DEVELOPMENT OF AN ULTRAFILTRATION PRETREATMENT SYSTEM FOR SEAWATER DESALINATION BY REVERSE OSMOSIS

by

NKH STROHWALD[*], EP JACOBS[**] and A WESSELS[*]

CONTRACT REPORT TO THE

WATER RESEARCH COMMISSION

by

MEMBRATEK (PTY) LTD[*]
PO BOX 7240
NOORDER PAARL
7623

and

INSTITUTE FOR POLYMER SCIENCE[**]
UNIVERSITY OF STELLENBOSCH 7600

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EXECUTIVE SUMMARY

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WRC PROJECT No 467

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PROJECT BACKGROUND

The need for the reliable supply of potable water to growing, remotely located coastal settlements, e.g. Walvis Bay, has recently received renewed attention. One of the most feasible processes for this purpose is the desalination of seawater by reverse osmosis.

The seawater along the Atlantic coast of Southern Africa is known for its high content of membrane fouling materials e.g. nutrients, suspended solids and organic materials. These conditions constituted major pretreatment problems during earlier reverse osmosis (RO) desalination trials near Swakopmund, Namibia in 1982/83. One of the findings of these trials was that membrane filtration may be a viable alternative to conventional pretreatment methods, provided that operation can be kept inexpensive, simple and preferably automated. The development of low-cost tubular MEMTUF^R modules at Membratek and capillary ultrafiltration modules at the Institute for Polymer Science (IPS), therefore, aroused renewed interest with regard to the pretreatment of seawater by ultrafiltration (UF).

The use of membrane filtration, in particular UF, in the pretreatment of seawater destined for desalination by RO, has been reported to be competitive with combined media and carbon filtration. Previous pilot plant work concerning seawater desalination by RO (WRC project no. 345), during which the pretreatment of seawater by UF was attempted, showed the main advantage to be the production of RO feedwater of sufficient quality for direct use with compact and highly efficient membrane desalting permeators such as hollow fine-fibre systems.

The incentive for this project, therefore, was to evaluate and optimise various UF membrane configurations for the pretreatment of seawater, with specific emphasis on membrane cleaning.

PROJECT OBJECTIVES

The aims of this project, concerning the development of a locally manufactured UF membrane system for seawater pretreatment prior to reverse osmosis, were as follows:

Technical feasibility of UF pretreatment

It was desired to identify the requirements of an ultrafiltration system for use in the pretreatment of seawater prior to desalination by reverse osmosis.

Development of UF pretreatment system

The second objective was to develop and refine an ultrafiltration pretreatment system, in conjunction with ancillary equipment, which would satisfy the desired requirements.

Evaluation of UF pretreatment system

The final objective was to evaluate the performance of the developed system through long-term continuous operation.

RESULTS AND CONCLUSIONS

For the successful application of ultrafiltration in the pretreatment of seawater, prior to desalination by reverse osmosis, two important system requirements were identified:

i) *LOW MODULE COST.* The module material cost, in conjunction with the productivity of a particular module, was regarded as the prime indicator of the economical viability of the UF membrane system. Therefore, rather than comparing module material cost per square metre membrane area (R/m^2), a cost factor, incorporating module cost per cubic metre of permeate per day ($R.m^{-3}.d^{-1}$), was adopted to allow a direct comparison between different module types. In this preliminary investigation of different module types, the cost comparison was limited to accounting for the module material cost rather than the installed plant capital cost. Since the different module types require dissimilar ancillary equipment, a comparison of installed plant cost on an identical basis is difficult, unless detailed plant design and costing exercises are performed.

ii) *MECHANICAL MEMBRANE CLEANING.* It was shown in earlier seawater desalination trials (WRC report no. 345/1/92) that foulants could be removed from the UF membranes by mechanical cleaning techniques. Module configurations which allowed mechanical membrane cleaning were considered to have operational advantages, provided that the mechanical membrane cleaning procedure was highly effective and inexpensive. In other words, the net gain in productivity obtained through mechanical cleaning had to offset the higher module material cost of these large-bore tubular modules, when compared to other module types of higher packing density *e.g.* capillaries.

EXPERIMENTAL APPROACH

Two distinct approaches were followed in an attempt to reduce the specific cost factor:

1) Operation at the highest sustainable flux, using frequent mechanical cleaning by sponge balls, with the new low-cost SWUF design in anticipation that the higher membrane productivity would offset the higher module material cost when compared to MEMTUF and capillary modules.
2) Operation at stabilised, lower flux with low-cost MEMTUF and capillary modules (respective development of these systems is documented in WRC reports 243/90 and 387/91), using infrequent chemical cleaning, trusting that lower module material cost of these configurations would outweigh the net loss in productivity. These systems do not lend themselves to sponge ball cleaning because of their inherent design.

MEMBRANE FOULING

Medium and low molecular mass cut-off (MMCO) UF membranes used in the pretreatment of seawater for RO systems, were found to be equally prone to fouling. This resulted in a substantial reduction of productivity. The nature of the foulants and mechanism of fouling could not be determined due to their complex nature. Physical examination and EDAX analysis of the membrane surface, however, indicated a combination of organic and inorganic fouling.

MEMBRANE CLEANING

Tubular seawater ultrafiltration (SWUF) modules (12,5 mm tube diameter) could be cleaned mechanically with sponge balls through short-cycle flow reversal, while in operation, to maintain flux values which were approximately three times higher than those which were achieved without routine mechanical cleaning. In contrast, the tubular MEMTUF (9 mm tube diameter) and capillary modules, which could not be cleaned by sponge balls, showed considerable lower, but stable flux. In these modules, the foulant could be removed by adopting a biochemical cleaning regime with a proteolytic enzyme, followed by a chloralkali rinse.

COST COMPARISON

It was shown that with module material cost and the experimental flux values as basis, permeate could be produced with similar cost factors by SWUF and capillary modules. The higher material cost of the SWUF module was balanced by the higher productivity which could be maintained with on-line sponge ball cleaning. Similarly the potential advantage of lower material cost of the capillary module was diminished by the lower productivity since sponge ball cleaning could not be used. The specific cost factors ($R.m^{-3}.d^{-1}$) were calculated as 0,89 and 0,94 for SWUF and capillary, respectively with that for MEMTUF slightly higher at 1,56. As such both the SWUF and capillary configurations show potential in the pretreatment of seawater, from both technical and economic points of view.

PRESENT STATE OF THE ART

The experimental work conducted in the course of this project, resulted in the development of an ultrafiltration module which is specifically designed for the pretreatment of seawater. Although the use of capillary modules in this application is technically feasible, the ability of the SWUF modules to be cleaned mechanically with the aid of sponge balls, is considered to be a substantial advantage. Chemical cleaning may be reduced considerably, resulting in longer membrane life, easier operation, less down-time and lower operating cost. These advantages may be regarded as somewhat subjective since they cannot be easily expressed in direct monetary terms. From an operational point of view, however, a membrane system which allows sponge ball cleaning is preferred.

RECOMMENDATIONS FOR FURTHER RESEARCH

The development of the SWUF^{R} module has resulted in the commercial manufacture and use of a practical membrane separation system for the pretreatment of seawater prior to desalination by RO. Further refinement of the system would entail the design and incorporation of an injection moulded sponge ball trap into the epoxy casting of the module ends.

The prototype capillary concept on the other hand may be improved with regard to two specific aspects, *viz.* module design and membrane characteristics. Module design and commercial manufacture are currently being addressed through the compilation of product specifications. Optimisation of membrane performance for the specific purpose of seawater pretreatment may be conducted once commercially manufactured capillary modules are available.

ABSTRACT

Low-cost tubular and capillary polyethersulphone ultrafiltration modules have been developed and their use in the pretreatment of seawater for reverse osmosis desalination investigated. Mechanical and chemical cleaning regimes were evaluated for the restoration of the productivity of fouled membranes. The cost-effectiveness of using these UF membranes for pretreatment to RO, was found to depend on a combination of membrane configuration, type and frequency of cleaning regime, as well as average productivity. A tubular ultrafiltration system, incorporating these aspects, was developed (SWUF^{R} system) for commercial use.

ACKNOWLEDGEMENTS

Grateful consideration is given to the Water Research Commission for funding which enabled the development of prototype UF membrane systems and the completion of this project. The authors furthermore express their thanks to all staff of the Institute for Polymer Science who assisted with membrane cleaning trials and West Point Fishing Co. for their support and cooperation during on-site work.

LIST OF ABBREVIATIONS

DMF	Dual media filter
HFF	Hollow fine-fibre (membrane configuration)
IPS	Institute for Polymer Science
LMH	Membrane productivity (volume rate of permeate flow expressed as litres per square metre area per hour)
MEMTUF[R]	Registered tradename for Membratek's low-cost unsupported (9 mm diameter) tubular ultrafiltration system
MMCO	Molecular mass cut-off
PVC	Poly vinylchloride
SDI	Silt density index (measure of fouling potential of feedwater to membranes)
STUF	Standard tubular ultrafiltration
SWUF[R]	Registered tradename for Membratek's low-cost unsupported (12 mm diameter) tubular ultrafiltration system for seawater pretreatment
TUF	Tubular ultrafiltration
UF	Ultrafiltration

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SECTION ONE : INTRODUCTION

1.1 PROJECT BACKGROUND

The use of membrane filtration, in particular ultrafiltration (UF), in the pretreatment of seawater destined for desalination by reverse osmosis (RO), has been reported to be competitive with combined media and carbon filtration *(Ericsson and Hallmans, 1991)*. Previous pilot work concerning seawater desalination by RO, during which the pretreatment of seawater by UF was attempted, showed the main advantage to be the production of RO feedwater of sufficient quality for direct use with compact and highly efficient membrane desalting permeators such as hollow fine-fibre systems *(Strohwald, 1992)*. The quality of the UF permeate was excellent with respect to turbidity and Silt Density Index (SDI) and was insensitive to variations in the quality of the raw seawater intake.

The seawater along the Atlantic coast of Southern Africa (refer Figure 1.1) is known for its high content of membrane fouling materials *e.g.* nutrients, suspended solids and organics. These conditions constituted major pretreatment problems during earlier RO desalination trials near Swakopmund, Namibia *(DWA-SWA, 1982)*. One of the findings of these trials was that membrane filtration may be a viable alternative to conventional pretreatment methods, provided that operation can be kept inexpensive, simple and preferably automated. The development of low-cost tubular MEMTUF^R modules at Membratek *(Barnard, 1991 and Strohwald, 1991)* and capillary ultrafiltration modules at the Institute for Polymer Science (IPS), therefore, aroused renewed interest with regard to the pretreatment of seawater by UF.

Previous pilot work near Lüderitz, concerning the ultrafiltration and desalination of seawater *(Strohwald, 1992)*, showed a rapid flux decline due to membrane fouling, as is the case with most UF applications. Although membrane flux on seawater stabilised asymptotically with time, operation at the substantially higher initial flux level was desired. If the initial flux levels could be maintained, significant plant capital cost savings would be achieved. A simple and inexpensive means of flux restoration would, however, be required since flux values reduced by 50% within approximately 35-40 hours of continuous operation. As such, subsequent cleaning methods and module design were directed towards the prevention of membrane fouling, rather than being approached from a membrane cleaning point of view.

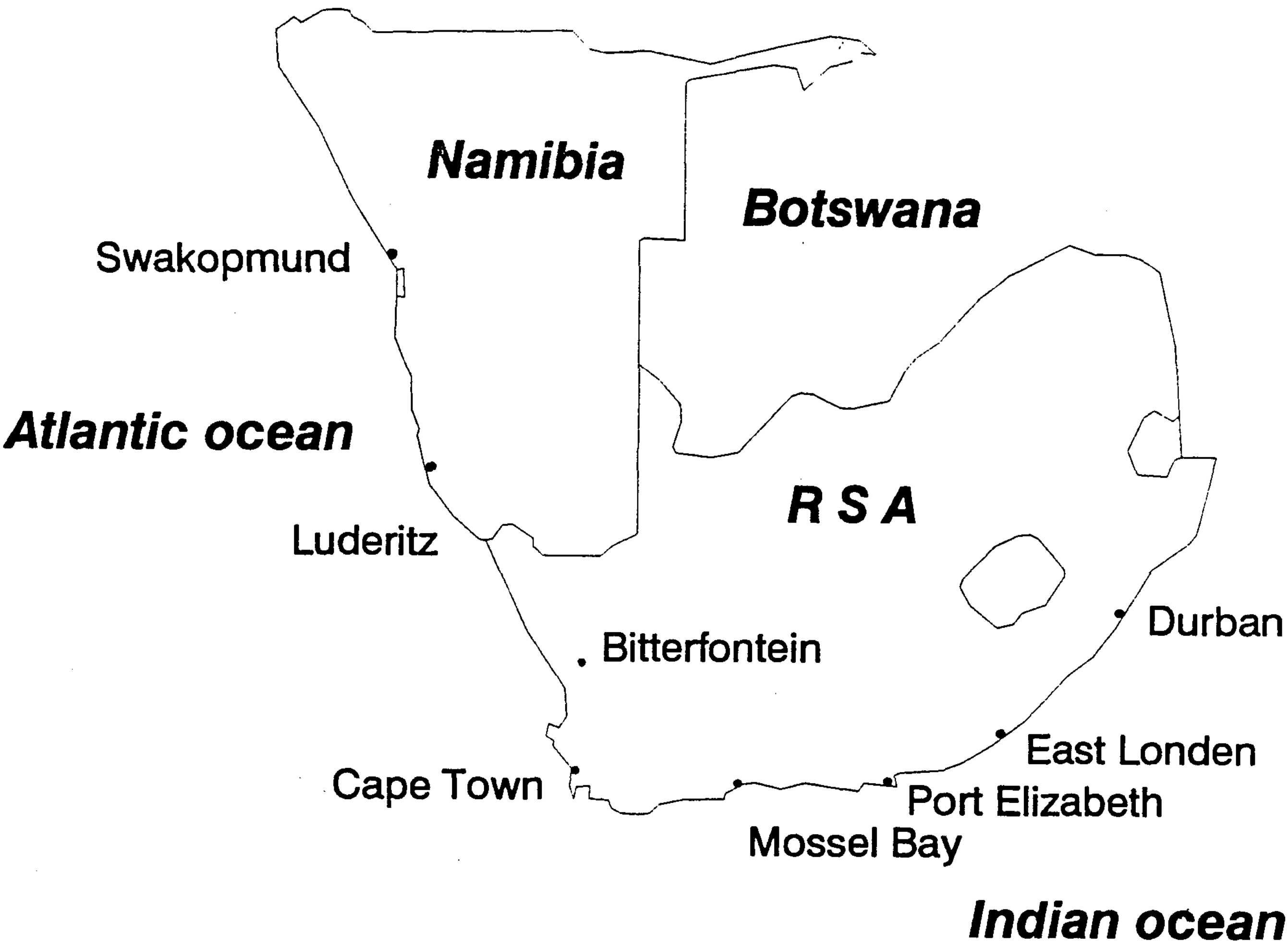


FIGURE 1.1 MAP OF SOUTHERN AFRICA

1.2 PROJECT OBJECTIVES

The aims of this project, concerning the development of a locally manufactured UF membrane system for seawater pretreatment for reverse osmosis, are summarised in the following paragraphs:

1.2.1 TECHNICAL FEASIBILITY OF UF PRETREATMENT

It was desired to identify the requirements of an ultrafiltration system for use in the pretreatment of seawater prior to desalination by reverse osmosis.

1.2.2 DEVELOPMENT OF UF PRETREATMENT SYSTEM

The second objective was to develop and refine an ultrafiltration pretreatment system, in conjunction with ancilliary equipment, which would satisfy the desired requirements.

1.2.3 EVALUATION OF UF PRETREATMENT SYSTEM

The final objective was to evaluate the performance of the developed system through long-term continuous operation.

SECTION TWO : EXPERIMENTAL

2.1 ULTRAFILTRATION SYSTEM REQUIREMENTS

For the successful application of ultrafiltration in the pretreatment of seawater, prior to desalination by reverse osmosis, the following important system requirements were identified:

i) *LOW MODULE COST.* The module material cost, in conjunction with the productivity of a particular module, was regarded as the prime indicator of the economical viability of the UF membrane system. Therefore, rather than comparing module material cost per square metre membrane area (R/m^2), a cost factor, incorporating module cost per cubic metre of permeate per day ($R.m^{-3}.d^{-1}$), was adopted to allow a direct comparison between different module types. In this preliminary investigation of different module types, the cost comparison was limited to accounting for the module material cost rather than the installed plant capital cost. Since the different module types require dissimilar ancilliary equipment, a comparison of installed plant cost on an identical basis is difficult, unless detailed plant design and costing exercises are performed.

ii) *MECHANICAL MEMBRANE CLEANING.* Module configurations which allow mechanical membrane cleaning were considered to have operational advantages, provided that the mechanical membrane cleaning procedure was highly effective and inexpensive. In other words, the net gain in productivity obtained through mechanical cleaning had to offset the higher module material cost of these large-bore tubular modules, when compared to other module types of higher packing density *e.g.* capillaries.

2.2 DEVELOPMENT OF SWUF MODULE CONCEPT

2.2.1 BACKGROUND

Desalination trials with hollow-fine fibre (HFF) reverse osmosis (RO) permeators at Elizabeth Bay near Lüderitz, Namibia *(Strohwald, 1992)* indicated that the pretreatment of seawater with tubular ultrafiltration could produce a RO feedwater of excellent quality. In contrast, conventional pretreatment comprising coagulation, dual media and cartridge filtration, could often not deliver a RO feedwater of the desired turbidity and silt density index (SDI). The permeate quality of the UF pretreatment regime was furthermore shown to be insensitive to variations in raw seawater quality during adverse weather conditions.

The low-cost MEMTUF modules used in these trials produced a high quality permeate, but suffered from rapid flux decline due to membrane fouling. Although stabilised flux values of 40-45 LMH were considered to be economical, operation at the starting level of 90-100 LMH was desirable. Unfortunately this flux decline occurred within the relatively short time of 35-40 hours. Chemical cleaning trials at both Elizabeth Bay and in the laboratory proved unsuccessful with the exception of an EDTA/NaOH solution. However, the high pH of this solution (being considerably in excess of the recommended maximum for the MEMTUF module), together with the rapid flux decline rate, excluded this chemical cleaning regime as a routine means for flux restoration. Positive results were nevertheless obtained with mechanical membrane cleaning operations. The two most promising regimes were ultrasonic and sponge ball cleaning. The high energy input and technical complexities associated with ultrasonic cleaning made this option impractical, especially on a large scale. Sponge ball cleaning, on the other hand, showed considerable potential, being both simple and comparatively inexpensive. Unfortunately the design of the MEMTUF modules does not lend itself to sponge ball cleaning by conventional means, *ie.* flow reversal and sponge ball traps, due to their internal flow configuration. MEMTUF module blocks used at Elizabeth Bay therefore had to be dismantled, followed by manual insertion of sponge balls into the flow passages. It was subsequently decided to modify standard tubular ultrafiltration (STUF) modules, which have a well-defined series flowpath, for the testing of the sponge ball cleaning concept on site.

2.2.2 MODIFIED STUF MODULES

STUF modules (1,75 m^2 membrane area; 12,5 mm tube diameter) were modified with regard to shroud material and the fitting of a sponge ball trap on both the inlet and outlet. The standard marine-grade aluminium shroud was replaced by PVC to reduce cost and investigate the adhesion characteristics of the epoxy end-castings (into which the membrane tube-ends are encapsulated) to the shroud material. The conventional tube support discs and 19 tube series configuration were retained.

With half-hourly sponge ball cleaning, effected with the use of the sponge ball traps and a manual flow reversal system, the flux could be maintained between 90 and 95 LMH using operating conditions similar to the MEMTUF unit. These experiments, which were performed during desalination trials at Elizabeth Bay (*Strohwald, 1992*), consitituted the basis for the refinement of the sponge ball cleaning concept and which subsequently led to the development of the so-called SWUF^R (seawater ultrafiltration) module.

2.2.3 PROTOTYPE SWUF MODULES

The incentive for the development of the SWUF concept was to develop a module with a cost basis comparable to the MEMTUF system, but having the facility of sponge ball cleaning.

Tube support systems and packing density had previously been identified as the major cost contributing factors in the construction of low-cost UF systems *(Barnard, 1991 and Strohwald, 1991)*. As such the conventional tube support system of the STUF module design was discarded, leaving the tubes essentially unsupported with the exception of the polyester backing fabric, as is the case for MEMTUF modules. The number of tubes housed in a single shroud was increased from 19 to 26. This number was considered optimum, taking into account standard available PVC pipe sizes, module pressure drop and flow characteristics. Together with an increase in overall module length, this resulted in a 67% improvement of packing density from 92 to 155 m^2/m^3 (refer Table 2.1).

The incorporation of custom designed, injection moulded sponge ball traps into the epoxy end-castings of the SWUF module was considered, but tooling costs were regarded as prohibitive for initial prototype construction. It was therefore decided to retain sponge ball traps, made from standard PVC fittings, as part of the manifold system, assuming the SWUF module to be a disposable item.

TABLE 2.1 : COMPARISON OF PACKING DENSITIES FOR VARIOUS TUBULAR MODULES

PARAMETER	STUF MODULE	SWUF MODULE	MEMTUF MODULE
Number of tubes	19	26	40
Tube diameter (mm)	12,5	12,5	9,0
Shroud dimensions (mm)*	98,2φ x 2500	88,2φ x 3160	130 x 63 x 3167
Shroud volume (m^3)*	0,0189	0,0193	0,0259
Membrane area (m^2)	1,75	3,0	3,0
Packing density (m^2/m^3)	92	155	115

* Not strictly applicable to MEMTUF since these modules have no shroud. Dimensions given refer to overall size of end blocks and module length which determine holding tank size.

2.3 PILOT STUDY SITE

A suitable test site for the evaluation of the various membrane systems had to be found and was chosen according to the following criteria:

1. *LOCATION.* If possible, the proposed site should be close to the base of operations in order to facilitate ease of plant supervision, data collection and plant maintenance;
2. *SEAWATER.* Untreated, raw seawater had to be available at a rate of 50 l/min at 150 kPa, preferably from an existing seawater intake.
3. *ELECTRICAL SUPPLY.* Electricity requirements of 1,5 kW (380V AC) had to be satisfied.
4. *WASTE DISPOSAL.* UF retentate and cleaning solution waste had to be disposed of in a practical fashion.
5. *FLAT AREA.* A suitable flat area of 4 x 5 metres on which the pilot plant equipment could be placed, had to be available.
6. *ACCESS AND SECURITY.* Ease of access for unloading and loading of plant equipment was desired, together with basic security to prevent damage of the equipment by vandals.

Based on these criteria, the most appropriate site proved to be on the premises of West Point Fishing Co. at St. Helena Bay on the Cape West Coast.

2.4 EXPERIMENTAL EQUIPMENT

2.4.1 MEMBRANE SYSTEMS

Several membrane systems were evaluated, ranging from Membratek's tubular MEMTUF and SWUF formats to IPS prototype capillary modules.

Ultrafiltration Modules

The MEMTUF and SWUF systems make use of unsupported tubular UF membranes with respective diameters of 9 and 12,5 mm. A MEMTUF tube bundle comprises 40 tubes which can be internally manifolded in various parallel-series flowpaths, *e.g.* 1 x 40, 2 x 20 or 4 x 10 according to the hydrodynamic requirements of the application. Modules are manufactured in lengths of up to 3 167 mm and effective membrane areas of up to 3 m^2 (refer to Table 2.1). Such modules are suspended either vertically or horizontally inside a holding tank which serves to protect the modules against mechanical damage and simultaneously acts as a permeate collection vessel. The MEMTUF module used in the experiment had a membrane area of 0,4 m^2 and a flowpath configuration of 2 parallel by 20 series (2 x 20) passes. A schematic of a typical MEMTUF module is shown in Figure 2.1.

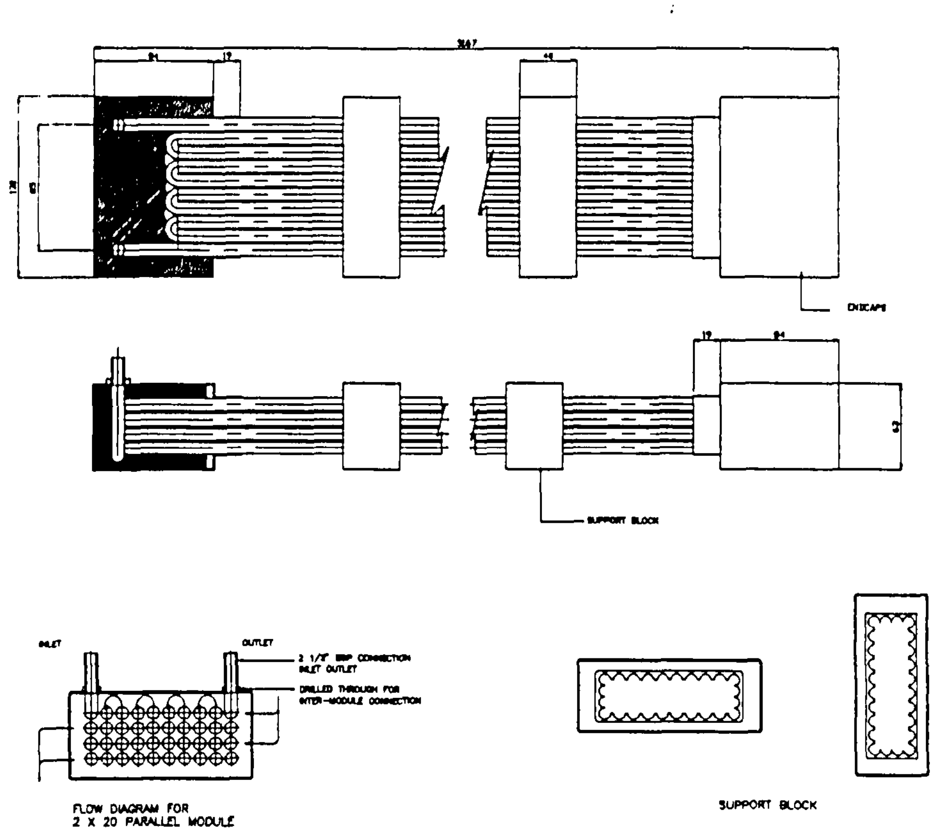


FIGURE 2.1 SCHEMATIC OF MEMTUF MODULE

SWUF modules, on the other hand, consist of 26 series-connected tubes which are housed inside a 3 160 mm long unplasticized PVC (uPVC) tube, with a membrane area of 3 m^2 per module (refer to Figure 2.2). The well-defined, single series flowpath of the SWUF module allows mechanical cleaning of the UF membrane surface with sponge balls. In both types of modules the membrane-ends and their interconnecting caps are cast into epoxy which serves to anchor the tube bundle and provides a barrier between the feed or retentate and permeate streams.

Capillary modules used in the experiment had membranes with typical external and internal diameters of 1,8 and 1,5 mm,respectively. Bundles of 200 to 250 capillaries were housed in clear uPVC tubes to give an overall module length of 1 200 mm. The internally-skinned membranes were end-potted in a tube-and-shell arrangement with a special epoxy resin which adheres well to PVC. A diagrammatic view of a capillary module is presented in Figure 2.3.

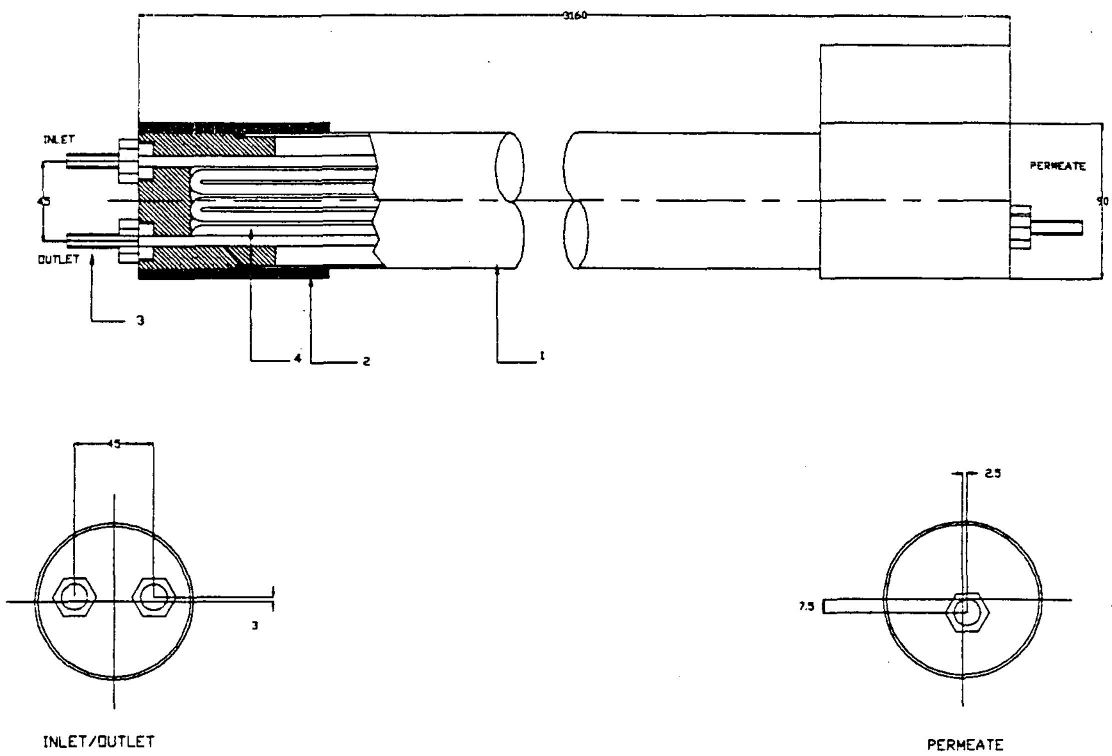
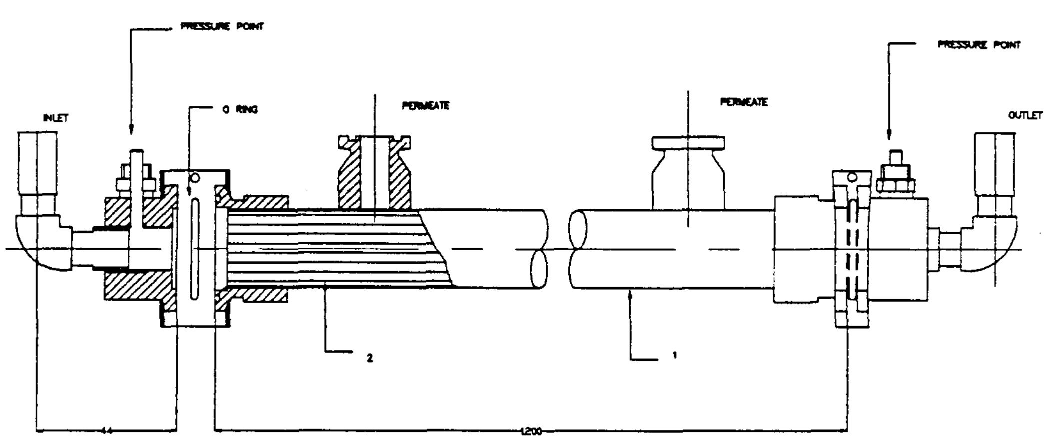


FIGURE 2.2 SCHEMATIC OF SWUF MODULE



FIGRE 2.3 SCHEMATIC OF CAPILLARY MODULE

Ultrafiltration Membranes

The 719-series UF membranes used in the MEMTUF modules had a molecular mass cut-off (MMCO) of 40 000 dalton while two types were used in the SWUF modules, a similar 719-series 40 000 MMCO membrane and a 442-series membrane of 6 000 MMCO. The 735N4-series membranes of the capillary modules had an effective MMCO of 4 000 dalton when tested on an aqueous solution of PEG.

2.4.2 CONFIGURATION OF PILOT PLANT

The various membrane systems were skid-mounted to allow simultaneous evaluation of the different configurations. The test equipment was installed on a jetty of West Point Fishing Co. where seawater could be obtained from existing intake piping. The raw seawater was first screened to 300 μm before being subjected to dual-media filtration. Filtered seawater was collected in a 200 l buffer tank from which it was distributed to the various modules by means of a centrifugal pump and ring manifold. Take-off points for the individual modules were provided with pressure gauges for the determination of operating pressure. The mechanical line diagram for the experimental skid is illustrated in Figure 2.4. A second 200 μm screen was installed ahead of the capillary module to prevent physical blocking of the capillaries by solids (e.g. carry-over grit from the dual media filter).

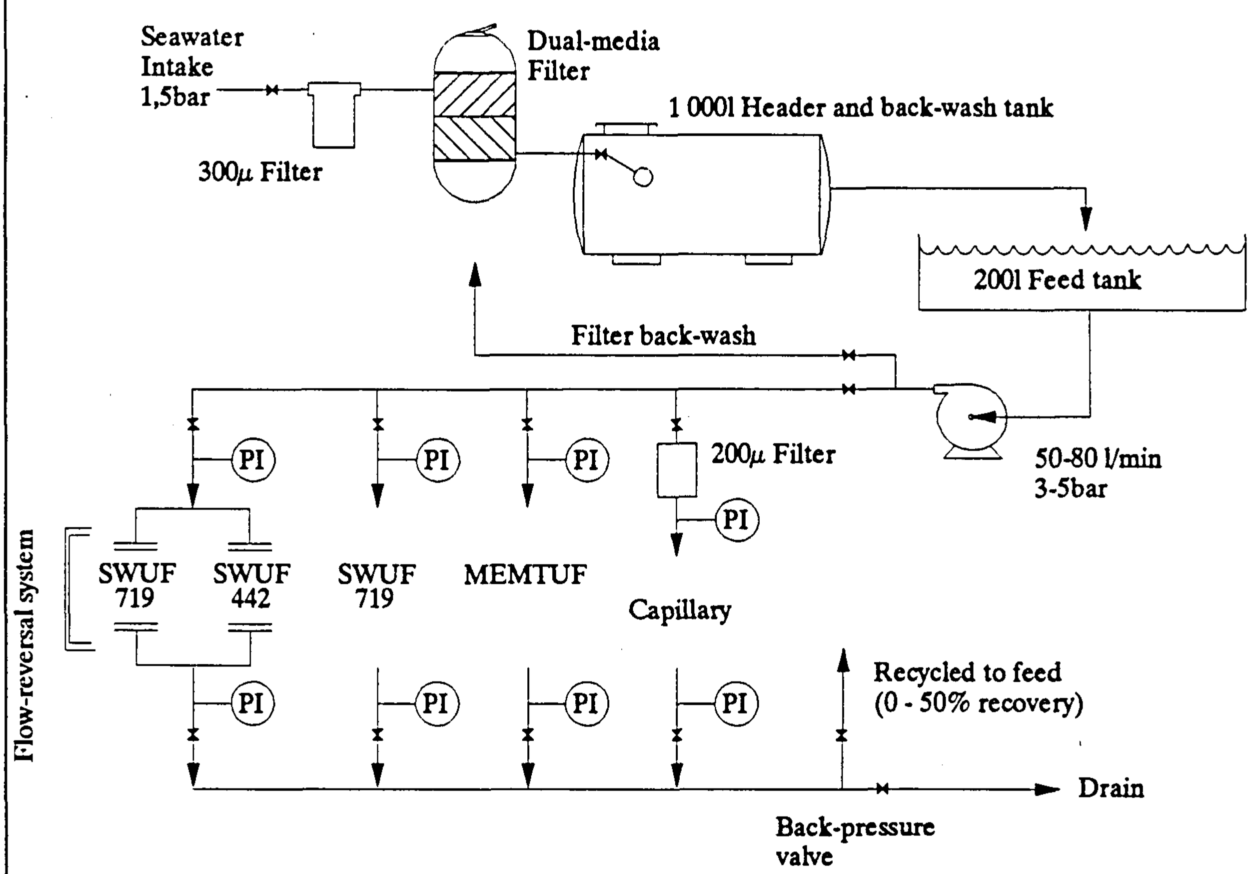


FIGURE 2.4 MECHANICAL LINE DIAGRAM OF EXPERIMENTAL EQUIPMENT

The SWUF modules were fitted with a flow-reversal system for sponge ball cleaning. The flow-reversal system consisted of a Wheatstone-bridge arrangement of four valves, mechanically linked and actuated by a pneumatic cylinder which was fitted with an air solenoid valve and timer. Each SWUF module was provided with a sponge ball trap on both the inlet and outlet.

2.4.3 OPERATING CONDITIONS

The operating conditions were chosen to suit individual membrane systems. Each system was operated at the particular set of pressure and flow conditions which were considered to be optimum for the particular membrane configuration (refer to Table 2.2). Feedwater quality, volume recovery and feed temperature were identical for all membrane systems.

TABLE 2.2: CHOSEN OPERATING CONDITIONS FOR THE VARIOUS MODULE SYSTEMS

PARAMETER	MEMTUF	SWUF	CAPILLARY
Inlet pressure (kPa)	200	300	200
Outlet pressure (kPa)	50	50	50
Linear flow velocity (m/s)	2,5	1,8	2,8
Membrane area (m^2)	0,4	3,0	0,4

2.5 EXPERIMENTAL APPROACH

As mentioned previously (paragraph 2.1), one of the major goals during the evaluation of the different membrane systems was to reduce the module cost factor ($R.m^{-3}.d^{-1}$) by lowering module material cost and optimising operational flux. Two distinct approaches were followed in an attempt to achieve this:

1) Operation at the highest sustainable flux, using frequent mechanical cleaning by sponge balls, with the SWUF design in anticipation that the higher membrane productivity would offset the higher module material cost when compared to MEMTUF and capillary modules.
2) Operation at stabilised, lower flux with MEMTUF and capillary modules, using infrequent chemical cleaning, trusting that lower module material cost of these configurations would outweigh the net loss in productivity.

SECTION THREE : RESULTS AND DISCUSSION

3.1 FLUX VALUES

3.1.1 OPERATION WITH SPONGE BALLS

Mechanical cleaning of the tubular SWUF modules, with the aid of sponge balls and a flow-reversal system, proved to be effective in removing substantial amounts of foulants, thereby resulting in significant flux restoration. The beneficial effect of sponge ball cleaning is illustrated by the higher average seawater flux values which could be maintained. The degree to which the flux could be restored and maintained, was determined by the frequency of sponge ball cleaning. Shorter sponge ball cycle times yielded better results (Figure 3.1) and a flow-reversal frequency of 5 minutes was finally adopted. For the SWUF 719 module the average flux value for the sponge-balled module was found to be higher by a factor of 3,4 during the first 5 minute cycle period (20 to 40 h) and increased to a factor of 5,0 (50 to 70 h) in the second 5 minute cycle period, as the membranes of the module without sponge ball cleaning became increasingly fouled (refer Figure 3.1). Corrosion on the pneumatic cylinder was experienced toward the second half of the trial period. This resulted in the system being stuck in one flow direction for extended periods which had a detrimental effect on the average flux value of the SWUF modules (Figure 3.2).

A combination of regular sponge ball and mild chemical cleaning served to maintain seawater flux values at 14 to 127 LMH for the 1 600 h test period (refer to Figure 3.2). Frequent replacement (optimum at 100 to 200 h) of the sponge balls was required in order to capitalize on their cleaning efficiency. The flux decline associated with wear on the sponge balls, and subsequent improvement after replacement, follows directly from Figure 3.2.

3.1.2 OPERATION WITHOUT SPONGE BALLS

The capillary and MEMTUF modules, which could not be subjected to sponge ball cleaning, showed a rapid flux decline within the first 100 hours of operation, as illustrated in Figure 3.3. For the remainder of the 1 600 h test period, the seawater flux fortunately stabilized at respective average values of 20 LMH for the capillary and 16 LMH for the MEMTUF module. Since these modules were operated in parallel with the SWUF modules, they were subjected to identical feedwater quality and chemical cleaning cycles. The efficacy of mechanical cleaning with sponge balls is therefore apparent when the flux values for the different modules are compared (see Figures 3.2 and 3.3).

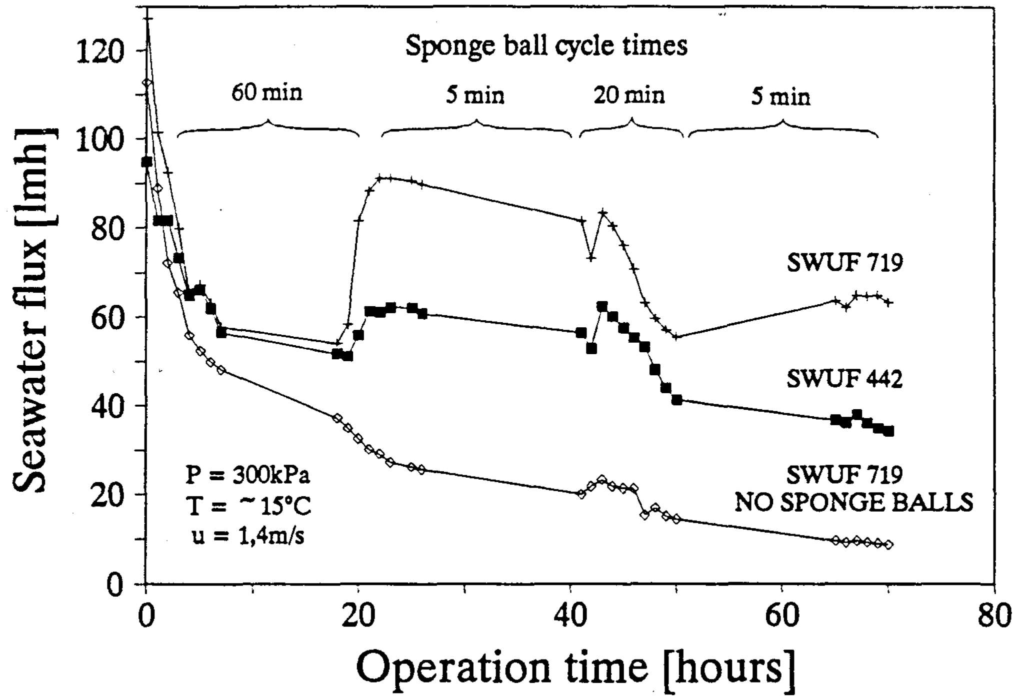


FIGURE 3.1 EFFECT OF SPONGE BALL CLEANING ON SEAWATER FLUX OF SWUF MODULES

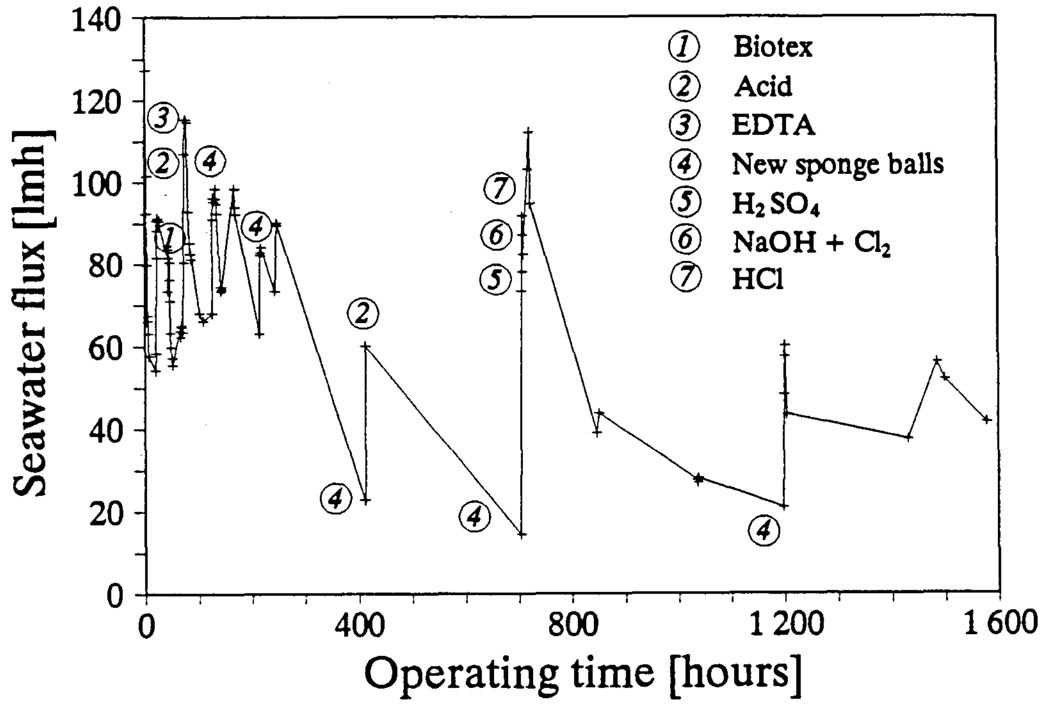


FIGURE 3.2 PLOT OF SEAWATER FLUX AGAINST OPERATING TIME FOR SWUF MODULE (WITH SPONGE BALL CLEANING)

3.2 CLEANING EXPERIMENTS

3.2.1 COMBINATION CLEANING BY SPONGE BALLS AND CHEMICAL SOLUTIONS

Membrane samples from the SWUF 719 module, which had been operating without sponge ball cleaning, were subjected to various cleaning regimes in the laboratory in an effort to restore pure-water flux to its original value. The first experiment entailed the use of a combination of enzymatic proteolytic cleaners, chloralkali solution and sponge balls. The chemical cleaning agents were chosen by virtue of the fact that they were found to be effective in the removal of foulants from membranes used to treat abattoir wastewaters *(Jacobs, 1991)*. It was reasoned that they should perform equally well on foulants from seawater, because of their similar organic nature.

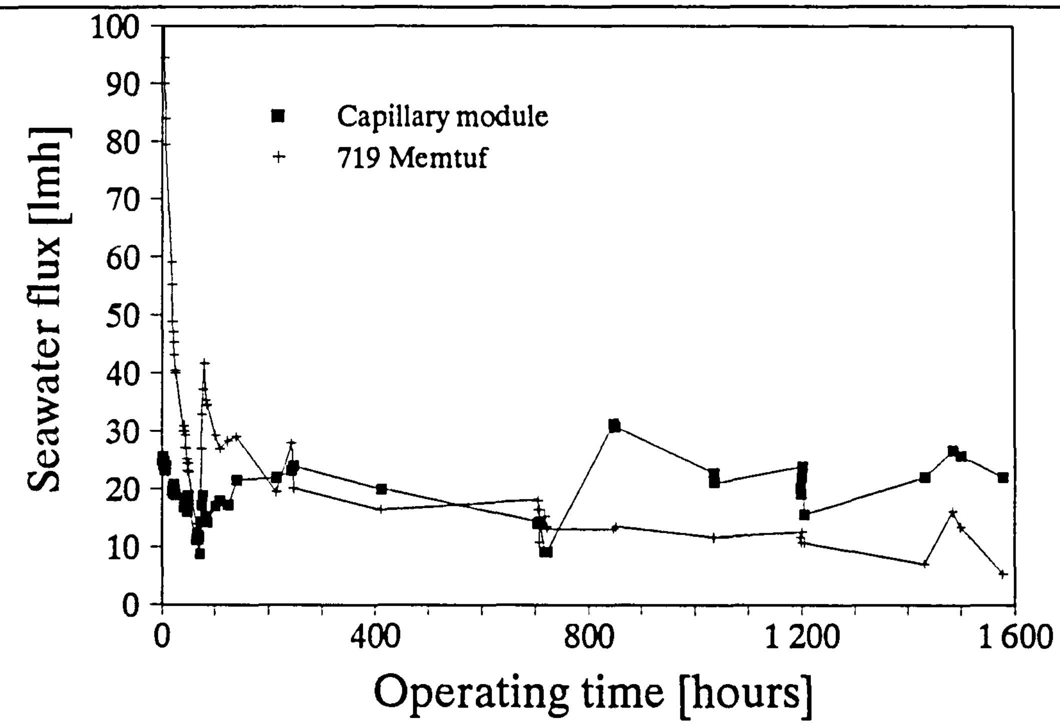


FIGURE 3.3 PLOT OF SEAWATER FLUX AGAINST OPERATING TIME FOR CAPILLARY AND MEMTUF MODULES
(NO SPONGE BALL CLEANING)

The effects of the different cleaning operations on pure-water flux restoration of membranes fouled by the seawater constituents, are illustrated in Figure 3.4. Sponge balls were employed to remove the bulk of the foulant prior to treating proteinaceous deposits with an enzymatic cleaning solution. A second sponge ball cleaning cycle resulted in a further pure-water flux increase. A final chloralkali rinse served to restore the pure-water flux to between 350 and 400 LMH, which was comparable to that of a new membrane of this type under similar test conditions. The use of an extended chloralkali wash alone, together with sponge ball cleaning, also yielded good results (Figure 3.5), but is not considered to be a viable practical alternative. This is due to the possible hydrolysis of the polyester support tubes at high pH *(Strohwald, 1988)* and permanent modification of the membrane porosity and structure by high dosages of chlorine *(Jacobs and Domröse, 1991)*.

3.2.2 CHEMICAL CLEANING OF MEMTUF AND CAPILLARY MODULES

The effectiveness of mechanical techniques to clean membrane surfaces of rapidly forming deposits is not queried. Flow-reversal, sponge balling and air/clean-water scouring are all tested and tried techniques. A summary of practical cleaning techniques for different membrane configurations is given in Table 3.1. However, these techniques cannot be used with the same effect on all tube-type configurations, as the narrow (also parallel) flow passages of the MEMTUF and capillary modules, for example, do not lend themselves to an effective sponge ball cleaning approach. As such it was important to determine whether similar flux increases could be obtained in the capillary and MEMTUF configurations by resorting to chemical cleaning only. If the foulants were amenable to removal by chemical means, these membrane configurations were thought to be viable alternatives to the SWUF technology. It follows from the pure-water flux data presented in Figure 3.6 that a combination of the proteolytic enzyme wash and extended chloralkali rinse alone yielded values similar to those obtained with chemical and sponge ball cleaning (see Figure 3.4). The removal of foulants by chemical cleaning alone is therefore possible, albeit at more frequent intervals.

TABLE 3.1 : PRACTICAL CLEANING REGIMES

	SWUF	MEMTUF	CAPILLARY
Mechanical			
Flow reversal	yes	yes	yes
Flow pulsation	yes	yes	yes
Air scouring	yes	yes	no
Sponge balling	yes	no	no
Backwashing	no	no	yes
Chemical	yes	yes	yes

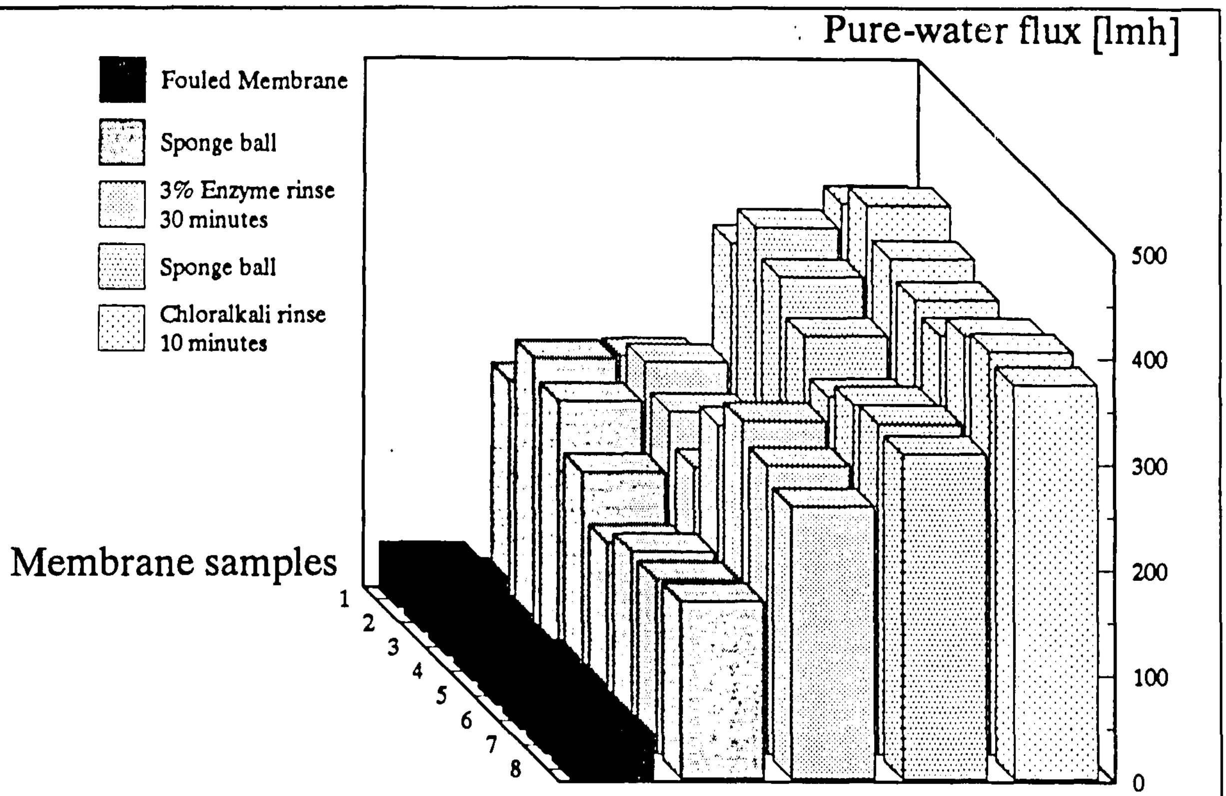


FIGURE 3.4 EFFECT OF ENZYMATIC, CHLORALKALI AND SPONGE BALL CLEANING COMBINATION ON PURE-WATER FLUX RESTORATION

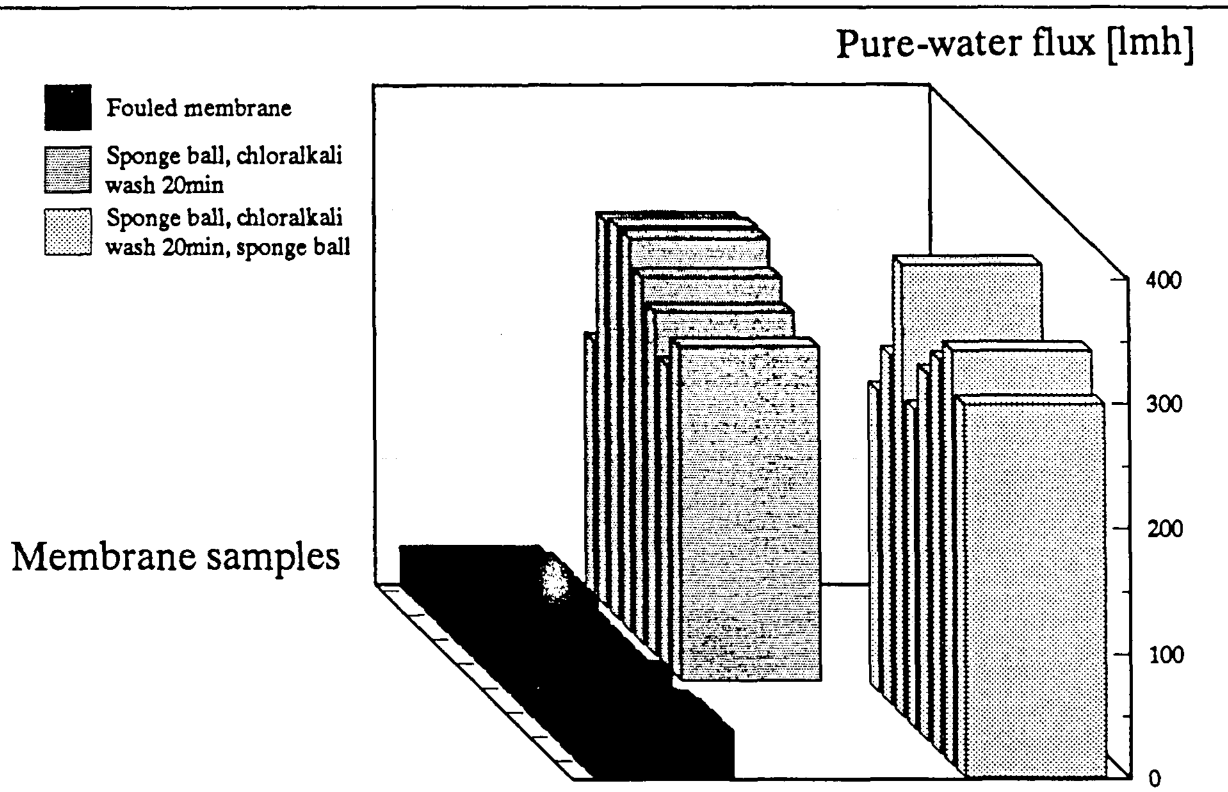


FIGURE 3.5 EFFECT OF CHLORALKALI AND SPONGE BALL CLEANING COMBINATION ON PURE-WATER FLUX RESTORATION

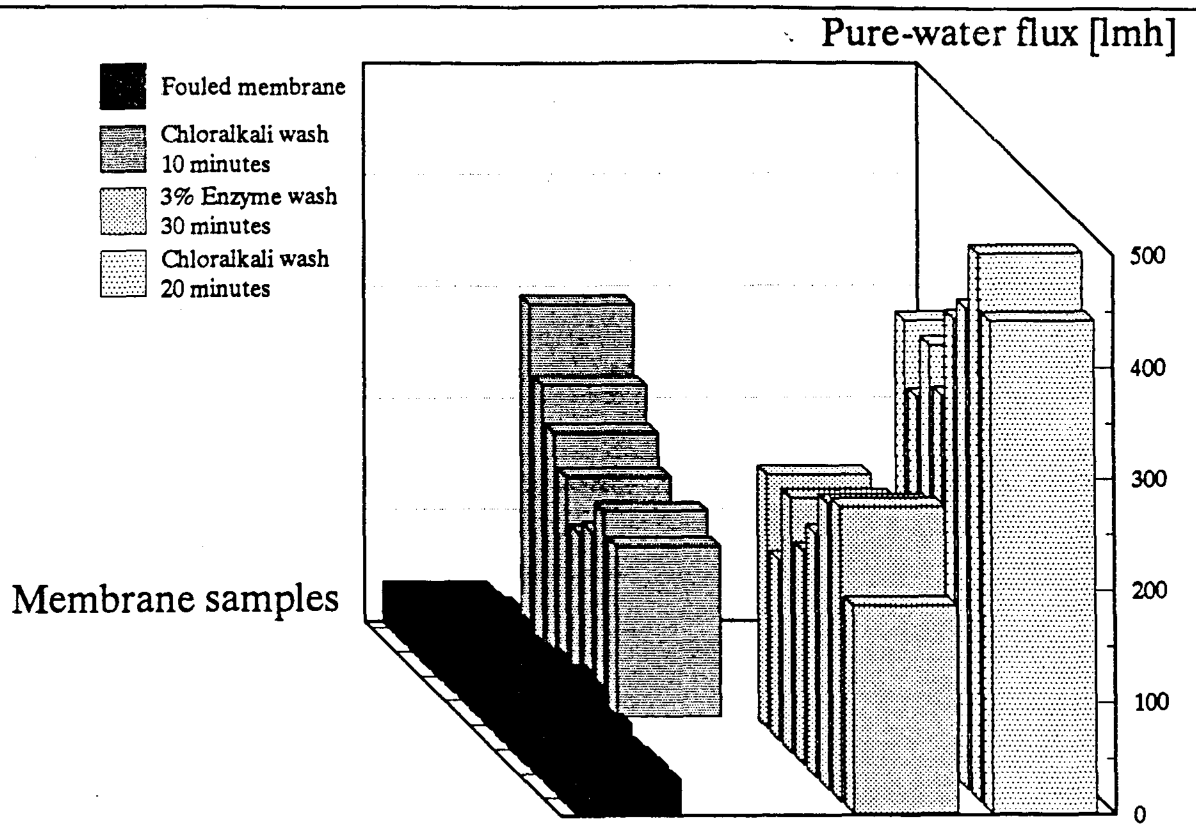


FIGURE 3.6 EFFECT OF ENZYME AND CHLORALKALI CLEANING ON PURE-WATER FLUX RESTORATION

(NO SPONGE BALL CLEANING)

3.3 NATURE OF FOULANT

Foulants and control methods against membrane fouling may be categorized into four groups, as summarised in Table 3.2. Several conventional control methods against membrane fouling may be used, all of which normally constitute specific pretreatment steps prior to the membrane system. In this case the UF system is considered to be the pretreatment step to the RO desalination unit and the control methods given in Table 3.2, with the exception of sandfiltration, are not used. The fouling of the UF membranes is therefore more severe, which underlines the importance of an efficient membrane cleaning mechanism.

The complexity and interactive nature of fouling problems has been recognized, although the complex fouling processes cannot be readily defined *(Walton, 1991)*. No significant effort was therefore made to determine either the mechanism of the fouling that occurred, nor the exact nature of the gel-layers which were deposited on the membrane surface. With regard to seawater, however, a variety of foulants may be encountered, as shown in Table 3.3.

TABLE 3.2 : FOULING CATEGORIES AND RELEVANT CONTROL METHODS

FOULING CATEGORIES			
PARTICULATE	COLLOIDAL	BIOLOGICAL	CHEMICAL
Suspended matter Sand Corrosion debris	Organic matter Silica Iron colloids	Bacteria Algae	Calcium carbonate Calium sulphate Strontium sulphate Barium sulphate Calcium flouride
CONTROL METHODS			
PARTICULATE	COLLOIDAL	BIOLOGICAL	CHEMICAL
Filtration Sedimentation	Coagulation Filtration	Biocides Chlorination Ozone	Acid dosing Polyphosphate Antiscalant

TABLE 3.3 : SEAWATER CONSTITUTENTS AND POTENTIAL MEMBRANE FOULANTS

INORGANIC	ORGANIC	BIOLOGICAL
Silica Quartz Silt Carbonates/sulphates	Lipids Phosphates Proteins Polysaccharides	Algae Plankton Krill Unicellular organisms

Physical examination of the membrane surface indicated that the foulant comprised a biofilm which could be removed easily by mechanical means. This explained the successful restoration of flux values by sponge ball and enzymatic cleaning. The organic fouling was thought to be compounded by inorganic and physical elements (*e.g.* rust, silt). This was confirmed by EDAX analysis which indicated the presence of amounts of silica, aluminium and iron (Figure 3.7). Subsequent cleaning with chloralkali, after enzymatic treatment to remove organics, resulted in the removal of all inorganic foulants from the membrane surface, as illustrated in Figure 3.8. The only visible emission peak on this spectrum is that of sulphur, originating from the membrane polymer material used.

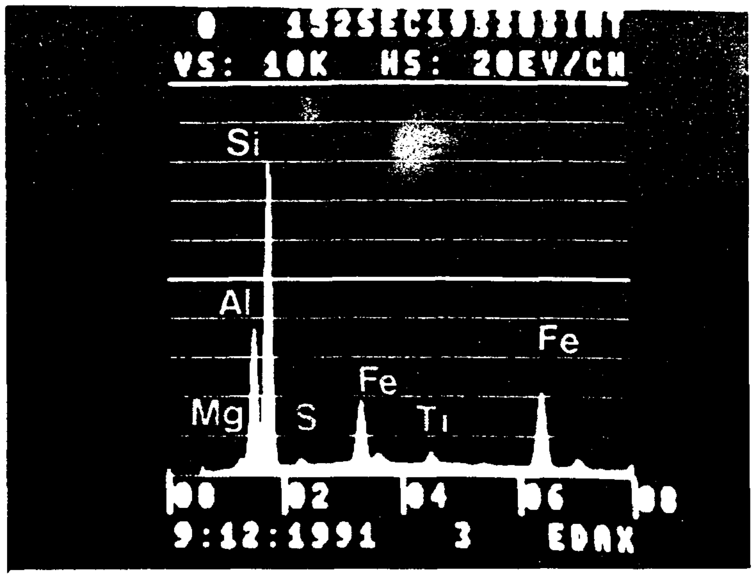


FIGURE 3.7 EDAX SPECTRUM OF FOULED MEMBRANE SHOWING VARIOUS EMISSION PEAKS

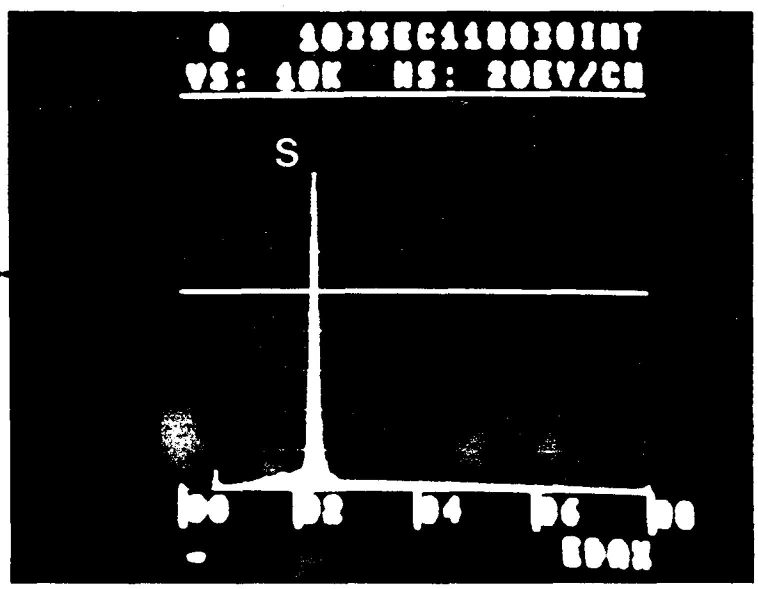


FIGURE 3.8 EDAX SPECTRUM OF MEMBRANE SURFACE AFTER CLEANING WITH A PROTEOLYTIC ENZYME AND CHLORALKALI SOLUTION

3.4 COST COMPARISON

Because of the different membrane and module configurations used, it is difficult to find common ground and a basis for a direct comparison of cost. The comparison was therefore based on the module material cost alone, labour and ancilliary equipment costs being regarded as similar. Average operating flux values for the various module types were taken from the experimental data (Figures 3.2 and 3.3) obtained when each module system was operated under the conditions chosen for that particular design (refer to Table 2.1). Cost factors for MEMTUF and capillary modules (no chemical cleaning) and SWUF modules (sponge ball cleaning) are presented in Table 3.4, with the cost per unit area of the SWUF module taken as basis. It is apparent that at the flux rates which could be maintained without chemical cleaning, the capillary module is competitive with the SWUF configuration due to its lower material cost. This is supported by similar specific cost factors of 0,94 and 0,89, respectively, for the capillary and SWUF modules.

It may be seen from the data in Figure 3.3 that it is doubtful whether the average flux rate of the capillary module can be raised significantly above 20 LMH by a daily chemical cleaning cycle since the starting flux was merely 26 LMH. Although the initial flux of 95 LMH for the MEMTUF module corresponds well with that of the SWUF module, the decline was very rapid, resulting in a 90% drop within 80 hours of continuous operation to below 10 LMH. The additional cost of a regular, high-frequency chemical cleaning cycle can therefore not be offset by the desired flux gain. Such a flux increase could rather be achieved through modification of the membrane's permeability characteristics or operating parameters.

TABLE 3.4: COMPARISON OF MODULE MATERIAL COST AND SPECIFIC COST PER m^3 PRODUCT AT FLUX RATES ATTAINABLE WITHOUT CHEMICAL CLEANING

	MEMTUF	SWUF	CAPILLARY
Cost factor (R/m^2)	0,60	1,00	0,45
Flux (LMH)	16	74	20
($m^3m^{-2}d^{-1}$)	0,384	1,128	0,480
Specific cost factor ($Rm^{-3}d^{-1}$)	1,56	0,89	0,94

SECTION FOUR : CONCLUSIONS AND RECOMMENDATIONS

4.1 CONCLUSIONS

4.1.1 MEMBRANE FOULING

Medium and low MMCO UF membranes, used in the pretreatment of seawater for RO systems, were found to be equally prone to fouling. This resulted in a substantial reduction in productivity. The nature of the foulants and mechanism of fouling could not be determined due to their complex nature. Physical examination and EDAX analysis of the membrane surface, however, indicated a combination of organic and inorganic fouling.

4.1.2 MEMBRANE CLEANING

Tubular SWUF modules (12,5 mm tube diameter) could be cleaned mechanically with sponge balls through short-cycle flow reversal, while in operation, to maintain higher average flux values. In contrast, the tubular MEMTUF (9 mm tube diameter) and capillary modules, which could not be cleaned by sponge balls, showed considerably lower, but stable flux. The foulant could be removed by adopting a biochemical cleaning regime with a proteolytic enzyme, followed by a chloralkali rinse.

4.1.3 COST COMPARISON

It was shown that with module material cost and the experimental flux values as basis, permeate could be produced with similar cost factors by SWUF and capillary modules. The higher material cost of the SWUF module was balanced by the higher productivity which could be maintained with on-line sponge ball cleaning. Similarly the potential advantage of lower material cost of the capillary module was diminished by the lower productivity since sponge ball cleaning could not be used. The specific cost factors ($R.m^{-3}.d^{-1}$) were calculated as 0,89 and 0,94 for SWUF and capillary, respectively (Table 3.4). As such both configurations show potential in the pretreatment of seawater, from both technical and economic points of view.

4.1.4 MEMBRANE SYSTEM

The experimental work conducted in the course of this project resulted in the development of an ultrafiltration module which is specifically designed for the pretreatment of seawater. Although the use of capillary modules in this application is technically feasible, the ability of the SWUF modules to be cleaned mechanically with the aid of sponge balls, is considered to be a substantial advantage. Chemical cleaning may be reduced considerably, resulting in longer membrane life, easier operation, less down-time and lower operating cost. These advantages may be regarded as somewhat subjective since they cannot be easily expressed in direct monetary terms. From an operational point of view, however, a membrane system which allows sponge ball cleaning is preferred.

4.2 RECOMMENDATIONS

The development of the SWUF^R module has resulted in the commercial manufacture and use of a practical membrane separation system for the pretreatment of seawater prior to desalination by RO. Further refinement of the system would entail the design and incorporation of an injection moulded sponge ball trap into the epoxy casting of the module ends.

The prototype capillary concept on the other hand may be improved with regard to two specific aspects, *viz.* module design and membrane characteristics. Module design and commercial manufacture are currently being addressed through the compilation of product specifications. Optimisation of membrane performance for the specific purpose of seawater pretreatment may be conducted once commercially manufactured capillary modules are available.

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