N K H STROHWALD

REMOVAL OF ALGAE FROM WATER BY ULTRAFILTRATION

Report to the
WATER RESEARCH COMMISSION
by
MEMBRATEK (Pty) Ltd

WRC Report No 337/1/90

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ABSTRACT

The feasibility of the removal of algae from natural waters by tubular ultrafiltration was investigated.

Membrane performance at various operating conditions and product quality was studied. It was found that ultrafiltration can successfully remove algae from natural waters, irrespective of the algal concentration of the feed water. The flow velocity within the tubular membrane filter and the volume recovery were found to significantly affect the permeate flux.

Cost calculations based on experimentally determined flux values are presented. Ultrafiltration in combination with UV-sterilisation and ozonation can substantially reduce overall operating costs and can obviate the problems associated with the formation of THMs in conventional treatment routes.

ACKNOWLEDGEMENT

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Removal of algae from water by ultrafiltration

The financing of the project by the Water Reseach Commission is gratefully acknowledged.

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LIST OF SYMBOLS AND ABBREVIATIONS

BPCV	Back pressure control valve
CSIR	Council for Scientific and Industrial Research
DAF	Dissolved air flotation
DWT	Division of Water Technology
GAC	Granulated activated carbon
FI	Flow indicator
LMH	Litres per square metre per hour
MEMTUF	Trade name for low cost ultrafiltration unit
MMCO	Molecular mass cut-off
NTU	Nephelometric turbidity unit
PAC	Powdered activated carbon
PI	Pressure indicator
THMs	Trihalomethanes
THMPs	Trihalomethane precursors
UF	Ultrafiltration

OBJECTIVES

The objectives of this preliminary study were the following:

(i) To determine the ability of tubular ultrafiltration to remove algae from water.

(ii) To study operating parameters and their effect on membrane performance.

(iii) To investigate scale-up criteria and to determine the economical viability of such a system.

1 INTRODUCTION

The widespread occurrence of algae in natural waters, and the problems associated therewith, have received increased attention recently. Research efforts are being devoted to the elimination of algae in potable water supplies and to more efficient means of removing substances which can pose health hazards.

The presence of algae in water bodies is not only aesthetically offensive, but can also lead to the release of toxins and to varying water quality. The abundant growth of algae in dams and lakes is ascribed mainly to the discharge of phosphate and nitrogen rich effluents and treated sewage into such water bodies. The actual reasons and phenomena leading to algal blooms are, nevertheless, considered to be more complex than originally thought (Jung, 1989).

Apart from aesthetic objections, the eutrophication of water sources also has considerable financial implications, such as the damage to property and boats and the detrimental effect on recreational activities (Haynes *et al.*, 1989). From a water purification viewpoint, the formation of undesirable trihalomethane precursors (THMPs) requires sophisticated and expensive treatment methods for their removal (Gehr, 1989), such as dissolved air flotation (Swartz, 1989), activated carbon adsorbtion (le Roux, 1989) and ozone treatment (Pearson, 1989).

An efficient, economical treatment for the removal of algae from water would thus not only enable the reduction of algal concentrations, but would also have beneficial effects on downstream water purification operations.

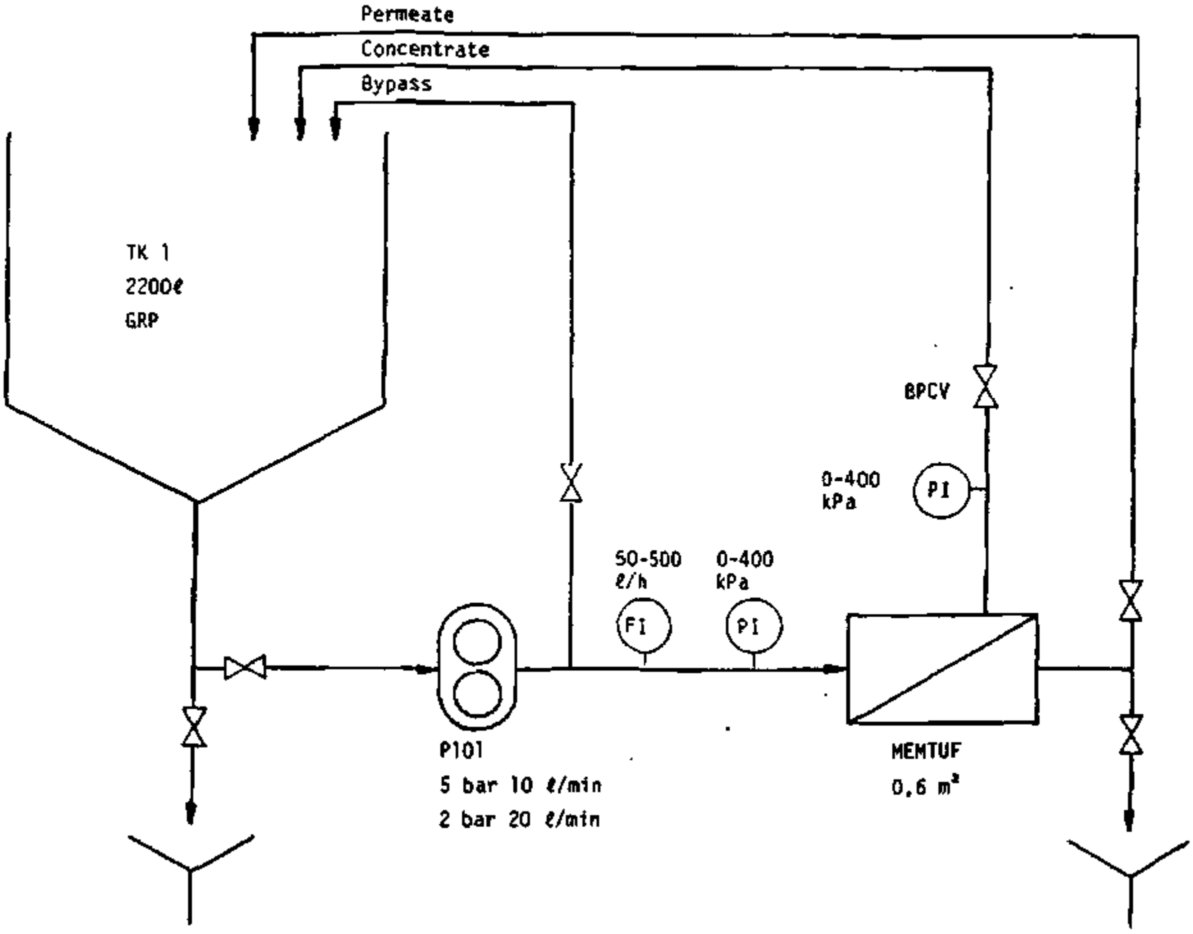

Figure 2.1 Schematic diagram of experimental ultrafiltration equipment

2 EXPERIMENTAL

It was decided to perform the study in the laboratory in order to ensure controlled experimental conditions as well as reliable plant monitoring and data collection.

2.1 Algae

No effort was made to involve particular strains of algae, but rather to utilise an easily accessible local source of water that was known to be infested with algal growth. Availability and proximity to the test site were the major factors in this regard.

After some consideration (Scott, 1989) two sources of algae invested waters were selected. These were Zeekoeivlei (Cape Flats, Muizenberg) and Noord Agter Paarl irrigation dam (Paarl). Both were found to contain substantial concentrations of green and blue-green algae.

The presence and concentration of algae were determined by the chlorophyll-a test and turbidity measurements. Analysis was performed by the Bellville branch of the DWT (CSIR). Total solids determinations were made using a micro-processor controlled microwave oven, fitted with a microbalance.

2.2 Ultrafiltration equipment

The ultrafiltration (UF) system, schematically depicted in Figure 2.1 , comprised a batch tank, feed pump and UF module.

A batch tank of relatively large capacity and UF module with a small membrane area were chosen to simulate high feed-volume-to-membrane-area conditions (3 600 l/m^2) and to achieve long space times (110 - 220 min). Long space times were considered necessary in order to simulate the condition where "fresh" feed water is in continuous contact with the membrane. The UF module used was of the MEMTUF type, having a tube diameter of 9 mm, a membrane area of 0,6 m^2 and which was fitted with membranes of 40 000 MMCO. No prescreening or temperature control was done and feed pressure was usually limited to a maximum of 300 kPa. A bypass pipeline was fitted to enable variation of the feed flow velocity inside the membrane tubes.

Various mechanical and chemical means of membrane cleaning were investigated. The MEMTUF unit was generally removed from the system during chemical cleaning so as not to contaminate the algal suspension in the batch tank.

2.3 Methods

Determination of membrane flux

Flux figures pertaining to operating conditions were determined by actual measurement of the permeate flow rate. Flux values presented in this report were not corrected for temperature as the feed temperature remained practically constant and the effect of feed temperature on flux was found to be insignificant.

Flux values are given throughout in litres per square metre membrane area per hour or **LMH**. Unless otherwise specified, all flux figures were determined at a feed pressure of 300 kPa and a linear flow velocity of 1,6 m/s.

Concentration cycle

During a concentration cycle, permeate was withdrawn from the UF system on a continuous basis. This resulted in the reduction of the original feed volume or, conversely, in a concentration of the feed solution. With a knowledge of the starting solids concentration and permeate solids content, the flux/solids relationship could be determined.

No effort was made to categorise the solids present in the feed water and the amount of total solids was taken to be indicative of the algal concentration.

Linear flow velocity

the effect of linear flow velocity on flux was determined by varying the feed flow to the MEMTUF module through adjustment of the bypass valve on the discharge side of the feed pump. Stabilised flux values were recorded at various velocities, but at identical average pressures. The average pressure is defined as the mean of the inlet and outlet pressures as experienced by the MEMTUF module. The experiment was repeated at various algal concentrations.

Membrane cleaning

The membranes were subjected to various cleaning agents in order to determine their effectiveness. Mechanical means of membrane cleaning was effected by sponge balls and stop/start operation. During sponge ball cleaning, a sponge ball was passed through the membrane tubes in order to remove deposits from the membrane surface. Stop/start operation entailed the off/on switching of the feed pump. The cleaning action was effected through relaxation of the membrane tubes during the off cycle and resultant turbulence at start-up, which removed deposits from the membrane surface.

The chemical cleaning agents which were investigated were restricted to a detergent (Biotex^{TM}) and a bleaching agent (Jik^{TM}) in the form of a sodium hypochlorite solution. Chemical cleaning solutions were circulated through the MEMTUF module for a predetermined period of time and flushed out thoroughly with tap water after completion.

After cleaning, the MEMTUF unit was characterised by recording the water flux at set conditions. The water flux figure provides an indication of how effectively the foulants have been removed from the membrane. A water flux figure similar to that of the virgin membrane indicates that the membrane is free of foulants.

Water flux

The water flux was determined at the following standard conditions:

Inlet pressure	= 300 kPa
Outlet pressure	= 100 kPa
Temperature	= 20 °C
Velocity	= 1,6 m/s

Algal concentration

The concentration of algae in water samples was taken to be directly related to the amount of chlorophyll-a present. This was determined by the ethanol extraction method of Sartory (1982) used by the DWT of the CSIR, Bellville. It was thought that the algal concentration would be related to the turbidity of the water samples. Corresponding turbidity measurements were, therefore, also performed on all water samples, since a quick and simple means to monitor permeate quality was desired.

3 RESULTS

3.1 Long-term flux stability

One of the most important criteria indicative of the feasibility of ultrafiltration to process any feed water, is flux stability. Solids and solutes in the feed solution can foul the membrane through adsorption, and if the resulting flux decline cannot be reversed then the use of ultrafiltration to process that specific feed water is impractical.

The variation of permeate flux, feed temperature and system pressure over a continuous period of 320 h of operation, are shown in Figure 3.1 .

3.2 Concentration cycle

The effect of solids content of the feed water (indicative of the algal concentration) on the permeate flux is depicted in Figure 3.2 .

As expected the flux, Y (LMH), is exponentially related to the solids content, X (g/l), according to the equation :

$$Y = a \cdot X^b$$

Regression analysis of the experimental data yielded the following results :

Coefficient	a	=	236,6
Exponent	b	=	-0,44
Regression coefficient R^2		=	0,98

3.3 Linear flow velocity

The flux values at various linear flow velocities and algal concentrations are depicted in Figure 3.3.

3.4 Membrane cleaning

The effect of various cleaning methods on flux restoration is illustrated by the water flux values given in Figure 3.4. Values for the virgin membrane and that obtained after fouling are included for comparison.

3.5 Chlorophyll-a / turbidity

As can be seen from Figure 3.5, the turbidity, Y (NTU), of the feed water is related to its clorophyll-a content, X (μg/l), according to the equation :

$$Y = a + b \cdot X$$

Regression analysis of the experimental data yielded the following results :

Intercept	a	=	0
Slope	b	=	0,121
Regression coefficient R^2		=	0,98

3.6 Permeate quality

The ability of the 40 000 MMCO ultrafiltration membranes to remove algae from water is illustrated in Table 3.1 in which the chlorophyll-a, turbidity values and reduction levels of the feed and permeate are related to volume recovery levels.

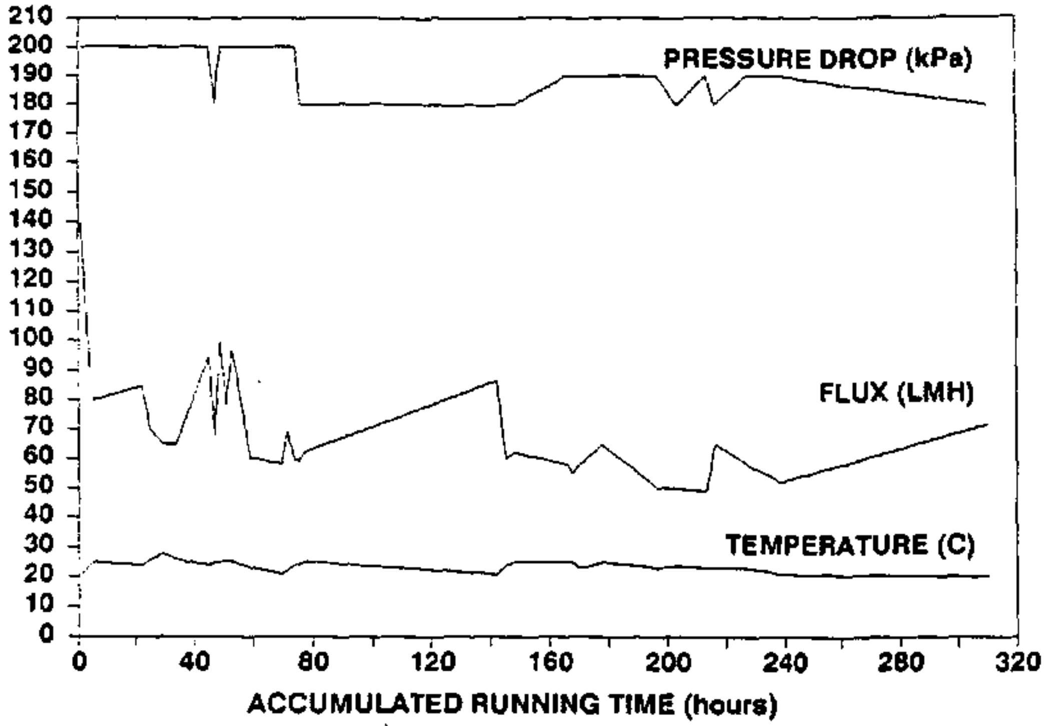

Figure 3.1 Permeate flux, feed temperature and system pressure drop versus time (Zeekoeivlei source)

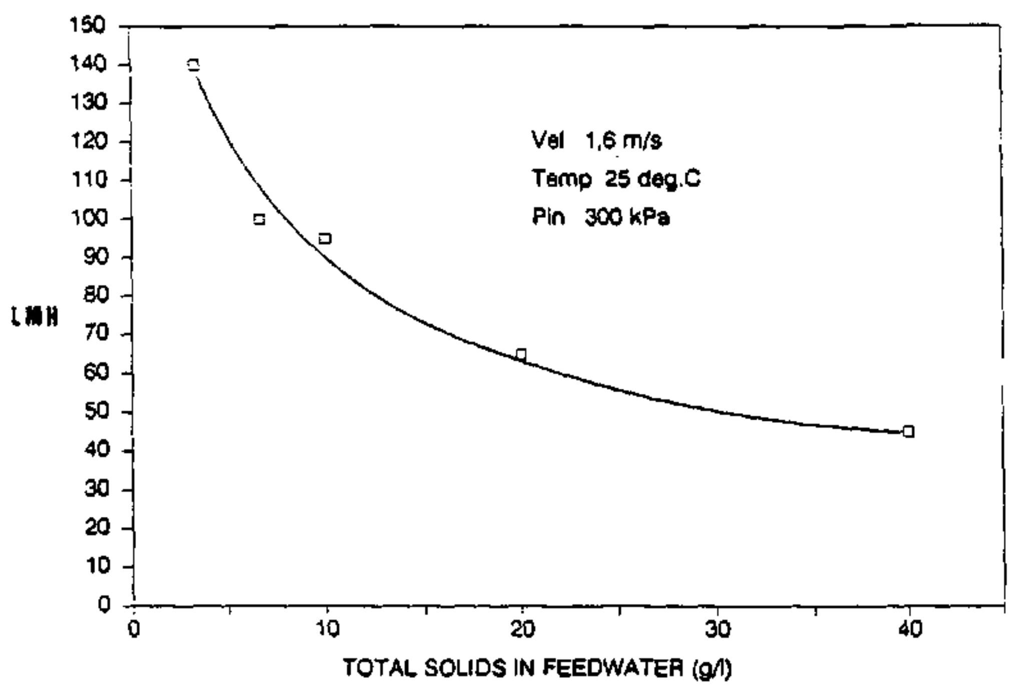

Figure 3.2 Permeate flux versus algal concentration expressed as total solids (Zeekoeivlei source)

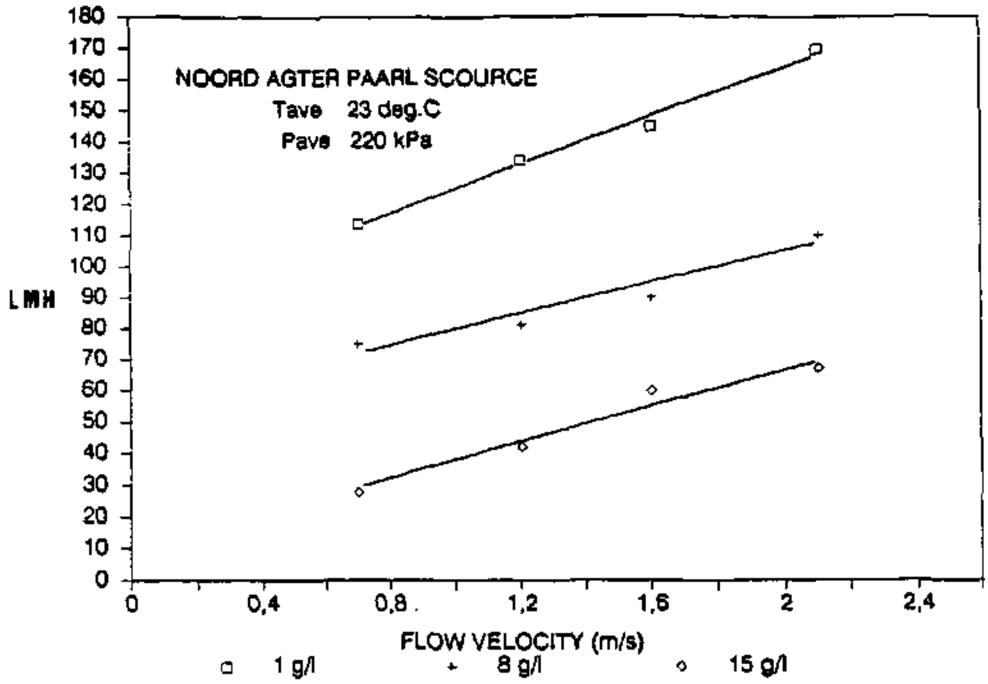

Figure 3.3 Permeate flux versus linear flow velocity at various algal concentrations (Noord Agter Paarl source)

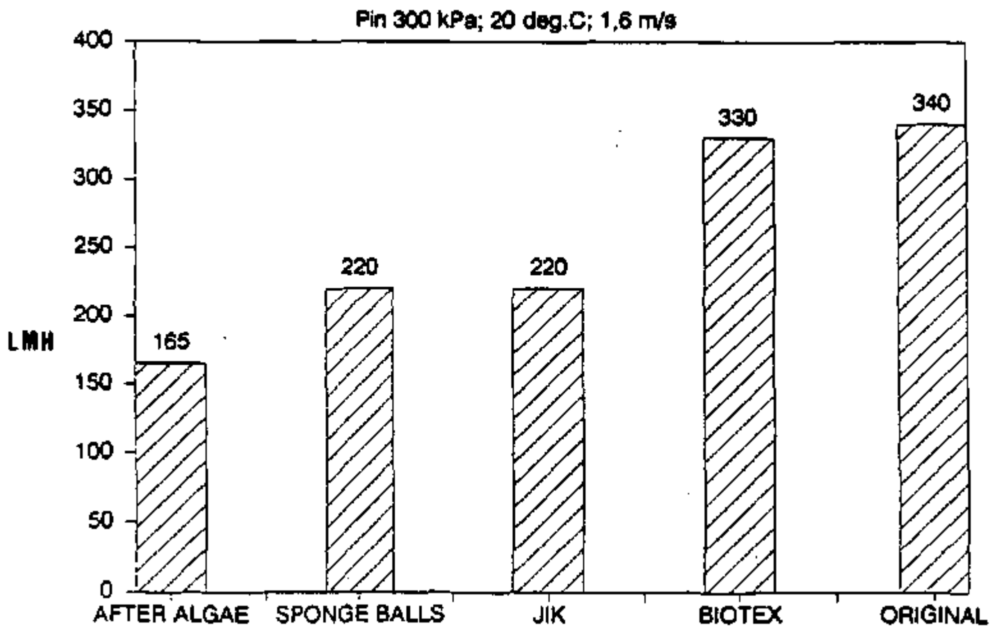

Figure 3.4 Effect of cleaners on water flux restoration

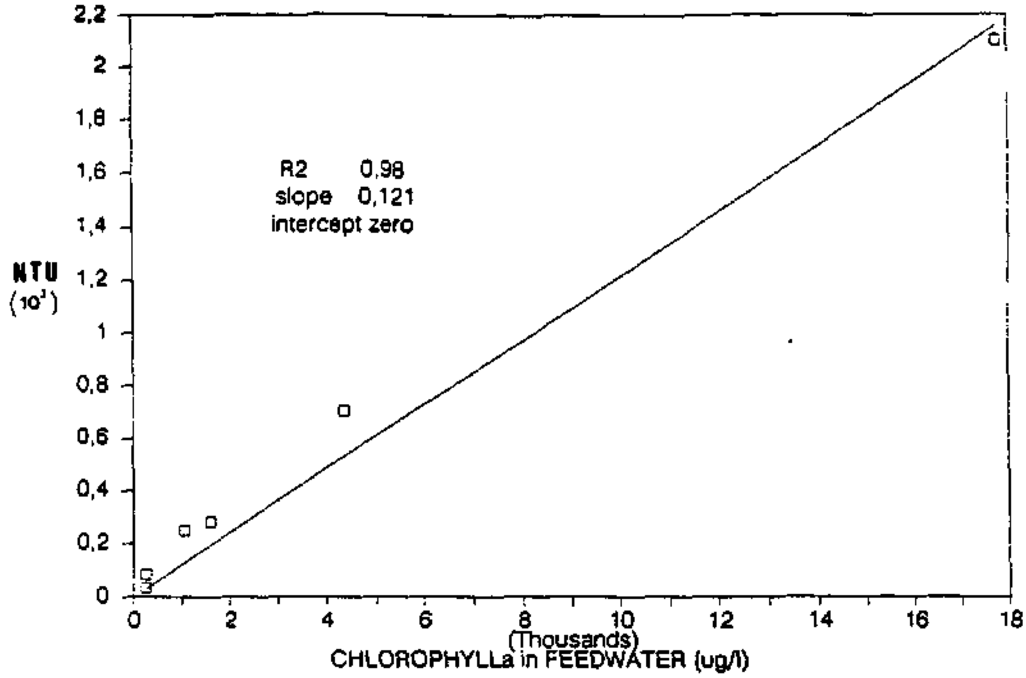

Figure 3.5 Relationship between chlorophyl-a content and turbidity of feed water (Zeekoeivlei source)

Table 3.1 Chlorophyl-a and turbidity values for feed and permeate at various recoveries (Sample analysis results)

RECOVERY	CHLOROPHYLL-a			TURBIDITY		
%	Feed	Permeate	Reduction	Feed	Permeate	Reduction
	10^{-6} g/l		%	NTU		%
1	252,21	0	100	35	0,50	98,57
40	257,94	0	100	85	0,38	99,55
70	1 042,18	0	100	250	0,40	99,84
80	1 596,77	0,31	99,98	280	0,45	99,84
90	4 356,32	0	100	700	0,34	99,95
95	17 769,00	0,91	99,99	2 100	0,50	99,98

3.7 Cost calculations

Capital and operating costs for various water purification methods used for algal control, are given in the literature (Haynes *et al.*, 1989). These costs are based on the total amount of water supplied by the Rand Water Board, viz. 2 200 000 m^3/d.

To allow comparison, the cost calculations for ultrafiltration were based on the same product capacity (refer Table 3.2).

The following basis was used for the estimation of capital and operating cost for a tubular ultrafiltration system:

Type	MEMTUF
Capacity	2 200 000 m^3/d
Feed pressure	300 kPa
Feed temperature	20 °C
Recovery	70 %
linear flow velocity	1,6 m/s
Design flux	90 LMH
Membrane lifetime	3 to 5 years
Operation	365 d/a
Pump efficiency	60 %
Energy cost	0,07 R/kWh

Table 3.2 Estimated capital and operating costs for a 2 200 000 m^3/d MEMTUF plant

Capital cost			R246 142 000
Operating cost	Energy consumption		0,034 R/m^3
	Membrane cleaning		0,007 R/m^3
	Membrane replacement	3 years	0,061 R/m^3
		5 years	0,036 R/m^3

4 DISCUSSION

4.1 Long-term flux stability

The flux data shown in Figure 3.1 depicts a sharp initial decline and subsequent stabilisation. This is in accordance with the behaviour of non-fouling media for which the rapid initial flux decline can be attributed to the formation of the dynamic boundary layer.

The flux averaged at 70,5 LMH, with a standard deviation of 19,4 LMH. The lowest flux recorded was 49 LMH, whereas the maximum flux was 140 LMH. The effect of stop/start cycles (2 min stoppages every 6 h) on flux can be seen in the vicinity of the 50 h ordinate mark. No subsequent efforts were made to increase the flux either mechanically or chemically for the remainder of the 320 h test period. It should, therefore, be possible to increase the average flux to approximately 90 LMH by inexpensive means such as stop/start operation or the use of sponge balls. The effect of sponge ball cleaning is discussed in a subsequent paragraph (Section 4.4).

The average feed temperature throughout the run was 23,8 °C with a standard deviation of 1,7 °C. The variations in permeate flux are thus not attributed to changes in feed temperature, but rather to the dynamic behaviour of the boundary layer.

No severe membrane fouling was experienced, as evidenced by the relative stability of the flux figures and the relative constancy of the system pressure drop. An increase in pressure drop is normally associated with membrane fouling.

4.2 Concentration cycle

The algae concentrations implied in Figure 3.2 and that shown in Table 3.1 are substantially higher than those likely to occur in fresh water bodies. A study undertaken by Gehr (1989) in January 1982 at Hartbeespoort dam shows typical chlorophyll-a values of between 5 and 100 μg/l, with the concentration peaking in the morning and ebbing around midnight.

The unusually high algae concentrations experienced during the concentration cycle can either be attributed to a higher algae content of the source water, or more likely to the growth of algae in the laboratory. Given ideal conditions the algae population could double every 24 h (Scott, 1989).

The flux decline, experienced with increasing algae concentration, is similar to that obtained when feed solutions containing suspended solids is ultrafiltered. This is contradictory to the problems experienced with the filtration of algal suspensions with ordinary depth filters. Algal suspensions normally show poor filtration characteristics, with the associated problems of rapid filter clogging or breakthrough, since they behave differently to colloidal suspensions (Haarhoff, 1989).

It was found that flux decline is reversed when the algal concentration is decreased. The flux decline which was experienced is attributed to the increase in the boundary layer thickness at high algal concentrations, rather than to fouling.

4.3 Linear flow velocity

The results of the regression analysis of the data presented in Figure 3.3 are shown in Table 4.1 .

The similar slope values tend to substantiate the conclusion that the flux values are governed by the algal concentration rather than by fouling. Since the boundary layer creates an additional resistance to permeate flux, an increase in the boundary layer thickness at higher algal concentrations results in lower flux values. The strong relationship between flux and the dynamic behaviour of the boundary layer is further borne out by the proportional flux difference at the three different algal concentrations.

As reflected by the slope values, an average increase of 31 LMH per unit increase in flow velocity can be expected at the prevailing experimental feed temperature and pressure. In order to assess the feasibility of high velocity operation the increase in energy costs, as a result of greater circulation volumes, will have to be weighed against the reduced capital costs resulting from the smaller membrane areas.

4.4 Membrane cleaning

Although not reflected in the flux levels encountered during the ultrafiltration of algal suspensions, some fouling did occur as can be seen from the water flux restoration data presented in Figure 3.4. It would seem, however, that this fouling was not of an organical nature. This is substantiated by the observation that membrane cleaning with sodium hypochlorite did not materially improve the flux restoration over that achieved with sponge ball cleaning. It, therefore, follows that sponge ball cleaning is capable of complete removal of algal deposits formed on the membrane surface.

Fouling by grime of unknown origin did occur to some extent. This is evidenced by the substantial restoration of water flux after cleaning the membrane with a detergent. The fact that the resultant flux was similar to that of the virgin membrane indicates that the detergent successfully removed all foulants.

4.5 Chlorophyll-a / turbidity

A linear relationship between chlorophyll-a and the turbidity of the feed water was observed. This fact may constitute a useful means of assessing algal concentrations during field trials, or for on-line plant monitoring of the feed stream quality once the calibration curve for the specific type of feed water has been established. Turbidity measurements could also be done on the permeate to monitor product quality and to serve as an early warning of membrane failure.

4.6 Permeate quality

The chlorophyll-a figures given in Table 3.1 indicate extremely successful algae removal from the feed water, even at excessive algal concentrations. The minute presence of chlorophyll in some of the permeate samples could possibly be due to contamination. Reductions in chlorophyll content were, nevertheless, virtually complete and for all practical purposes no chlorophyll-a is present in the permeate.

Similar results were obtained with the turbidity measurements, with reduction figures in excess of 99%. Permeate turbidity values were usually below 0,5 NTU irrespective of the feed water turbidity level. This result is similar to that obtained when tap water is ultrafiltered using a membrane having the same MMCO.

Table 4.1 Regression analysis of the data presented in Figure 3.3

Solids concentration g/l	1	8	15
Regression coefficient R^2	0,99	0,93	0,96
Intercept	86,06	54,30	8,44
Slope	39,1	24,8	29,2

Table 4.2 Cost comparison for various algal control measures (Adapted from Haynes *et al.*, 1989 ; Schutte, 1988 and Degremont, 1985)

MEASURE ADOPTED		TOTAL COST	SPECIFIC COST
		R/year	c/m³
UV Sterilisation [1]		1 043 900	0,13
Ozonation [1]		6 102 800	0,76
Chlorination [1]		8 395 000	1,2
Microscreening [1]		41 572 000	5,8
DAF [1]		50 370 000	6,9
Activated carbon [1]	PAC	63 250 000	8,6
	GAC	83 110 500	10,4
MEMTUF	3 year life	81 906 000	10,2
	5 year life	61 831 000	7,7

All costs are based on a capacity of 2 200 000 m³/d
[1] Costs reported in the literature have been adjusted for inflation at an annual rate of 15%

4.7 Cost calculations

Given the criteria listed in Section 3.7 a MEMTUF plant capable of producing water at a rate of 2 200 000 m^3/d would require a total membrane area of 1 008 304 m^2. It would clearly be more practical to use a number of smaller independent units in parallel as this will not only facilitate greater plant flexibility but also allow component interchange. For this exercise the number of parallel units was taken as 68; the choice being governed by the maximum capacity (1 800 m^3/h) of available centrifugal pumps. The pump information quoted was obtained from a major local pump supplier (Crowley, 1990).

Cost comparison

Specific cost figures for various algal control measures are given in Table 4.2. It can be seen that if the assumed membrane lifetime is three years then the costs for a MEMTUF system is comparable to that of a treatment system incorporating granular activated carbon (GAC). Whereas, if the membrane lifetime is five years the cost is comparable to that of a powdered actived carbon (PAC) system.

A conventional treatment process for the removal of algae and THMs would typically include prechlorination, followed by DAF or microscreening for algae removal, and finally activated carbon treatment for THM reduction. A further post-chlorination step might be required to render the water safe for distribution. It can be seen from the operating costs listed in Table 4.2 that ultrafiltration would not be a viable replacement for DAF or microscreening in a conventional treatment process. Although UF can achieve complete algal removal, as opposed to microscreening and DAF which are only capable of approximately 60% and 95% algal removal, respectively, (Haynes *et al.*, 1989) UF is not able to remove THMs from the water.

Although a reduction in the load on the activated carbon step can be expected, when the replacement of DAF/microscreening by UF is considered, the combined operating cost of the individual treatment steps is not favourable (refer to Figure 4.1).

However, since the *formation of* THMPs and THMs is mainly due to the reaction of chlorine with organic materials which are present because of the occurrence of algae (Gehr, 1989 and van Steenderen *et al.*, 1989) the elimination of chlorine dosing in water treatment would practically eliminate THMs. In some cases the use of chlorine for disinfection has been reported to intensify the problems associated with THMs and alternative use of ozone has been suggested (Pearson, 1989).

The use of ultrafiltration for algal removal in combination with sterilisation methods such as UV radiation and ozonation would, in terms of operating cost and technical feasibility, constitute a viable alternative treatment route, as is illustrated in Figure 4.1.

The capital costs for PAC and MEMTUF compare well when the costs for PAC are adjusted to present day values. The cost for the MEMTUF system was calculated in Section 3.7 as R246 142 000 while the figure for PAC (Haynes *et al.*, 1989) after adjustment for inflation comes to R230 000 000.

Unfortunately no figures for DAF and ozonation could be obtained, while the capital cost for UV sterilisation was estimated to be R30 800 000 (Schutte, 1988).

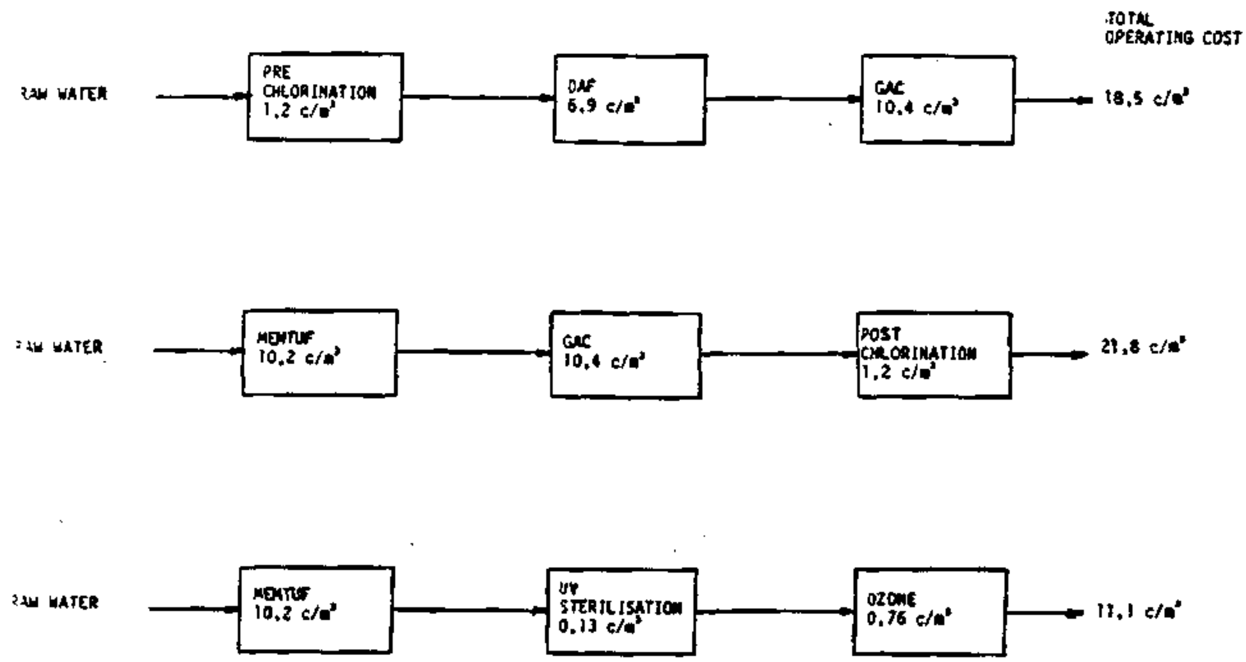

Figure 4.1 Various routes for water treatment when applied to the control of algae

5 CONCLUSIONS

The purpose of this final section is to determine whether the objectives of this project, as set out at the beginning of this report, have been satisfactorily met.

Ability of UF to remove algae from water

The ability of tubular ultrafiltration to successfully remove algal suspensions from natural waters has been demonstrated by the absence of algae in the permeate, irrespective of the algal concentration of the feed water. This is substantiated by the results presented in Section 3.6.

Stable flux values could furthermore be maintain over prolonged periods of operation without the need for frequent chemical membrane cleaning. Algal deposits on the membrane could be removed by inexpensive mechanical means such as sponge balling or stop/start operation. Relevant results are given in Sections 3.1 and 3.4.

Operating parameters and membrane performance

Linear flow velocity and volume recovery were found to have a substantial effect on permeate flux. An average flux increase of 31 LMH per unit increase in velocity was obtained, while an exponential flux decline with increasing volume recovery was experienced. These relationships are mathematically formulated in Sections 3.2 and 3.3 and are expanded on in Sections 4.2 and 4.3.

Cost considerations

It was shown that the replacement of DAF or microscreening by MEMTUF for the removal of algae in a conventional treatment route would not be cost effective due to excessive operating cost (Table 4.2). In combination with UV sterilisation and ozonation, MEMTUF could substantially reduce overall operating cost (Figure 4.1) and obviate the problems associated with the formation of THMs in conventional treatment routes.

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