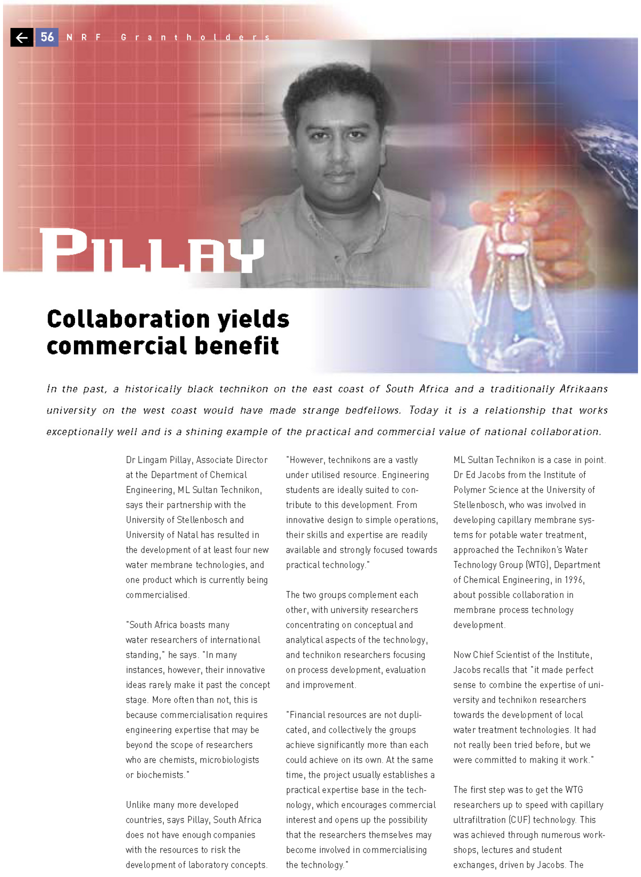
Besides an astounding wealth of natural resources found nowhere else on the planet, Africa – and particularly South Africa – is home to some of the most sophisticated scientific knowledge and research centres in the world. The NRF's national research facilities are used by experts across the globe, and because research is driven by our own country's needs, outputs have an immediate and measurable impact on our everyday life.

Turn a few pages to see for yourself: collaboration between researchers on opposite coastlines has brought potable water to rural villages. Community based technologies have created new markets, new jobs, and new income.

Environmental and animal studies are boosting tourism, and archeological digs are literally uncovering layer upon layer of national heritage and pride.

This search for opportunity, sharing of knowledge and spirit of discovery, is what gives us power. And when her countries are strong, Africa will be strong.

And when Africa is strong, the rest of the world will sit up and notice.



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Pillay

Collaboration yields commercial benefit

In the past, a historically black technikon on the east coast of South Africa and a traditionally Afrikaans university on the west coast would have made strange bedfellows. Today it is a relationship that works exceptionally well and is a shining example of the practical and commercial value of national collaboration.

Dr Lingam Pillay, Associate Director at the Department of Chemical Engineering, ML Sultan Technikon, says their partnership with the University of Stellenbosch and University of Natal has resulted in the development of at least four new water membrane technologies, and one product which is currently being commercialised.

"South Africa boasts many water researchers of international standing," he says. "In many instances, however, their innovative ideas rarely make it past the concept stage. More often than not, this is because commercialisation requires engineering expertise that may be beyond the scope of researchers who are chemists, microbiologists or biochemists."

Unlike many more developed countries, says Pillay, South Africa does not have enough companies with the resources to risk the development of laboratory concepts. "However, technikons are a vastly under utilised resource. Engineering students are ideally suited to contribute to this development. From innovative design to simple operations, their skills and expertise are readily available and strongly focused towards practical technology."

The two groups complement each other, with university researchers concentrating on conceptual and analytical aspects of the technology, and technikon researchers focusing on process development, evaluation and improvement.

"Financial resources are not duplicated, and collectively the groups achieve significantly more than each could achieve on its own. At the same time, the project usually establishes a practical expertise base in the technology, which encourages commercial interest and opens up the possibility that the researchers themselves may become involved in commercialising the technology."

ML Sultan Technikon is a case in point. Dr Ed Jacobs from the Institute of Polymer Science at the University of Stellenbosch, who was involved in developing capillary membrane systems for potable water treatment, approached the Technikon's Water Technology Group (WTG), Department of Chemical Engineering, in 1996, about possible collaboration in membrane process technology development.

Now Chief Scientist of the Institute, Jacobs recalls that "it made perfect sense to combine the expertise of university and technikon researchers towards the development of local water treatment technologies. It had not really been tried before, but we were committed to making it work."

The first step was to get the WTG researchers up to speed with capillary ultrafiltration (CUF) technology. This was achieved through numerous workshops, lectures and student exchanges, driven by Jacobs. The

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Jacobs

researchers progressively took on greater responsibilities, eventually becoming involved in process and systems development at various test sites around the country, and as far afield as Windhoek.

Over four years and with extensive development and field evaluation, the CUF system was developed into a product that is currently being commercialised.

Today, a very firm partnership exists between the groups. Collaboration has now extended to at least five new projects, and researchers at two other institutions have come on board. This includes the departments of Biochemistry, Microbiology and Chemical Engineering at the University of Stellenbosch, and the Department of Biological Sciences at ML Sultan.

Five years on, the team's success can be judged from the following:

- → The partnership is involved in contract research projects to the tune of about R8 million;
- → The jointly developed system for potable water provision to rural and peri-urban areas offers excellent quality of water, is robust and reliable in "developing economy" conditions, and is economically viable;
- → An expertise base has been developed in the WTG that can handle all aspects of the technology – from design and construction to commissioning, operations, monitoring, troubleshooting, and maintenance. The system is currently being commercialised;
- → Four patents have been developed, and two more are being prepared;
- → Three other technologies are under development that have significant commercial potential – an oil-water separation system; an active precoat microfilter for effluent treatment; and an immersed membrane filter for membrane bioreactor applications.

"This approach yields all the prerequisite elements for commercialisation of technologies," says Pillay. "It offers a product that has been tested, developed and evaluated in the field; a practical expertise base that can handle all engineering aspects of the technology; and an expertise base in the fundamentals of the technology that can contribute to new product development and product improvement."

The incredible chemistry, dedication and efforts of the team have led to the ultimate result: a new company, VulAmanz Membrane Technologies, formed in partnership with UNISTEL (the commercial arm of the University of Stellenbosch). The company was formed in September last year, and will focus on the development and commercialisation of water treatment technologies developed at South African institutes, with special emphasis on the University of Stellenbosch and the ML Sultan Technikon.

[Note: ML Sultan Technikon is now the Durban Institute of Technology]

APPENDIX I

CASE HISTORIES

A1 Hermanus

Description of unit

A 10 m^2 capillary membrane plant has been on test at a farm near Hermanus since 1998. The plant is not operated by PLC or by timers, and is extremely simple in design. It consists of two modules, a recycle pump, pressure switches and constant flow valves. The only instrumentation on the plant is two pressure gauges, one located on the feed side of the modules and the other on the product line.

The plant has various other features that makes it quite unique when compared to the other membrane units in operation :

(i) *No feed pump* - The plant is fed from water drawn from a reed bed 70 m higher than the membrane plant. Because of this elevation no feed pump has been installed.

(ii) *Filtration control* - The plant delivers its product via a float valve into asbestos tanks situated 3 m above the plant. This valve closes when the tanks are full, and the plant stops operating once the pressure in the product line exceeds a pre-set value. Another contact pressure gauge situated on the water distribution line engages the plant when the level in the tanks reaches a certain minimum value.

(iii) *Water recovery control* - The water recovery ratio is controlled at 90% recovery by means of flow control valves. One of these valves is located on the inlet side, allowing a specified volume of water into the plant. Constant flow valves also control the product and retentate flows.

(iv) *No back-flush pump* - The plant is not equipped with a back-flush pump, to save on the cost of a timer, back-flush pump and electrical switchgear. Instead of using a back-flush pump to reverse product flow through the membranes, a slow back-rinse feature was built into the unit. It was observed at other installations that the differential pressure across the membranes was nearly always lower at start-up after the plant has left standing after operation. It was decided to introduce a slow back-rinse when the plant stops operation. This was accomplished by first filling a reservoir on the product line before water is dispensed into the product tanks. The bottom of the reservoir is on the same level as that of the module manifold, which will allow the reservoir to drain its complete content in the reverse direction through the membranes.

(v) *Reverse pulse* - The plant is equipped with a reverse pulse unit to destabilise the feed flow through the membranes. At set intervals solenoid valves on the inlet line and down-stream of the modules close. The recirculation pump keeps on operating and fills an air vessel situated between the pump and the valve downstream of the modules. Some suction is created and some water from the slow-rinse tank is drawn in the reverse direction through the membranes.

Inlet water is fed into the plant downstream of a 150 micron vortex strainer. It was initially left to the owner of the farm to install a cross-flow sand filter at the draw-off point in the reed bed, but that never realised. Problems were experienced with an in-line strainer upstream of the membrane unit. Leaves and small creatures occasionally clogged the inlet diaphragm valve when the strainer on the up-stream side of the membrane unit was remove for cleaning and not replaced. It was decided to by-pass the inline strainer and rather install a bio-filter unit as only means of pre-treatment.

Before installation of the bio-filter, the plant was visited nearly every three weeks to replace fouled membranes with restored membranes. Since installation of the bio-filter, however, the membranes heve to be cleaned approximately once in six months. The product quality is maintained.

The plant does not allow in-situ chemical cleaning. An external pump and feed tank was initially taken to the farm to conduct chemical cleaning in place. For various reasons it was decided rather to remove the modules and replace them with cleaned modules when cleaning was required. The manifold was modified to allow module removal without disturbing the manifold. This simplified cleaning in that the modules would be soaked in cleaning solutions for a few days, after which the membranes were cleaned by back-flushing them with Stellenbosch tap water.

Operational history

The unit was commissioned in early 1999. Initially problems were experienced due to blockages of the in-line strainer. These were obviated by bypassing the strainer and installing a biofilter. No further significant problems were experienced. Membrane cleaning was performed every six months, on average. As as the end of 2001, the unit was still operating successfully.

The inlet water has a colour content above 100 °H and a turbidity of less than 2 NTU on average. The water is also biologically active, with high coliform counts. The product has a Hazen value of less than 15 on average, turbidity of around 0.1 NTU at a set delivery rate of 200 L/h.

On average it appears that people are aware of the quality of the water that they drink only when there is colour and haziness in the water. Because they cannot see the micro-organisms present in the water they do not worry about the possibility that the water is contaminated by microbes. The initial excitement after the introduction of purified and clean water soon dies down, and the people that supervise the filtration unit start skipping that responsibility. It is often the case when telephone calls are made to enquire after pressure differentials and feed and product water quality, that one gets responses such as: 'I don't know, will have to take a look', or 'I have water in the fridge and will have a quick look to see whether there is colour in the water.'

This raises the question of the usefulness of relying on farmers/farm workers to maintain units and ensure that they are operating sucessfully. The experience at Hermanus was that interest in the unit is progressively lost when the unit operates successfully, and that interventions are only made when the unit crashes.

A2 George

Description of unit

A capillary membrane plant was tested on a farm near George, the heartland of brown-coloured water. The unit consisted of 6 modules, giving a filtration area of 30 m^2. . It was designed to operate in the cross-flow mode, and was equipped with a flow-reversal unit and a back-flush facility. The flow-reversal unit switched the direction of feed flow every 10 minutes. Back-flush was performed for 2 minutes every 20 minutes, and occured in the opposite linear flow direction to that of the feed flow immediately prior to the back-flush operation. The unit was controlled by a PLC. A 150 lm vortex strainer was installed in the recirculation loop to strain large particles from the feed and recycled water. The required product flow rate was 500 L/h.

The ultrafiltration plant could be operated on its own (in parallel to another treatment facility), or as a polishing filter after the treatment facility. The treatment facility consisted of sand filtration, membrane filtration (option), ozone treatment, followed by granulated activated carbon and UV disinfection. This option was never exercised, for reasons beyond the control of the project team.

Operational history

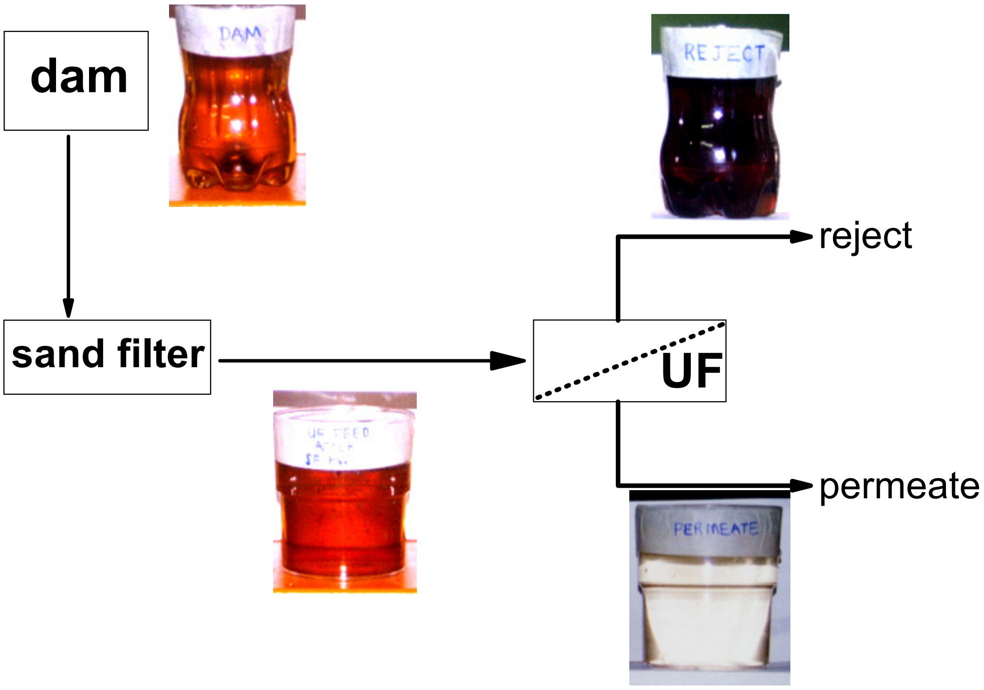
The inlet water was drawn from an unstabilised soil dam fed with run-off water from the mountains nearby. A grab sample of the reportedly source water was tested prior to construction and commissioning of the ultrafiltration plant. This grab sample, taken from a furrow that fed into a soil dam, had a turbidity of around 2 NTU, with a colour content of 350° Hazen. Unknown to the research team at the time, the walls of this and other dams were to be raised, but the construction had not been started at the time of sampling.

Construction to heighten the dam wall commenced just before the plant was commissioned. These activities had a direct impact on the quality of the inlet process water. Over a period of two to three weeks after construction of the dam had started and plant commissioning, the turbidity of the feed water rose from 30 NTU to above 200 NTU. Virtually no settling occurred when samples of the feed water was stood in a vessel for 24 h, indicating that the suspended/colloidal solids in solution was very stable. The turbidity of this feed water was unaffected by sand filtration, and inlet turbidities as high as 250 NTU was fed to the ultrafiltration plant on occasion. The ultrafiltration unit was operating at recovery ratios of >90%.

Samples of the high-turbidity water were filtered through a 0.45 lm Millipore filter. Whereas one would normally expect a very low turbidity filtrate as result, the turbidity of microfiltered water was still above 30 NTU, indicating that apart from the organic material present in the water, the membrane plant was fed water containing colloidal material of sizes smaller than 0.45 lm. This had an obvious impact on the flux performance of the membranes.

Initially, the UF unit was operated in parallel to the treatment facility, drawing water from the sand filters. However, as stated above, the sand filters were completely ineffective in reducing the high turbidity, and the UF was essentially drawing raw water as its feed.

The quality of the ultrafiltered product was excellent. Turbidities were in the region of 0.1 to 0.2 NTU and the colour of the product was between 20 and 30°H. The product also tested negative for coliforms on all occasions.



Colour removal at George

However, due to the extremely high turbidities that the membranes were being exposed to, the membranes fouled rapidly, with consequent decline in flux. The 500 L/h membrane plant was sized based on prior experience of waters of similar quality. Operating on a feed water equivalent quality as that of the initial grab sample, it was anticipated that the membranes would require a chemical clean at no less than monthly intervals. As it turned out, when operating on the high turbidity water the membranes had to be cleaned bi-weekly, which was clearly unacceptable.

An obvious choice would have been to follow the more conventional approach, that of inline flocculation, coagulation and pressure sand filtration prior to UF. However, the whole initiative was to move away from chemical dosing to assist in water clarification and disinfection, and the idea was shelved. This initiated experimentation to reduce the turbidity of the feed water by some non-chemical pre-treatment technique. Two non-chemical pretreatment methods were evaluated – biofilters and the vertical microfilter.

(i) Bio-filtration - Microfiltration filters were constructed of open-celled phenolic foam. The filter elements had surface areas of about 2 m^2 and was fitted inside 200mm OD PVC pipes. Filtration was operated in the outside-in configuration, and the filters could be back-flushed. It was also thought possible that micro-organisms would establish themselves within the 150 lm pores of the foam, giving rise to bio-filtration and a reduction in the organic load of the water. Although excellent quality water was produced when the filter was tested on Theewaterskloof water, the filter did not perform that well at the George site. Part of this problem could be ascribed to the high throughput required from the one filter to provide a reasonable flow to the ultrafiltration plant. Typically the filter would bring about a reduction of 5 % in colour and 20 to 40 % in turbidity. The filter is simple to construct and not expensive when compared to the price of the 50 NW strainer installed in the recirculation loop.

(ii) Vertical Microfilter (VMF) - A new-design vertical microfilter was fabricated from flexible woven fibre, similar to that used in cross-flow microfiltration. Depending on the construction, up to 5 m^2 filtration area could be housed in a 2 m tall filter. The filter responded very well to back-rinsing. When tested on Theewaterskloof and Inanda dam water, the VMF gave very good turbidity reductions. However, when the filters were tested at the George facility, their performances were very poor, with permeate turbidities of > 100 NTU being achieved for feed turbidities of about 200 NTU. The fine colloids present in the George water caused rapid blinding of the filter, with a resultant fast rise in differential pressure and decrease in product flow. Inline flocculation with poly(aluminium chloride) produced a fragile floc, but did not contribute to a solution for the process.

The objective of obtaining an effective non-chemical pretreatment was not achieved, primarily due to the horrendous quality of the particular water. Without such a pretreatment, the operating the UF on its own was not viable. While the quality of the UF product was excellent, fouling was excessive and necessitated frequent cleaning.

The contractor eventually pursued the conventional route of flocculation, coagulation, settling and pressure sand filtration. A request was made to the project team to install the UF after the pressure filters as a final polishing step. However, this deviated from the one of the main aims of the project - i.e. to develop a stand-alone UF system without chemical dosing. It was decided to terminate the exercise at George, and concentrate on more appropriate applications.

Problems abounded during this exercise. Expectancies of the client were unduly raised by the simplicity of the plant design. The problem of aesthetics also played its part. The mere fact that a glass filled with product looked fine, but a bath filled with the same product did not, as a point of serious conjecture.

The main problem, and one that is not indigenous to this particular exercise, is that of either farmer interference or non-interest. In this particular case, the farmer-owner was not interested in overseeing the unit, not even in twice daily monitoring two pressure gauges. Although the membranes could withstand the maximum operating pressure of the feed pump as differential pressure, and would therefore not fail unit such operating conditions, membrane blockages could occur in such instances.

This is indeed what happened when the farmer did not report when the flux dropped below an indicated minimum. Irreversible blockage of an entire bank of membranes was a direct result of this.

One problem for which there is no immediate solution is that of inexpensive automatic valves. The coils of solenoid valves have limited life, and need replacement sooner or later. Failure of some of the valves on a plant can be critical to the operation of a plant. Ideally one would not like to see a coil being excited for the full duration of a filtration run, because it would have an adverse effect on its service life.

A3 Wiggens

Description of unit

The Wiggens unit was located at the Umgeni Water Process Evaluation Facility, Wiggens Water Works, Durban. The capital cost of this unit was paid for by Umgeni Water, but the unit was made available to the project in terms of Umgeni Water's broader objective of evaluating capillary UF for water purification.

The unit consisted of a feed pump, four recycle pumps, a product pump, feed and recycle strainers and six modules (giving a filtration area of 30 m^2.) . Post-treatment facilities for lime contacting or activated carbon contacting were included in the unit, but these were not used during the course of this project. A CIP tank and CIP pump were integrated into the unit, to facilitate onsite membrane cleaning. The unit was fully automated with PLC control. It was designed to operate in the cross-flow mode, and was equipped with a back-flush facility. At a later stage of the project a flow-reversal unit was added. The flow-reversal unit switched the direction of feed flow every 10 minutes. During the course of the project various automated monitoring devices were added, and eventually all critical pressures, flowrates and turbities were monitored and recorded online. This unit is complete (stand-alone) and is mounted inside the container, with only the feed holding tank outside.

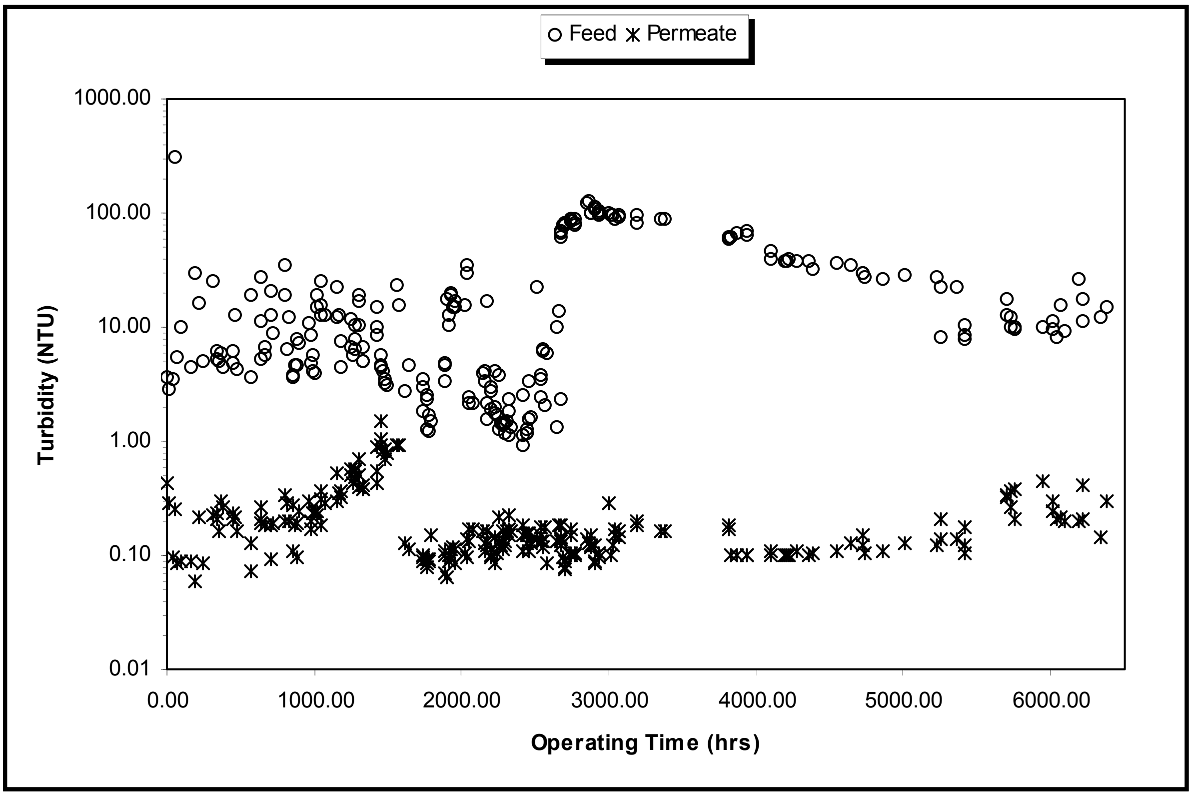
Pretreatment is minimal and consisted of a sand filter after the feed pump. There was no coagulation/flocculation before the sand filter. In practise, the sand filter proved to be of little effect, and was often bypassed during operations.

The unit was designed to operate in the cross-flow mode at a constant flux. The constant flux is achieved with the product pump, which withdraws permeate at a preset rate. During the course of the current project, however, the unit was operated in the cross-flow mode at constant pressure. This was achieved by bypassing the product pump, and controlling the operating pressure via a valve on the reject line. Primary flux enhancement was via back-flushing. At a later stage of the project, reverse flow and reverse pulse were added.

Operational history

This unit was constructed and commissioned in 1997, and formed part of the investigation for WRC Project No 764, *Water Supply to Rural and Peri-Urban Communities Using Membrane Technologies*. Most operational problems and modifications were sorted out during 1998. Accordingly, when the unit became available to this project during 1999, there were no significant operational or mechanical problems, and the unit was operated successfully till the end of 2001. The operation from 1997 to 1999 is reported in WRC Report No 764/1/00.

The unit draws water from the head of Wiggens Water Works. During the first 1000 hours of operation, the feed turbidity ranged from 5 NTU to 30 NTU. The permeate turbidity ranged from 0.1 NTU to 0.3 NTU. Between 1000 hours and 1500 hours, the permeate turbidity progressively increased to about 1 NTU. Investigations indicated that this increase was due to compromised fibres in the modules.



Turbidity History of Wiggens Unit – 1999 to 2001

Up to this point, the unit was operated with the so called "skinless" membranes. Previous field experience had shown that while the skinless membranes were capable of producing a good quality of permeate, their quality was very sensitive to the production process. Since all membranes were being produced on a research production line that did not have adequate quality controls, the quality of the membranes being used in the field were not optimal. Hence, breakages were occurring in the field, yielding poor permeate turbidities.

Recognising that the skinless membranes were very sensitive to the production process, Dr Jacob's team at the Institute of Polymer Science, University of Stellenbosch, had begun the development of a new membrane, #798, which was fundamentally different from the skinless membranes. These new membranes did not have the open pore structure typical of the skinless membranes, and were expected to be more robust. Accordingly, the skinless membranes were removed and replaced with the new #798 membranes after about 1500 hours of operation.

From about 2000 hours, the feed turbidity decreased slightly, down to as low as 1 NTU. After about 2500 hours, however, there was a sudden increase to about 100 NTU, coincident with heavy rains in the KZN region. From 2500 hours to 6500, the feed turbidity showed a slow decrease to about 20 NTU. From the changeover to the new membranes, the permeate quality remained very good, ranging from 0.08 NTU to around 0.25 NTU, despite the high feed turbidities.

After about 7000 hours of operation, the unit was modified for flow reversal and reverse pressure pulse. The effects of these flux enhancement strategies on the units performance were studied as an MTech project by Mr N Moodley, and the findings will be made available as his MTech thesis shortly.

In overview, the operation of the Wiggens unit was relatively problem free. However, various possible improvements to the mechanical design were identified, and are discussed below.

A4 Stanger

Description of unit

The unit that was employed at George was revamped and relocated to a farm near Stanger at the beginning of 2001. The revamping consisted of adding a second frame which held a feed pump, flow reversal setup and cartridge filters, as described below.

The unit is designed to operate both on dead-end as well as cross flow. It consists of two pumps that are situated on the main frame. These pumps are used for back flush and recycling. The feed pump, which is also used for CIP, is mounted on the external stand with the CIP tank. The unit has a 200 μm online strainer on the recycle line. For pre-treatment, the unit has a series of cartridge filter of varying pore sizes. These filters are on an external stand and are connected to the unit using high-pressure flexible hose. There are six cartridge filters, divided into two parts. Each part consists of three-cartridge filters ranging from big to small pore sizes. The two sections are symmetrical, they can be used in parallel, with all six being used or just one bank. The filters can handle 3 kl/h flow through it.

The unit has a small PLC, which is used for automation. The PLC is used for back flush control as well as flow reversal control. The unit is protected by the high pressure switch, which control the feed pump. The unit can also be operated manually, but in this mode, flow reversal is not applicable due to the type of valves used. CIP is only done manually and is done on site. The unit is capable of performing back flush as well as purge for flux enhancement purpose. Back flush duration and intervals are set on the timers and these are done before the plant is started.

The unit was design for the twelve modules, but only six were installed. This gives a capacity of 1200 L/hr or 28.8 kL/day, but the permeate rate was restricted to 550 L/h or 13.2 kL/day. The restriction was done to prolong the runtime between the chemical cleans.

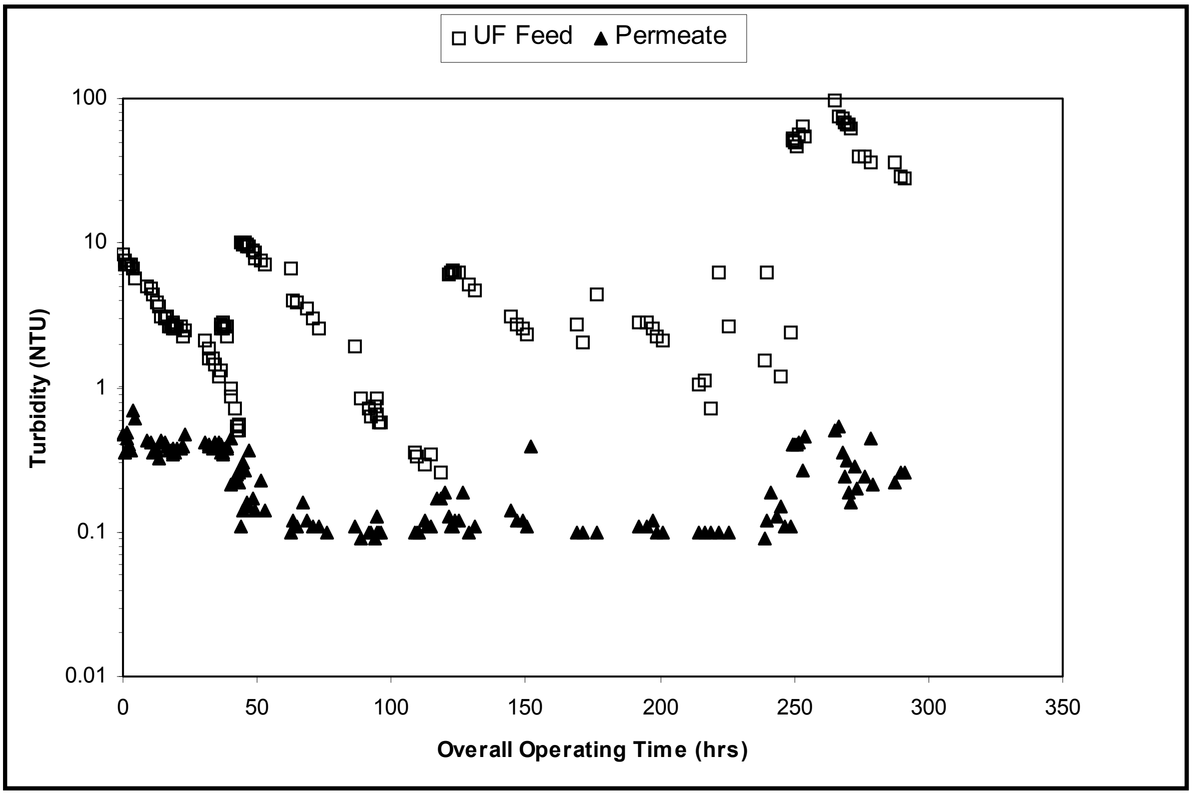
Operational history

The unit was relocated to the farm in January 2001. The existing system at the farm was that feed water was drawn directly from the Nanoti River by a submersible pump. This was then pumped into a concrete tank which fed the household by gravity. The CUF unit was installed next to this concrete tank. The outlet from the concrete tank was connected as the feed to the CUF unit. The permeate was fed into a PVC tank installed above the concrete tank, from where it was gravity fed to the household.

From February to June, the unit was run intermittently, as various site specific mechanical problems were experienced with obtaining a regular feed from the submersible pump. These were eventually solved by completely replacing the line from the river to the concrete tank, and replacing the submersible pump with an inline pump with a suitably large suction head. . The unit was then commissioned and operated smoothly for about three weeks. During this period, the feed turbidity was approximately 10 NTU, and a permeate of 0.5 NTU to 0.1 NTU was produced. It was apparently the first time that the farm had seen clean running water on the premises. Previously, drinking water was transported in vessels from the nearby town. A worker at the farm was trained to monitor the unit, and the project team left the unit in his charge.

Then disaster struck in the form of the concrete tank collapsing under the weight of the permeate tank, and destroying parts of the building structure in the process. A PVC tanks was installed to replace the old concrete tank, and the unit was restarted in September. In the interim, heavy rains had been experienced, and the feed from the river had a turbidity exceeding 200 NTU. The unit continued to give a good product with this water, but the load on the cartridge filters was too high, necessitating them being cleaned very frequently. An attempt was made to reduce this loading by installing a second PVC tank before the CUF unit to act as a settler. This did reduce the turbidity marginally, but not sufficiently to reduce the loading on the cartridges. Accordingly, the project team had to intervene almost twice weekly to clean out the cartridges as well as perform frequent chemical cleans on the membranes.

Eventually it was decided that the feed turbidity was too high to operate the CUF unit without effective pre-treatment, and the unit was shut down in November. The overall turbidity removal history is shown below :



Turbidity removal at Stanger farm

A5 Cramond

Description of unit

Towards the end of 1999 the project team was contacted by a farmer in the Natal midlands who intended producing and bottling potable water. An experimental rig was fabricated and relocated to the farm in July 2000. The unit was designed to operate on dead-end mode only. It consists of two small pumps that are situated on the unit itself. One pump is used for back flush and the other one is used for CIP. The feed pump is external to the unit. The unit does not have the PLC, and the different operating cycles are controlled by timers. The unit is capable for automatic and manually operation. For normal operation, the unit is run automatically while the CIP (Clean In Place) is done manually. The mode of operation can be selected on the control panel. The plant is capable of performing back flush as well as purge for flux enhancement purpose. Back flush duration and intervals are set on the timers and these are done before the plant is started. The unit was commissioned with one but has the capacity for the three modules. This gives an installed capacity of 200 L/hr or 4.8 kL/day, and a design capacity of 14.4 kL/day. The Cramond unit is the simplest unit that was constructed during this project.

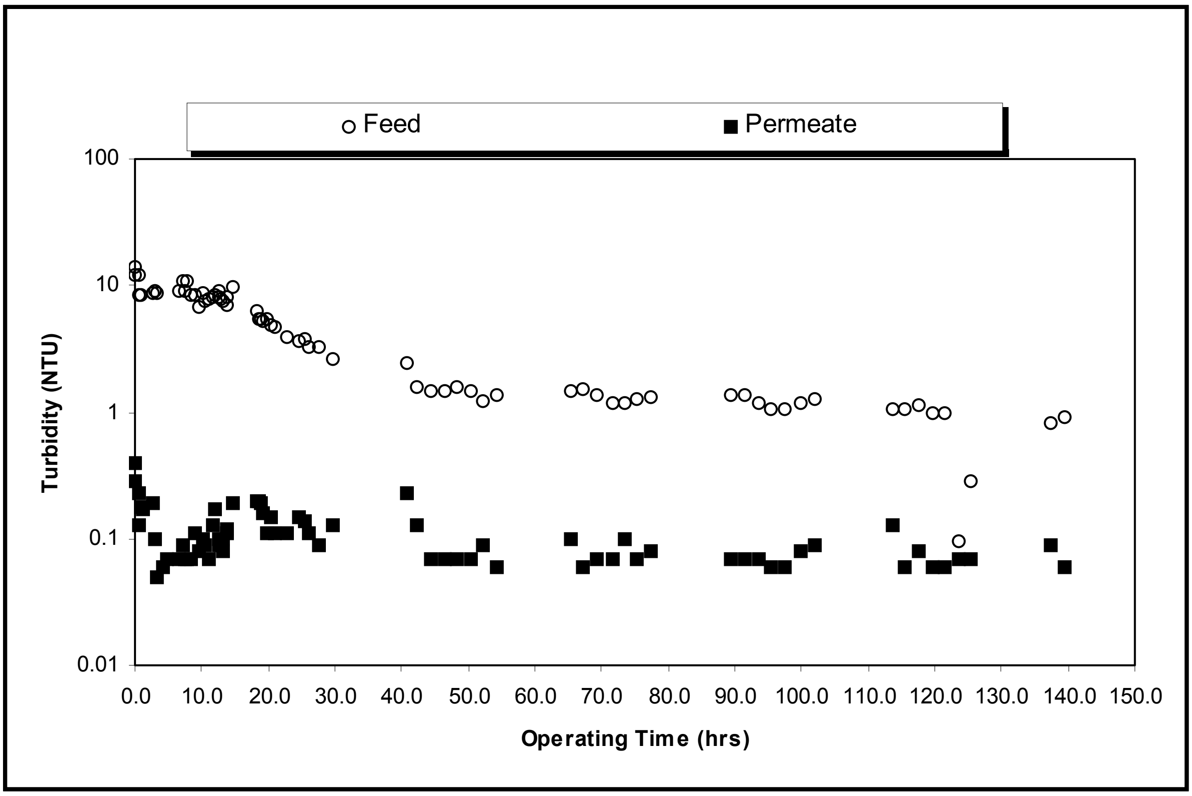
Operational history

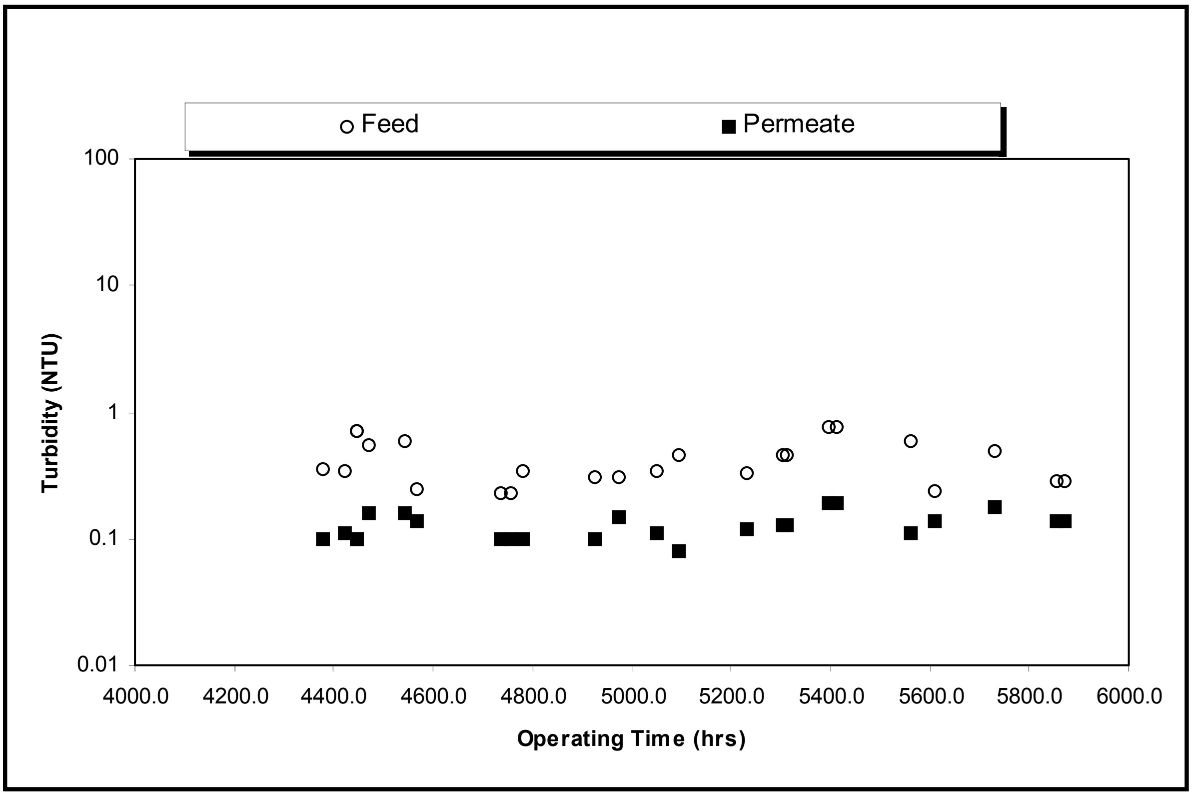
The feed water originated in a spring, and is piped by gravity to the farm. The raw water is firstly settled in a tank, and then pumped through a 25 micron filter followed by a 5 micron filter. Thereafter the water is pumped through a UV disinfection unit. The farmer intended using a capillary UF unit after UV disinfection, to act as a positive barrier and a final polishing step. The feed water quality varies from very good to poor, as shown below.

DETERMINAND	RAW WATER		WATER TO UV
	Analysis 1	**Analysis 2**	**Analysis 2**
Coliforms	150	0	0
E.Coli	90	0	0
F.Strep	150		
Total counts (37 ^{o}C)	600	456	632
Total Counts (25 ^{o}C)	9 100	> 1 000	768
pH	6.6	7.14	7.23
Turbidity	9.53	1.37	0.41

Accordingly, it was regarded as essential to have an ultrafilter as part of the treatment system, to guarantee removal of pathogens, when they occurred.

Turbidity removals at the commissioning of the unit and after about 4000 h of operation are shown below :





<u>Turbidity removal at Crammond</u>

The farmer has had the product water from the CUF unit tested by a leading water authority, and it met all drinking water standards. The product also compared very favourably with various leading brands of bottled water that are currently available on the market. The water is being bottled and marketed under the tradename "Boschspruit".

Chemical cleaning has been performed approximately once in every six months. There have been no significant operational problems with the unit. As at the end of 2002, the unit was still operating successfully.

A6 Bottlenecks Identified / Lessons Learnt

(i) The Hermanus experience contributed to the view that the user should not be depended on to maintain the unit and effect membrane cleaning. For long term sustainability, it would be necessary to "farm" maintenance and cleaning out to a dedicated person, who will accept full responsibility for the unit. This gave rise to the "regional" maintenance concept, where one appropriately skilled person would be responsible for maintenance and membrane cleaning in a gepgraphic region.

(ii) Running a unit on a widely varying feed turbidity and depending on the user monitoring the unit to identify potential problems before they occur is not realistic or sustainable. In the George experience, this resulted in an entire bank of membranes becoming completely blocked. It is feasible to build sufficient intelligence into the unit to get it to shut down prior to blockages developing. However, this would be fairly expensive, and introduce a further element of complexity. For long term reliability, it would most probably be necessary to limit the turbidity of the feed entering the UF unit, by installation of suitable pretreatment.

(iii) Although the unit is fully automated, daily monitoring is preferable, in order to ensure that the unit is operating and also to ensure "ownership" and "responsibility" for the unit. However, from both the Hermanus and George experiences, it emerged that the user (farmer) may not be the best person to monitor the unit. This responsible for this should be given to someone else with easy access to the unit, e.g. farm supervisor or senior farm worker, and should be made a part of their daily duties. In addition, paying a small stipend for the monitoring would probably go a long way towards ensuring the monitoring gets done, while adding very little to the operating costs.

(iv) The aspect of mechanical failure of valve actuators must be addressed in any maintenance strategy.

(v) In the original unit design, the modules fitted into the manifolds as bayonets, and the manifolds were held together by turnbuckles. Since the Wiggins unit was used as an experimental and training unit, the modules were frequently removed to facilitate modifications etc. It emerged that the existing module and manifold design was problematic, in that it took quite some effort to align the manifolds and obtain the right tension in the turnbuckles. This motivated the development of a new manifold and endblock design which would be easier to assemble and take apart. This new design is described in the final report of Project No 965.