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Biofouling of spiral-wound membranes in water treatment

Partnership project Kiwa Water Research-AwwaRF

Fifth Periodic Report

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Biofouling of spiral wound membranes in water treatment

Fifth periodic report

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Title
Biofouling of spiral-wound membranes in water treatment: fifth periodic report

Project number
305921.100

Project Manager
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Preface

The project on Biofouling is part of a larger BTO (Joint Research Program) project on defining and achieving Drinking Water Quality for the 21st Century (Q21). The Q21 project, which has been approved by the Board of BTO Clients in October 2003, includes the following projects: (i) defining Q21 water quality goals; (ii) integral approach of water treatment; (iii) application of membrane filtration in water treatment, including the effects of membrane filtration on biological stability, on the growth of *Legionella* in biofilms and biofouling of membranes, and (iv) water quality changes in the distribution system, e.g. sedimentation of particles in relation to brown water problems. These Q21 projects have been defined in more detail in 2004, in communication with the involved Program Advisory Committees (Microbiology, Water Treatment Technology and Asset Management). Contacts with AwwaRF led to the decision to cooperate in the research on biofouling. A workshop was organized at Kiwa Water Research (KWR) on October 11, 2004 to identify the scientific objectives of this cooperative project. Following the workshop, the Joint KWR-AwwaRF project on Biofouling was defined and the starting date was set on February 15, 2005. The project description is presented in Appendix 1. The research activities on Biofouling are discussed in the BTO Project Group Biofouling (BTO-PG Biofouling). Periodically, the results will be reported to the AwwaRF project manager.

The members of BTO-PG Biofouling are listed below:

Name	*Company*
Ir. Hilde Prummel (chair)	Water Laboratory North (WLN)
Ing. Stephan van de Wetering	Brabant Water N.V.
Ir. Sjack van Agtmaal	Evides NV
Ir. Wilfred Burger	Oasen
Ir. Harrie Leyssen	Hydron Advies en Diensten
Ing. Jacques van Paassen	Vitens NV
Dr. Maarten Nederlof	Vitens NV
Ing. Gilbert Galjaard	N.V. PWN
Dr. Jan Hofman	Kiwa Water Research/Waternet
Ir. Joost Kappelhof	Kiwa Water Research
Ing. Wim Hijnen	Kiwa Water Research
Dr.Ir. Dick van der Kooij	Kiwa Water Research
Dr. Emile Cornelissen	Kiwa Water Research

Summary

This report presents the progress of the project, which effectively started at the beginning of 2005. Generally, the experimental part of the project related to the development and application of test methods is on schedule, but reviewing the literature on biofouling is delayed. This delay is due to the complexity of the available information and staff changes. Investigations at locations 1 (pilot plant with NF) and 2 (full scale RO installation) have been completed, the experimental work at location 3 (full scale RO installlation) has been completed in September 2006 and reported (draft) in February 2007. Also experimental work has been conducted at location 4 (full scale RO installation) and completed in 2006 and reported in January 2007. A final location has been identified. Experimental details and planning of this work will be discussed in May 2007.

The investigations at the selected locations included chemical analysis, application of AOC and biofilm monitor for biological stability assessment, use of a pilot plant (location 1), application of a membrane test unit (bench scale) with two spiral-wound membrane elements (one NF and one RO) and the use of a small scale membrane unit, the membrane fouling simulator (MFS). The membrane test unit and the MFS were applied at locations 2 and 3. Operational aspects (pressure drop, cleaning frequency) of the pilot plant (location 1) or full scale plant (locations 2 and 3) were also recorded and autopsies were conducted on membranes from the pilot plant (location 1), the membrane test unit and the MFS at locations 2 and 3, and membranes from the full scale plant (location 2 only). In all cases high biomass concentrations were observed in the membrane elements, confirming that biofouling occurred and caused the observed feed channel pressure drop increase. At one location high concentrations of metals (Al, Mn) were observed in the membrane elements. Water types causing biofouling had relatively high Biofilm Formation Rates.

Information about cleaning procedures as applied in practice in the Netherlands has been collected, and the scientific literature has also been reviewed. However, the quality of the available information is disappointing; quantitative data about water composition are generally very limited and operational aspects are poorly described in the literature. Methods for determining the concentration of attached biomass have been improved. Investigations on determining cleaning efficiency have been continued, with the objective to develop a test method for determining the effect of chemicals used for cleaning under defined hydraulic conditions.

Contents

1 Introduction

This report describes the progress made in a Kiwa Water Research-AwwaRF partnership project on controlling biofouling in high-pressure membrane processes, using spiral wound membranes. A short description of this project is given below. More detailed information about the various project stages and the project plan is given in Appendix 1.

Objectives
The main objective of this research project is to identify effective biofouling control strategies for high pressure membrane systems based on defining conditions for feed water quality (i.e. pretreatment) in combination with cleaning strategies which enable optimal control (prevention/cure). For achievement of this main project objective the following research objectives have been identified:

- Collection and critical evaluation of information about biofouling in the scientific literature;
- Optimization of methods for the assessment of the biofouling potential of water;
- Optimization of methods for the quantification and characterization of biomass accumulating in the membrane elements;
- Development of tools for real-time monitoring (and early warning) of biofouling;
- Assessment of the relationship between selected water quality parameters (biofouling potential) and the rate and extent of biofouling in spiral-wound membranes;
- Elucidation of pretreatment effects on (water quality parameters affecting) biofouling;
- Evaluation of cleaning techniques and protocols for the removal of biomass from spiral-wound membranes;
- Defining pretreatment in combination with cleaning strategies for a cost-effective control of biofouling in spiral-wound membranes in water treatment.

Investigations to achieve these research objectives will be completed by 31 September 2007. The project includes experiments at the laboratory facilities of Kiwa Water Research (KWR) and investigations in pilot plants and full scale plants at selected locations. Involved researchers include specialists in the fields of microbiology, water treatment and chemistry. The Biofouling project is closely linked to the Q21 water quality project in the Joint Research Program (BTO) of the Water Supply Companies in The Netherlands. This Q21 project (with a total budget of about 4 M€) also includes desk studies on Water Quality Goals, Integral Treatment Concepts and experimental studies with pilot plants on effects of membrane types and process conditions on water quality and a study on the interactions between high quality water and surfaces in distribution systems.

The experimental approaches and the results are discussed with the representatives of the water supply companies participating in the BTO-PG Biofouling (see Preface) and decisions regarding adapting the program, including go-no-go for certain aspects when necessary, will be taken. For example, a reduction of the program for testing the cleaning effects of chemicals would enable intensification of the investigations on growth potential assessment or pretreatment effects, or vice versa

These decision moments are mentioned in the program and indicated in the time schedule.

2 Review of literature

The information available in the scientific literature has been collected and incorporated in a first draft. Information from recent conferences, e.g. AWWA Membrane Technology Conferences, IWSA/IWA conferences, specific conferences on Membranes, has been collected and partially added to the draft, which was discussed in the meeting of the BTO PG Biofouling (September 27, 2005). The PG Biofouling agreed with the proposed outline of the report. The chapters are mentioned below:

Chapter 1. Introduction
Chapter 2. Membrane filtration
Chapter 3. Biofilm formation
Chapter 4. Symptoms, diagnosis and prediction of biofouling
Chapter 5. Control of membrane biofouling
Chapter 6. Practical experiences with NF and RO
Chapter 7. Evaluation, conclusions and recommendations.

Chapters 5 and 6 of the draft are still incomplete and others need further editing When Chapters 1 to 6 are completed, the evaluation chapter will be added. A main reason for the delay is the large number of publications that have to be reviewed, both scientific publications and also papers on the application of membranes in practice. Furthermore, the interpretation of reports about observations in practice and in pilot plants in many cases requires experience and is hampered by the poor descriptions of the situation . The original planning to complete the literature review at the end of the first quarter of 2005 was far too optimistic.

It was intended to complete a first draft of the review at the end of 2005, but the person responsible for the biofouling literature review had left KWR and it was not possible to make the desired progress. Further work on the review has been scheduled before 31 December 2006, but completion was not achieved. The review will be included in the final report.

3 Test locations

Test locations were selected for investigating the effect of the feed water composition on membrane biofouling. Selection of the locations was done in the BTO-PG Biofouling, partly based on requests of participants. Table 3.1 gives an overview of the selected locations.

Table 3.1 Test locations

Location nr	*Description*	*Membrane type*	*Water source*
1	Pilot plant	NF	Treated groundwater
2	Full scale plant	RO	Surface water from open storage reservoir
3	Full scale plant	RO	Surface water from canal
4	Full scale plant	RO	Surface water from a canal
5	Pilot plant	RO	Surface water from a storage reservoir

3.1 Location 1

The raw water at location 1 is abstracted from an anoxic aquifer, containing high concentrations of methane (>10 ppm), ammonia-N (3.3 ppm), organic carbon (8 ppm), iron (14.6 ppm) and manganese (0.7 ppm). Water treatment includes: intensive perforated-plate aeration, rapid sand filtration, aeration, pellet softening and rapid sand filtration. Chemical disinfection is *not* applied. The impact of membrane post treatment on the quality of the treated water (particles, organic carbon, biological stability) as produced in regular treatment, was investigated with a pilot plant with ultrafiltration (UF) followed by nanofiltration (NF). The composition of the feed water for NF, as obtained by UF treatment of the treated groundwater, is presented in Table 3.2.

Table 3.2 Water quality characteristics before and after ultrafiltration.

Parameter	*Treated water*		*Treated water after UF*		*Removal (%)*
	Avg.	*Stdev*	*Avg.*	*Stdev*	
MFI (s/l^2)	6.8	2.6	n.d.	n.d.	n.a.
Suspended matter (mg/l)	< 2	n.d.	< 2	n.d.	n.a.
DOC (mg C/l)	7.4	0.5	7.5	0.5	0
UV-ext (l/m)	20	1.1	19	1.6	3
Color (mg Pt/l)	16	1.4	16	1.4	0
pH	7.6	0.1	7.6	0.1	n.a.
Conductivity (mS/cm)	50	1.6	50	1.1	0
Bicarbonate (mg/l)	287	9	286	8	0
Iron (mg Fe/l)	0.03	0.02	< 0.01	<0.01	>71
Manganese (mg Mn/l)	< 0.01	<0.01	< 0.01	<0.01	n.a.
Sodium (mg Na/l)	72	6	73	6	0
Calcium (mg Ca/l)	33	6	32	6	3
Magnesium (mg Mg/l)	9.9	0.9	9.9	0.9	0
Potassium (mg K/l)	2.3	0.1	2.4	0.1	0
Arsenic (µg/l)	0.02	0.008	<0.01	0	>71

n.d. = not determined; n.a. not applicable

A schematic overview of the pilot plant used at location 1 is given in Fig. 3.1 (ultrafiltration unit not included).

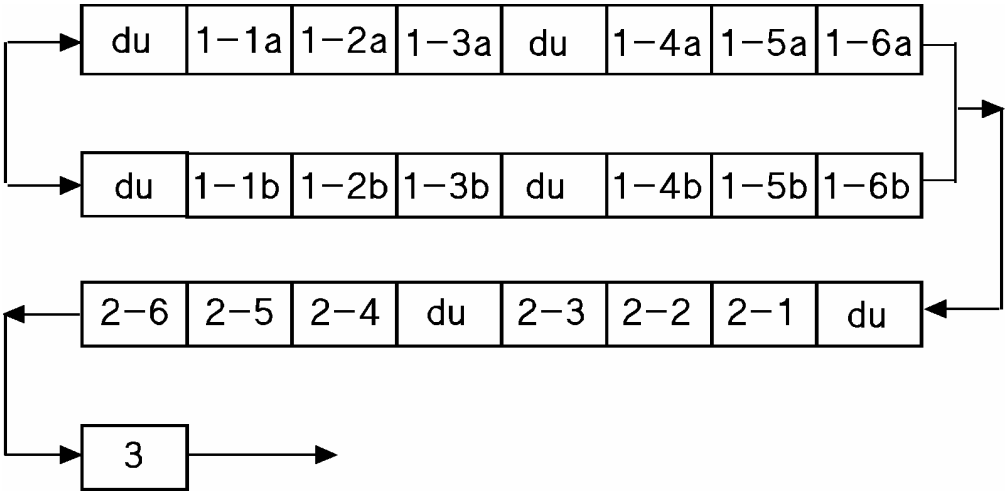

Fig. 3.1 Schematic of the NF pilot plant as used at test location 1. Du = dummy (no membrane element in vessel). Membrane elements 1-1b and 3: no permeate production.

3.2 Location 2

Water originating from the river Meuse is used at location 2 for the production of a high quality water by applying membrane filtration (UF followed by RO on full scale). River water, that has been stored in open surface reservoirs (about 150 days), is treated with in line-coagulation (addition of iron salts) and UF. The quality characteristics of the water after storage in the open surface reservoirs are given in Table 3.3. Acid and an antiscalant (AS) is added to the water treated with UF. The full-scale RO plant includes two stages of membrane vessels, each containing each 6 membrane elements, with 4 vessels in the first stage and 2 vessels in the second stage.

Table 3.3. Quality characteristics of river Meuse water after storage in open surface reservoirs (data 2004).

Characteristic	*Min.*	*Max.*	*Avg.*
Temperature (°C)	4.3	21.9	12.2
Turbidity (Fte)	7.3	13.3	10.6
Chlorophyll (µg/l)	<2	36.3	4.1
pH	8.4	9.2	9.0
Conductivity (mS/m)	43.5	49.1	46.3
NH_4-N (mg/l)	0.02	0.21	0.07
NO_3-N (mg/l)	2.42	3.6	2.9
Ortho-P (mg/l)	0.01	0.091	0.058
Total-P (mg/l)	0.046	0.107	0.077
Fe (mg/l)	0.005	0.013	0.005
Mn (mg/l)	0.005	0.9	0.072
TOC (mg/l)	2.9	3.87	3.45
UV extinction $_{254}$ (m^{-1})	8.41	9.6	9.07

3.3 Location 3

Water is abstracted from a canal, which is carrying groundwater to a lake. This groundwater contains a high concentration of NOM and also receives discharges of treated industrial waste water. Water treatment includes:

- addition of polyaluminum chloride (10 ppm)
- sand filtration
- pH correction (with caustic)
- addition of polyaluminum chloride (2 ppm) in summer
- ultrafiltration.

Antiscalant (AS) is added to the UF filtrate which subsequently passes through a cartridge filter. The membrane installation consists of a two-stages RO process. The quality characteristics of the feed water are shown in Table 3.4.

Table 3.4 Quality characteristics of raw water and UF filtrate (feed water for the RO plant in the period of investigation *

Characteristic	*Raw water*	*UF filtrate*
Temperature (°C)	Range: 15-25	Range: 15-25
Turbidity (Fte)	19.2 ± 9.2	<0.1
Chlorophyll (µg/l)	Range 5-100	Nd
pH	7.7 ± 0.3	7.7 ± 3.3
Conductivity (mS/m)	51.9 ± 10.6	56.7 ± 0.5
NH_4-N (mg/l)	Nd**	0.32 ± 0.5
NO_3-N (mg/l)	Nd	3.4 ± 2.3
Ortho-P (mg/l)	Nd	0.028 ± 0.0014
Al (µg/l)	267 ± 93.9	40.5 ± 10.6
Fe (mg/l)	1.3 ± 1.0	<0.02 ±<0.005
Ca (mg/l)	Nd	49 ± 5.6
Mn (mg/l)	Nd	0.068 ±0.056
DOC (mg/l)	18.2 ± 3.0	9.2 ± 0.9
UV extinction $_{254}$ (m^{-1})	54.8 ± 12	20.4 ± 2.8

* periodically, treated water (drinking water) serves as feed water; ** no data

3.4 Location 4

At location 4, surface water (canal) is used for the production of water with RO membranes. Pretreatment includes in line coagulation/flocculation, cartridge filtration and ultrafiltration. Subsequently, an antisclant is added. The following raw water quality characteristics are available:

- Conductivity: 500 uS/cm
- pH 7,7
- total suspended solids: 1.2 mg/l
- Totaal SiO_2: 6.4 mg/l

3.5 Location 5

Under discussion

4 Growth potential of feed water and pretreatment effects

4.1 Optimization of methods

The following methods have been applied for determining the microbial growth potential of water:

- assimilable organic carbon (AOC), as determined in a bioassay using two bacterial cultures;
- the biomass production potential (BPP) test, based on determining the growth of the indigenous population, using ATP analysis for biomass quantification;
- The biofilm monitor, which gives the Biofilm Formation Rate (BFR) of the water type involved.

These methods are applied as standardized methods. The focus of their use concerns the effect of pretreatment and the relationship between these parameters in the feed water and the rate of biofouling.

4.2 Application of methods

4.2.1 Location 1

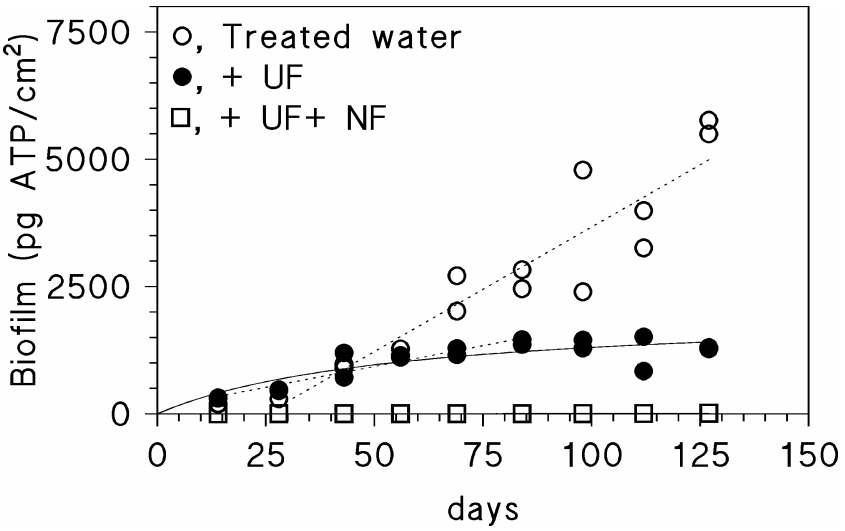

Fig. 4.1 Effect of ultrafiltration (UF) followed by nanofiltration (NF) on the biofilm formation in the biofilm monitor. The treated groundwater contains a high concentration of NOM (NPOC= 8 ppm).

The growth potential of the feed water of a nanofiltration (NF) process was determined at location 1 (groundwater treatment plant) where ultrafiltration (UF) followed by nanofiltration (NF) was applied on the treated water. The AOC concentration of the treated water was about 12 µg C/l and UF did not significantly affect the AOC concentration, which is relatively low in relation to the high NPOC concentration (Table 4.1). The biofilm formation rate (BFR) of the treated

groundwater was relatively high and UF caused about 60 % reduction of the BFR. No biofilm formation was observed in water after NF (see Fig 4.1).

Table 4.1 Water quality characteristics related to biological stability at location 1

Water type	*NPOC (mg/l)*	*ATP* (ng/l) (sd)*	*AOC (µg C/l)*	*BPP (ng ATP/l)*	*BVS (pg ATP/cm².d)*
Treated groundwater	7.4 ± 0.5	10.3 ± 3.9	12.2 ± 0.4	23.4 ± 1.6	48.9 ± 4.9
After UF	7.5 ± 0.5	3.4 ± 1.5	11.3 ± 2.7	11.2 ± 0.6	16.4 ± 1.8
After UF +NF	< 0.1	0.3 ± 0.3	2.8 ± 1.4	12.1 ± 1.6	0.06 ± 0.01

* adenosinetriphosphate (active biomass)

4.3 Location 2

Water quality characteristics related to biological stability of the feed water of the RO installation have been determined at location 2 using batch tests (AOC, BPP), and the biofilm monitor in September – November 2005. Fig. 4.2 shows the biofilm formation in the biofilm monitor, demonstrating that AS dosage strongly increased the BFR, which attained a value of about 270 pg ATP/(cm².d) at the beginning of the experimental period.

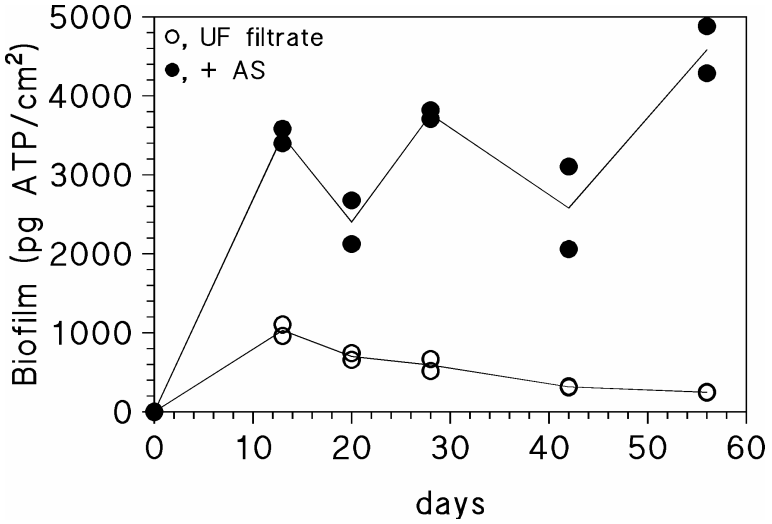

Figure 4.2 Biofilm concentration in the biofilm monitor before and after AS dosage.

Tabel 4.2 Feed water quality characteristics related to biological stability at location 2

Water type	*NPOC (mg/l)*	*ATP (ng/l) (sd)*	*AOC (µg C/l)*	*BPP (ng ATP/l)*	*BFR (pg ATP/cm².d)*
Feed before UF	3.5	786*	321	872	n.d.
After UF	2.9	44 ± 94	17- 25	16- 35	16**
After UF + AS	3.0	56 ±79	17- 33	34	270**

*, a singe observation in spring; **maximum value observed at start of the experiment

UF clearly reduced the concentrations of biomass (ATP) and AOC, most likely by removing biomass of algae and other particles. AS dosage slightly increased the AOC concentration and had a large impact on the BFR. This effect may be due to the presence of biologically-available phosphorous in the AS. Indications that AS dosage may lead to the introduction of bioavailable P have been obtained in a separate

study. A paper about the subject has been presented at the AWWA Membrane Technology Conference (Tampa, 2007). This paper is included as *Appendix II* in this Progress Report.

4.4 Location 3

The biofilm formation rate (BFR) of the water after ultrafiltration (and prior to AS dosage) was measured with the biofilm monitor in two periods, viz. May-July 2006 and August – September 2006. The biofilm concentrations generally increased as a function of time, but sudden changes were observed (Fig. 4.3). The changes are attributed to variations in water composition, e.g. large variations in ammonia concentrations were observed (cf Table 3.4). These variations may have occurred in combination with variations in the concentration of biodegradable compounds which stimulate biofilm formation. Biofilm formation in the second period was much stronger than in the first period. A low frequency of growth potential measurements, as conducted in batch tests (Table 4.3), may not give a true picture of the water quality related to biofouling.

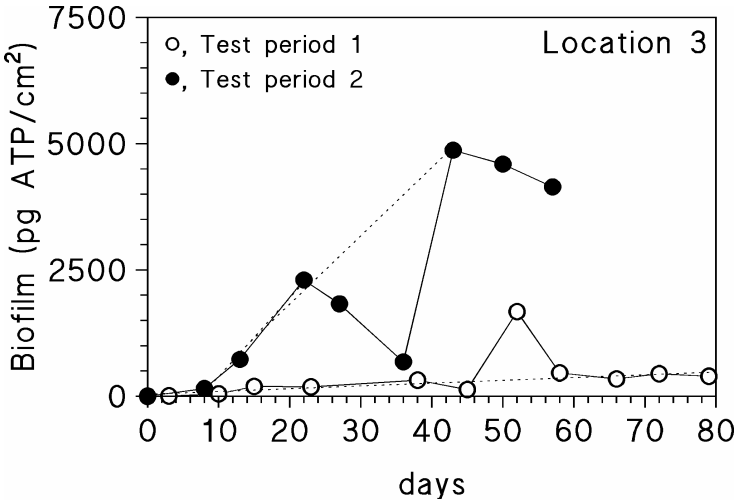

Figure 4.3 Biofilm concentration in the biofilm monitor in two periods of investigation on UF filtrate. .

Tabel 4.3 Water quality characteristics related to biological stability at location 3 at two test periods

Water type	*DOC (mg/l)*	*ATP (ng/l) (sd)*	*AOC (µg C/l)*	*BPP (ng ATP/l)*	*BFR (pg ATP/cm².d)*
Feed water period 1*	9.2 ± 0.9	11.9 ± 2.7	11.9 ± 2.7	20.7 ± 20.8	5.5
Feed water period 2*		17.2	17.2	64	156**

*feed water for test unit. Feed water for full scale plant with included AS dosage not accessible for experiments.
**, biofilm concentration fluctuated (cf. Fig. 4.3).

4.5 Location 4

At location 4, a relatively strong biofilm formation was observed in the biofilm monitor supplied with the UF product prior to and after AS dosage (Fig. 4.4). The

strong decline of the biofilm concentration in the monitor on day 48 is attributed to the accidental introduction of cleaning compounds. The batch test results confirm that AS dosage increase the growth potential of the feed water. Also at this location, (feed) water quality shows variations, which may be attribute to variations in raw water quality.

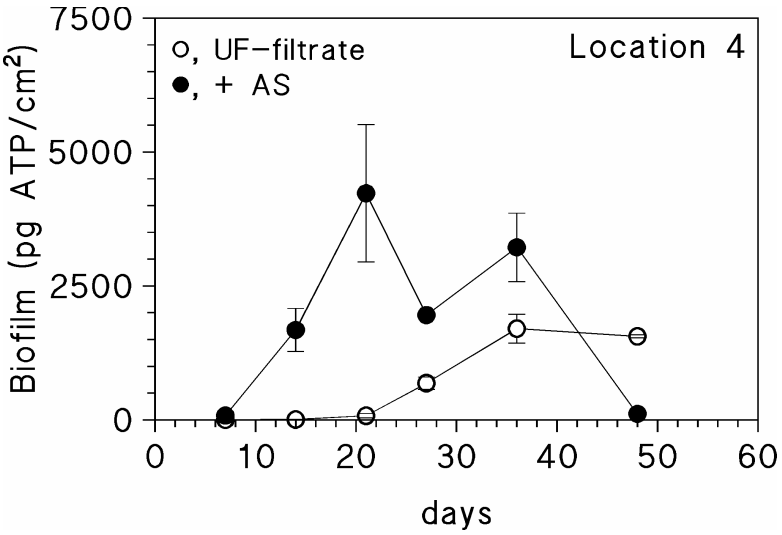

Figure 4.4 Biofilm concentration in the biofilm monitor prior to and after AS dosage at location 4.

Tabel 4.4 Water quality characteristics related to biological stability at location 4

Water type	*DOC (mg/l)*	*ATP (ng/l) (sd)*	*AOC (µg C/l)*	*BPP (ng ATP/l)*	*BFR (pg ATP/cm².d)*
After UF	2.8 ± 0.4	2.9 ± 0.22	8.8 ± 0.9	19.5 ± 12.5	109*
After UF with AS	2.8 ± 0.4	3.3 ± 0.44	14.7± 1.7	43.4 ± 35	296*

* maximum value

4.6 Location 5

Investigations in 2007

4.7 Discussion and conclusions

Will follow when results at location 5 are available

5 On site early warning monitoring

Early warning of biofouling of the membranes is considered important. because it enables timely application of corrective measures, e.g. dosage of chemical, or cleaning. Methods for early warning under investigation include: (i) assessment of the specific oxygen consumption rate (SOCR. mg $O_2/m^2.h$) of the membrane, (ii) sensitive monitoring of the feed channel pressure drop increase (dP) and (iii) the membrane fouling simulator (MFS).

5.1 Oxygen consumption rate monitoring

5.1.1 Test protocol

The method has been optimized and made operational. The hydraulic conditions during oxygen measurement must be controlled carefully to be sure that oxygen is measured in the water that had been in contact with the membrane. In the pilot plant (location 1) sample points are situated on the pressure vessel between each membrane element to sample each element separately. A change in residence time distribution was observed below capacities of 500 l/h (in 4"elements). Therefore the capacity during sampling was chosen at 500 l/h. The reaction time of the oxygen sensor exceeds the time necessary to refresh one membrane element with a capacity of at least 500 l/h. Therefore the sample needs to be collected in a circulation system (Fig. 5.1). The measurement procedure was as follows:

- the oxygen concentration of the concentrate was measured;
- the installation was shut down for approximately 1 h;
- one chosen element was sampled by opening a valve on the sample point with a capacity of 500 l/h. The first 1.5 liter of sample was not used (valve 1. 2. 3 are open). The second 15 seconds. the sample was collected in a recirculation system (valve 2 is closed);
- The sample was recirculated (valves 1 and 3 are closed) over an oxygen sensor during 5 minutes (until stabilization);
- The SOCR was calculated based on the oxygen depletion. the membrane area of the specific membrane element and the thickness of the spacer.

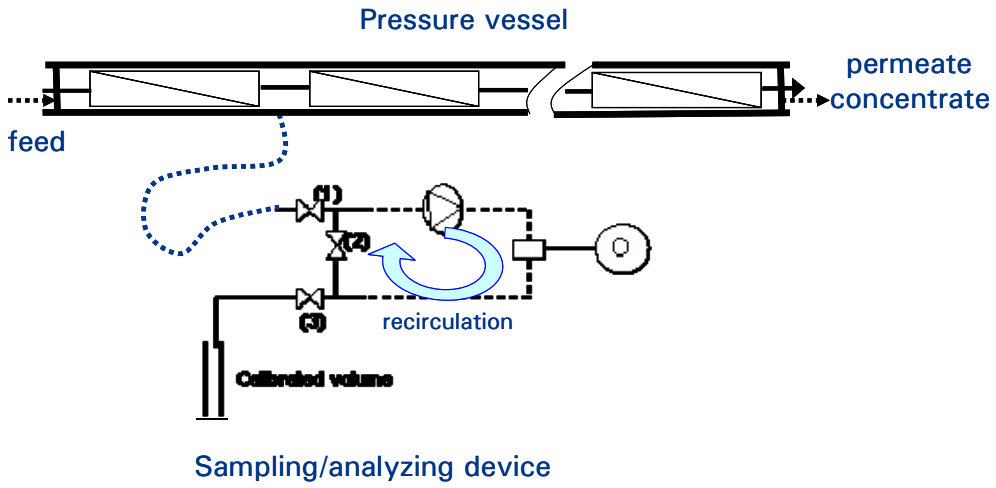

Fig. 5.1 Analyzing device and positioning of the sample points

The complexity of the protocol was caused by the relative slow stabilization of the oxygen sensor used (Cellox 325 Sensor with a WTW Oxi 340i device). In case of a faster reacting oxygen sensor (less than 10 seconds) the protocol can be simplified: the recirculation device can be avoided.

5.1.2 Application and testing

Oxygen monitoring has been applied on NF membrane elements at location 1. Oxygen consumption in these NF membrane elements was below the detection limit of the method (SOCR < 0.14 mg/m²/h) despite the observation of a feed channel pressure drop caused by biofouling. These findings indicate that oxygen consumption measurements are not suited for early warning of biofouling in membrane elements. The observations at location 1 have been presented in BTO-PG Biofouling on May 17, 2005. At the meeting of 27 September 2005, a draft report was discussed. It was concluded that investigations on the SOCR method will be terminated. because of the complexity of the method and the inability to detect oxygen consumption at biofilm concentrations which cause biofouling (feed channel pressure drop increase). The report will be completed with a critical evaluation. Also a scientific publication in English language covering the latest and earlier observations will be prepared.

5.2 Optimization of dP method

Monitoring of the feed channel pressure drop (dP) in membrane elements has been optimized and the usefulness of accurate dP measurements in NF elements was tested at location 1. A pressure difference sensor was selected and tested, enabling to determine small pressure changes.

5.2.1 Test system

A Differential Pressure Transmitter (DPT) was used to determine the pressure difference over spiral wound membrane elements in test rigs and over the Membrane Fouling Simulator (Fig. 5.2). The detection range of the DPT is between 0.01 to 1000 mbar (overall accuracy of 0.2 mbar). The DPT can be used at pressures up to 70 bar.

The DPT was provided with transparent tubes and stainless steel quick connectors. Transparent tubes were used to visually determine the presence of gas bubbles. Gas bubbles were removed from the tubes by flushing of the tubes with water prior to assessment of the pressure difference.

The DPT is a relative small unit (approximately 0.4 x 0.3 x 0.5 m) and easy to carry. The pressure difference can be determined by reading of the display and by data logging on a computer using provided software.

Figure 5.2 Front view of the Differential Pressure Transmitter. Quick connectors are used for assessment of the pressure difference.

5.2.2 *Application of dP method*

The dP monitoring in membrane elements was applied at location 1. Pressure difference measurements over a membrane element were more reliable than values for the feed channel pressure drop calculated from the measured feed channel pressure at the inlet and the outlet side of the element (Fig. 5.3).

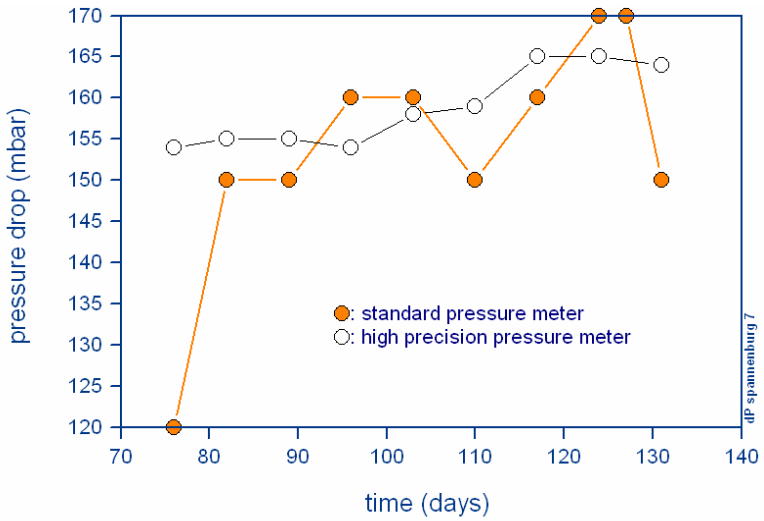

Fig. 5.3 Pressure drop in membrane element at location 1, as determined with a standard procedure and with a pressure difference sensor.

5.3 Membrane fouling simulator (MFS)

5.3.1 *Method*

A flat sheet membrane system (the Membrane Fouling Simulator MFS) (Figure 5. 4) was developed with hydraulic conditions similar to those in spiral wound membrane elements. The MFS uses the same membrane materials and spacers as applied in spiral wound RO and NF membranes. Various sheets of membrane and spacers can be placed in the MFS. Additional BTO funds have been acquired to enable further

development of this method. Challenge experiments have been conducted to the flat sheet membrane system to assess the reproducibility of the response to biofouling in relation to the pressure drop.

Figure 5.4 Four Membrane Fouling Simulators (MFS) installed in parallel during comparison studies. The external dimensions of a MFS is 0.07 x 0.30 x 0.04 m.

Tests showed that the relationship between linear flow and the pressure drop in the MFS system and in a spiral wound membrane module were identical. Furthermore. the same relationship was observed with different MFS's containing different sheets of membrane and spacers (Figure 5. 5).

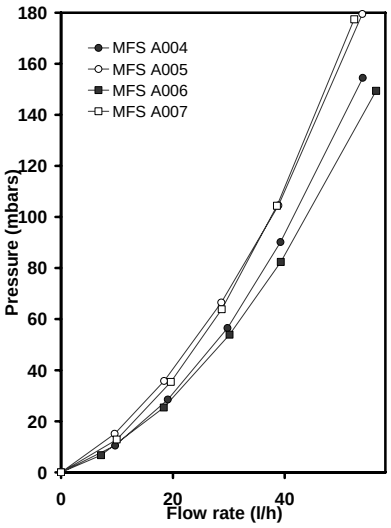

Figure 5.5 Relationship between flow velocity (m/s) and pressure drop (mbar) of 4 MFS's containing different sheets of membrane and spacers.

Dosage of biodegradable nutrients (acetate-C/L) to the feed water of the MFS resulted in an increase of the pressure drop (Figure 5.6). Different concentrations of the same biodegradable compound in the feed water resulted in differences in (i) the rate and extent of pressure drop increase and (ii) the concentration of biomass in the

MFS. An increased concentration of nutrient in the feed water gives a higher pressure drop increases and a higher biomass concentration. The study shows that the MFS was able to discriminate between water qualities differing in nutrient concentration. The studies were conducted within a relative short time (12 days) with a minimum of water spent (16 L/h per MFS). Details of the development and properties of the MFS systems have been published (Vrouwenvelder et al. 2006).

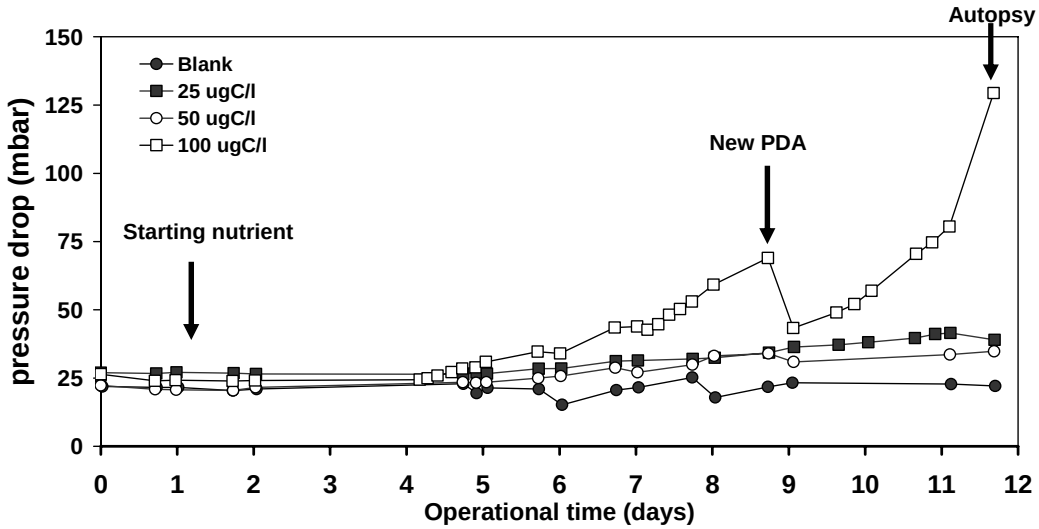

Figure 5.6 Pressure drop increase (%) as function of time with different nutrient concentrations in the feed water of the MFS. New DPA = new pressure drop equipment applied.

5.3.1.1 Application at locations

The MFS, which came available after completion of the investigations at location 1 is used at locations 2, 3 and 4. The results are presented in Chapter 6.

5.4 Discussion and conclusions

Will follow when all experimental data are available.

6 Effect of water composition on membrane performance

This part of the project is aiming at determining the relationship between water composition and the rate of biofouling in spiral-wound NF membranes, monitored as the increase of the normalized pressure drop (NPD). For this purpose investigations are conducted at a number of selected locations. This study was initially intended to be combined with studies on the effects of UF on treated water composition. as part of the Q21 project. After completion of the investigations at location 1, it was decided to proceed with a separate bench scale test unit enabling the use of one or two NF spiral wound membrane elements (RO and/or NF). Membranes used in this unit are FilmTec BW30LE-4040 and NF TRisep TS80-4040. Both are thin-film composite membranes. The In this This approach increases the flexibility for selecting locations to study the effects of water composition on biofouling. The test system had been prepared and tested at Kiwa facilities in Nieuwegein with regular tap water as the feed. Subsequently, it was used at location 2 and 3.

6.1 Location 1

The pressure drop in the NF pilot plant increased (Fig. 6.1) and autopsies revealed that biofouling of the NF membranes occurred (cf. Fig. 7.3) despite additional UF treatment of the treated ground water. The results of the investigations at location 1 have been discussed with representatives of the involved water supply company on December 9. 2005 and reported (BTO 2006.004). Membrane filtration as tested will not be used to upgrade the quality of treated groundwater. Optimization of the biological filtration process in combination with ion exchange for the removal of organic compounds is the preferred approach.

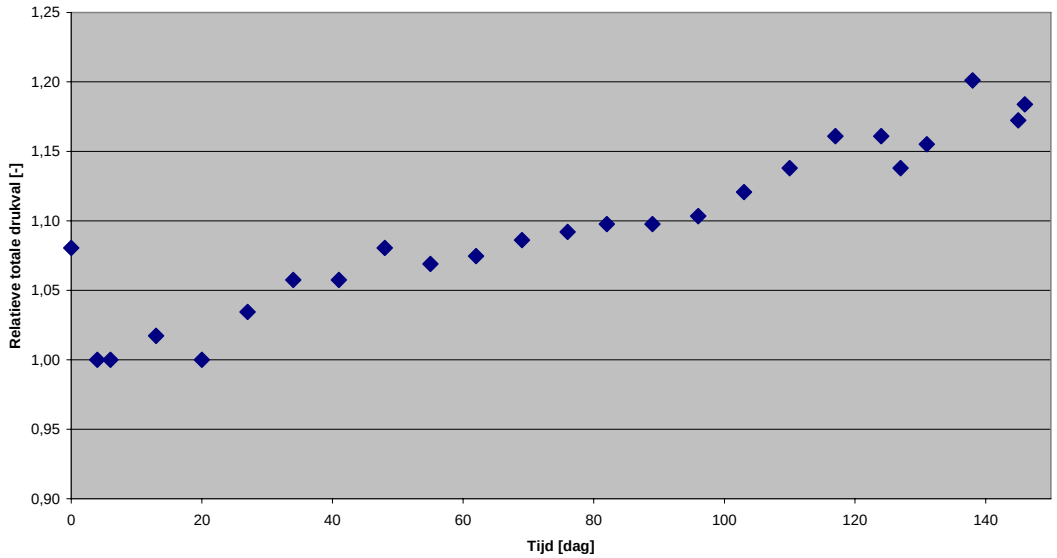

Fig. 6.1 Increase of feed channel pressure drop in the pilot plant membrane installation at location 1.

6.2 Location 2

6.2.1 *Pressure drop increase in test unit*

A rapid increase of the feed channel pressure drop (NPD) was observed with the bench scale membrane test unit and in the MFS (Figure 6.2). The increase exceeded 15% within 6 days (fig. 6.3). The data show that fouling in the test unit and in the MFS was similar. Observations with the biofilm monitor demonstrated that the feed water had a high biofilm formation rate (BFR) which was increased after AS dosage (Fig. 5.2). Based on the results of this study, the type of AS has been replaced in the full-scale installation. Further research is being conducted to determine the influence of AS dosage on membrane fouling. The results of the study at location 2 have been discussed with representatives of the involved water supply company and reported in detail (BTO 2006.030).

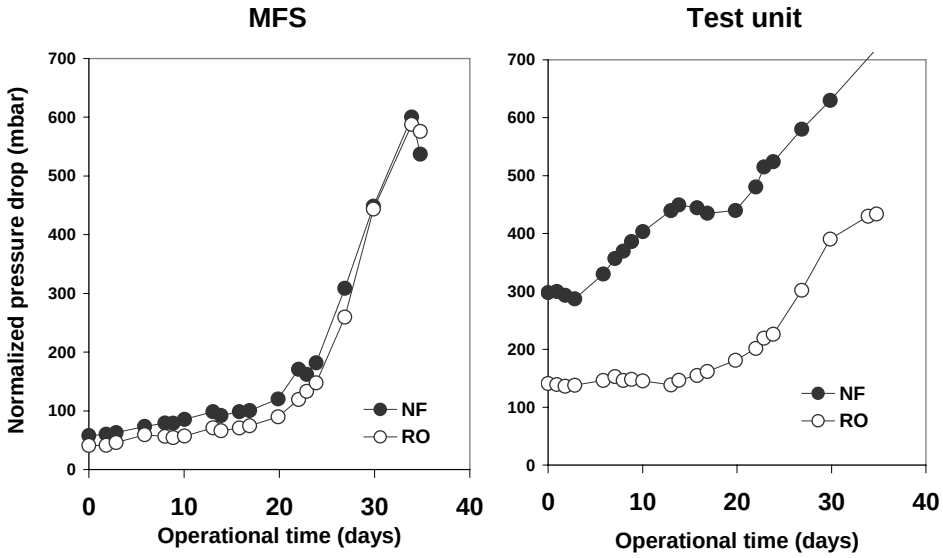

Fig. 6.2 Normalized pressure drop increase in the MFS system and in the membrane test unit (bench scale) supplied with feed water of the RO installation at location 2.

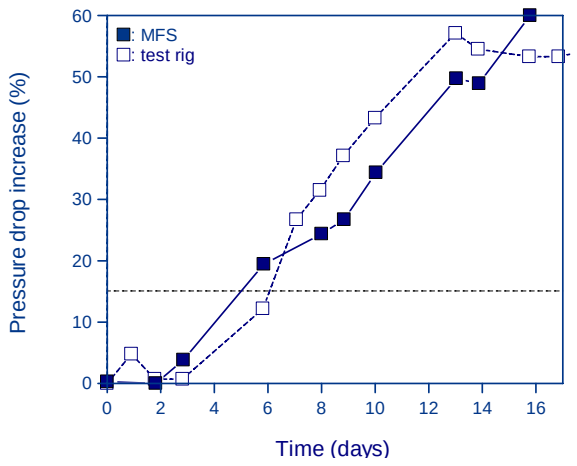

Figure 6.2. Pressure drop increase (% of start value) of the MFS and test unit supplied with the RO feed water including 3 ppm antiscalant.

6.3 Location 3

Investigations at location 3 started in March 2006 and were completed in September 2006. Due to restrictions at the plant, it was not possible to investigate the feed water after AS dosage with the bench scale membrane test unit and therefore this unit was supplied with the UF filtrate. Two series of experiments were conducted with the bench scale test unit and the MFS. The first test series was from May to July, and the second series from August to September. Figs. 6.4 and 6.5 show that a rapid increase of the pressure drop was observed in the test units with RO and NF membranes. The observations with the MFS differed from those with the test unit.

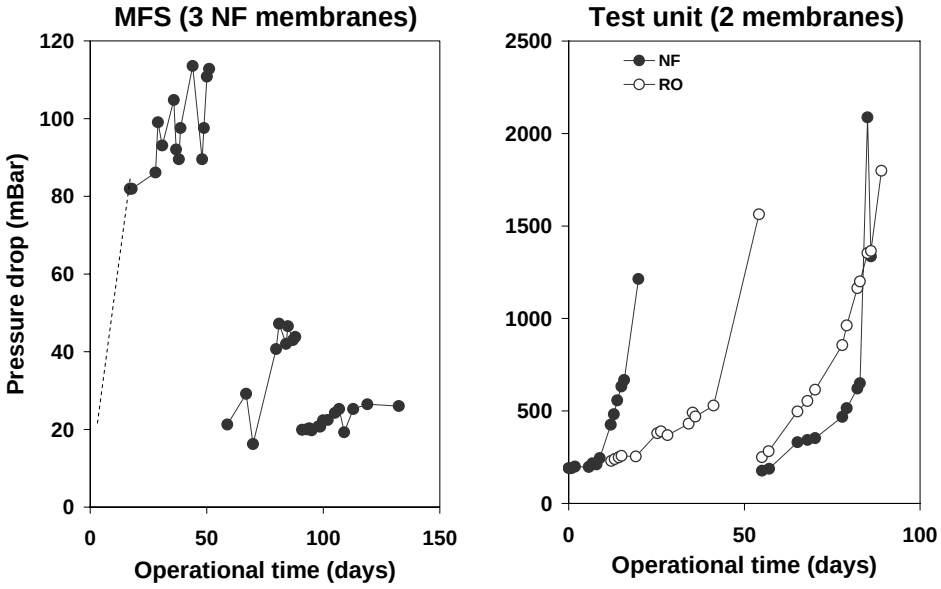

Fig. 6.4. Pressure drop increase in the MFS unit and in the test unit in the two experimental periods at location 3. Feed water: UF product, without AS dosage.

The experiments were terminated when the feed channel pressure drop in the test units had reached a level of about 500%. Subsequently, membranes were investigated for accumulated biomass and inorganic compounds.

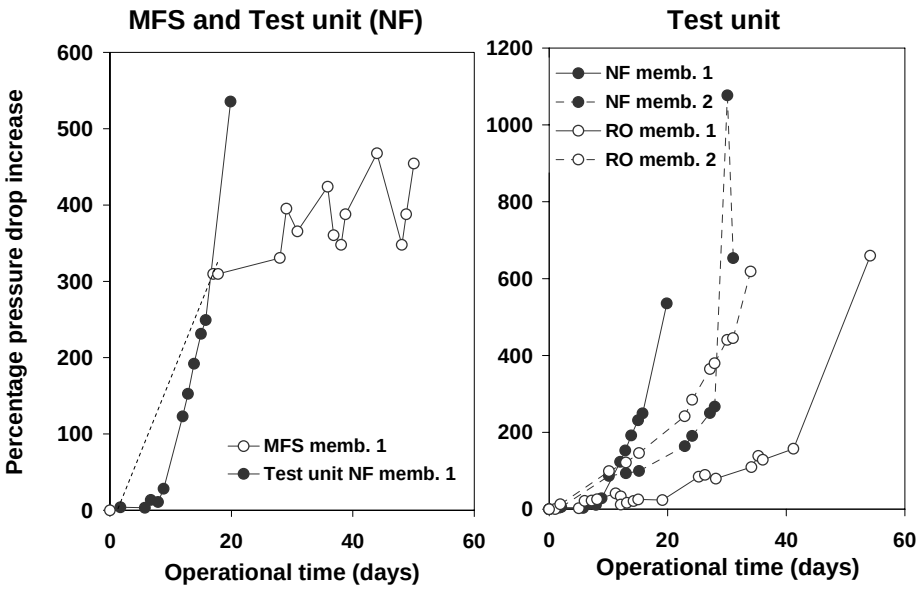

Fig. 6.5 Percentage increase of the feed channel pressure drop in the MFS and in the test unit supplied with water prior to AS dosage in two experimental periods at location 3.

6.4 Location 4

At location 4, the feed water of a full-scale RO plant was investigated in the period August 24 to December 2006. Also here a strong pressure drop increase was observed in the membrane elements of the test unit. The percentage increase in the MFS system was similar to the percentage increase in the membrane elements.

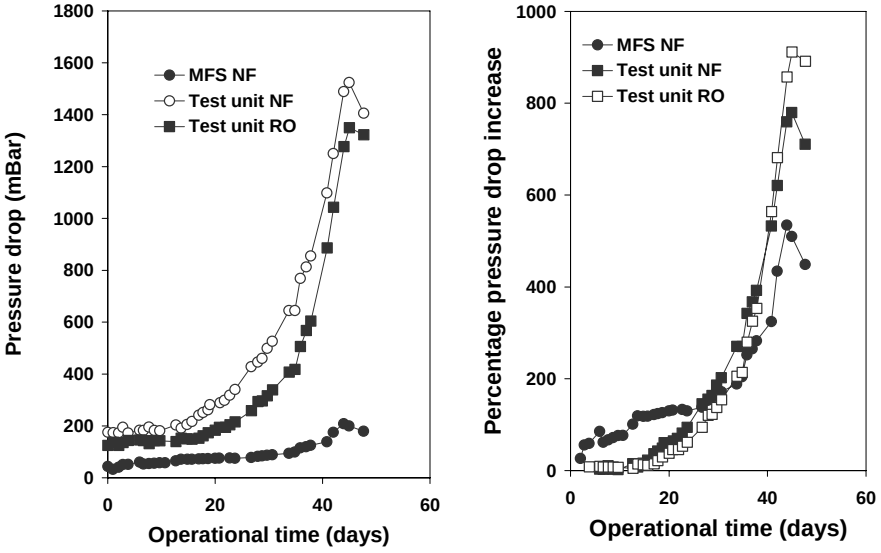

Fig. 6.6 Increase of the feed channel pressure drop in the MFS and in the test unit supplied with feed water at location 4.

6.5 Location 5

Test program is being discussed with the owner of the plant.

6.6 Discussion and conclusions

Follows after completion of investigations at location 5.

7 Analysis of biomass in membrane elements

Methods for accurate quantification of biomass in membrane elements are essential for determining the degree of biofouling and for evaluating the effects of cleaning procedures.

7.1 Selection and optimization of methods

Quantification of biomass on membranes includes the following activities: (i), complete removal of biomass from the membranes and (ii), quantitative analysis of the removed biomass. Various sonication methods (low energy, high energy) have been tested for their efficacy in removal of biomass from the solid surfaces. For this purpose, biofilm was grown on pieces of plasticized ('soft') PVC (PVC-P) and also membranes available from pilot plants and practice were used. A series of low energy sonications (LES) using a water bath (Branson model 5510E-DTH) output 135 watts, 42 kHz) appeared to be insufficiently effective for the removal of attached biomass from PVC-P and from membranes. Application of high energy sonication using a Branson W-250 system (20 kHz) removed (more than) 90 % of the attached biomass when two treatments were applied of 1 min each. Swabbing was used to achieve complete removal. Fig. 7.1 shows typical results as obtained with biofilm grown on PVC-P. Fig. 7.2 shows results obtained with an NF membrane. Two times HES treatment of 1 min followed by swabbing, or 3 times HES treatment of 1 min yielded over 90% attached biomass, measured as ATP.

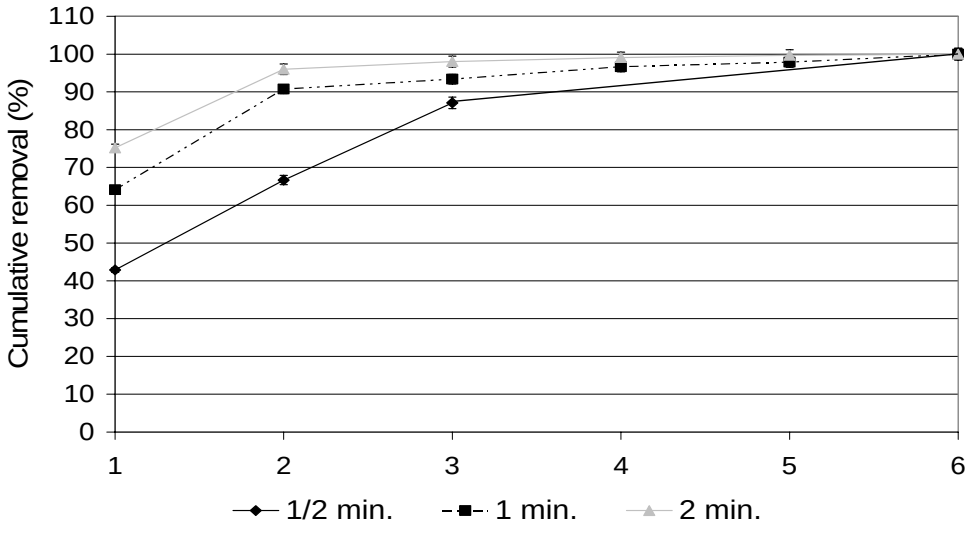

Figure 7.1 Biomass removal from pieces of plasticized PVC using 3xHES during ½, 1 and 2 minutes at 45%; 1 to 5 is 1 to 5 times HES; 6 is the swab treatment; 100% is 28926, 18023 and 17812 pg ATP/cm², respectively.

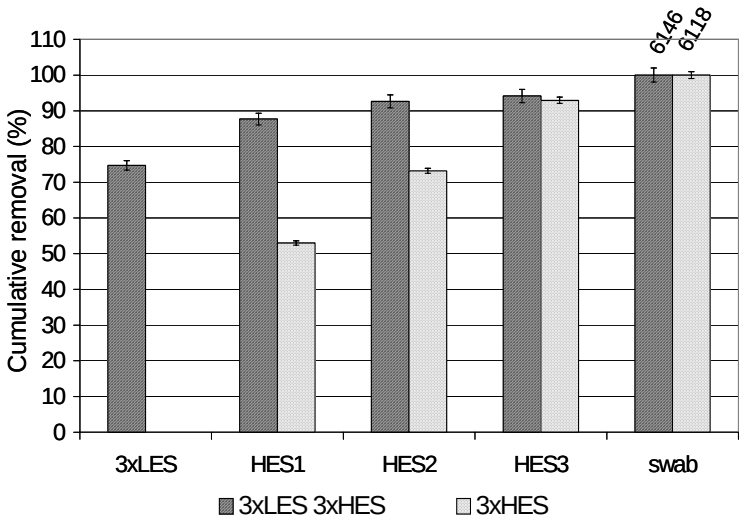

Figure 7.2 Biomass removal from sample pieces of an NF-membrane, using low energy sonication (LES) and/or high energy sonication (HES). The amount obtained after additional swabbing is considered to represent the total amount (100%) of attached biomass.

A number of analytical methods has been selected and tested to evaluate their relevance for biofouling analysis. These methods include: ATP, heterotrophic plate count (on R2A medium), total direct cell counts, total organic carbon, carbohydrates and proteins. The detection limits and accuracy of the methods for determining the concentrations of carbohydrates and proteins were tested to enable evaluation of the usefulness of these methods for determining biofouling and effects of cleaning procedures on attached biomass. ATP analysis gives rapid and reliable results but is only related to active biomass. Hence, this parameter does not determine the amount of (dead) biomass after chemical inactivation. TDC analysis is rather laborious and HPC counts only provide semi-quantitative information (high/medium/low) about the biomass concentration because only a fraction of the cells produced colonies on agar. Analysis of total organic carbon (TOC), proteins and carbohydrates (Dubois method) gives quantitative data about biomass components. Analysis of proteins and carbohydrates do not cover all TOC, representing variable fractions (Table 7.1). Determination of the protein fraction is hampered by the required liberation from the cells. Application of the Kjehldahl-N method enables complete liberation of organic-N, but this analysis also includes genetic material (RNA, DNA) and cell wall components.

Table 7.1 Concentrations of biomass attached on PVC-P tubing and on NF membranes, as determined with different analytical methods

Material	HPC (CFU/cm²)	TDC (n/cm²)	ATP (pg/cm²)	TOC (µg/cm²)	CH* (µg/cm²)	Protein (µg/cm²)
PVC-P	1.3 x 10e7	Nd**	7284	nd	6.1	5.3
PVC-P	9.1 x 10e5	Nd	7357	nd	4.3	29
PVC-P	3.7 x 10e7	Nd	20589	257	14.2	58
NF membrane	Nd	Nd	15621	674	132	103
NF membrane	Nd	Nd	40656	716	49	55
NF membrane	Nd	Nd	5019	1143	22	20

*, CH, carbohydrates; ** Nd, not determined; TDC, total direct cell count (with microscope)

It is concluded that a combination of biomass parameters (ATP, TOC, CH, proteins), when conducted under defined conditions may give useful information, but that a database for comparing values in different situations must be obtained.

7.2 Inorganic compounds

Chemical analysis of inorganic elements in membrane has been standardized. For this purpose membrane pieces (10 x 10 cm) are cut from the envelopes of the elements available for autopsy. Subsequently, the pieces are treated with concentrated acid (HNO_3) and element concentrations are determined using Inductive-Coupled Plasma Mass Spectrometry (ICP-MS) (e.g. Table 7.2).

7.3 Application in membrane autopsies

7.3.1 Location 1

Only a limited number of tests were applied in the first series of autopsies on NF membranes obtained from the pilot plant installed at a full scale groundwater treatment plant (test location 1). The most rapid and quantitative test is the ATP analysis. Fig. 7.3 shows the biomass concentrations as determined with ATP analysis, conducted after autopsy on a number of membrane elements. The concentrations of inorganic compounds observed on these membranes are presented in Table 4.2.

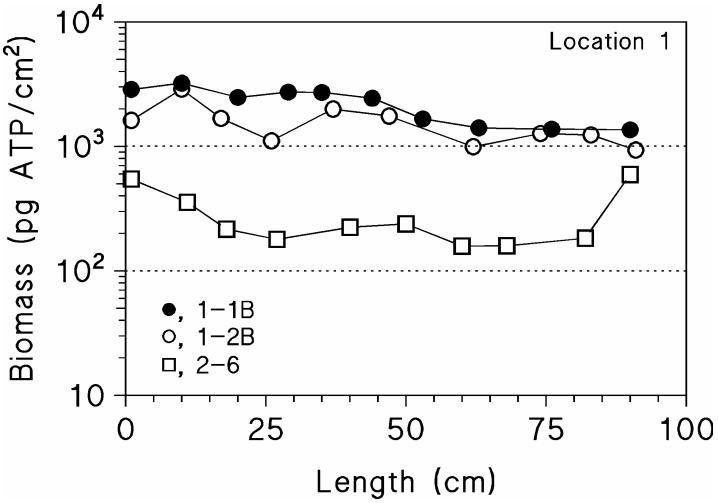

Fig. 7.3. Biomass concentrations in NF elements at location 1. Nrs 1, first element from 1st stage; nr 2 element from second stage. Run time: 146 days.

The data show that the highest biomass concentrations were observed at the front side of the first membrane element. The biomass concentrations were clearly lower in the membrane element placed at the end of the installation. Concentrations of inorganic compounds were all relatively low (Table 7.2).

Table 7.2 Concentrations (mg/m²) of inorganic elements in membrane (NF) elements from the pilot plant at location 1 after an operational period of 146 days at 75% recovery. Concentrations represent average values and standard deviations of concentrations on coupons at 20, 50 en 80 cm from the inflow side of the element.

Inorganic component	Membrane element		
	1-1b	1-2b	2-6
Ca	10.1 (2.7)	72 (104)	106 (28)
Na	18.2 (4.1)	22.6 (10.9)	25.6 (3.2)
Mn	17.3 (2.4)	15.9 (5.1)	2.8 (0.8)
Fe	7.4 (1.4)	6.1 (1.0)	2.2 (1.9)
K	6.0 (2.2)	5.0 (4.1)	7.2 (1.1)
Si	4.2 (1.0)	6.4 (6.5)	4.3 (1.9)
Sb	3.1 (0.6)	4.4 (2.7)	6.0 (3.5)
Mg	1.8 (0.1)	6.5 (5.1)	2.2 (0.3)
Al	0.4 (0.4)	1.2 (1.2)	0.6 (0.2)
Ni	0.2 (0.03)	0.15(0.03)	0.14 (0.1)
Zn	0.1 (0.0)	0.3 (0.3)	0.2 (0.06)
Cu	0.07 (0.06)	0.2 (0.2)	0.07 (0.06)
Ba	0.6 (0.2)	0.5 (0.0)	0.13 (0.06)
total	69 (7.3)	141 (109)	157 (39)

Calcium (Ca) concentrations are elevated in the final element, but these concentration do not cause problems (no pressure drop increase observed; no MTC decrease observed).

7.4 Location 2

Destructive studies of the membrane module from the test rig and membrane sheets from the MFS showed relatively high concentrations of active biomass ($1.3x10^4 \pm 0.2x10^4$ pg ATP/cm²) at the inlet side (cf. Fig. 7.4), but concentrations of inorganic compounds were low (< 100 mg/m²) (Table 7.3). The MFS showed the same level of biofouling as observed with the membrane element of the bench scale test unit.

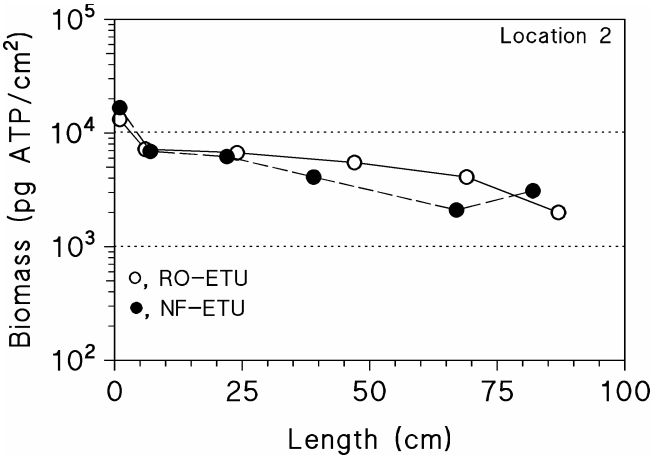

Fig. 7.4. Biomass concentrations in membrane elements at location 2. RO-ETU: RO membrane from experimental test unit; NF-ETU, NF membrane from experimental test unit; FS, full scale plant.

Table 7.3. Inorganic compounds on the membranes in the test unit at location 2

Component	*Concentration (mg/m²)*	
	RO	*NF*
Ca	11.0	15.6
Mn	14.6	16.5
Sb	4.8	5.5
Na	4.4	6.5
B	0.2	0.4
Zn	0.6	0.0
Si	1.6	3.8
K	4.6	4.0
Fe	9.5	13.7
Al	0.4	6.9
Mg	1.5	1.9
Co	0.4	0.3
Total	**53.6**	**75.1**

7.5 Location 3

7.5.1 Biomass on membranes

Destructive studies of the membrane module from the test unit revealed that relatively high concentrations of active biomass were present in the membrane elements. The highest levels were observed at the inlet side in the second test period. In the first period, biomass concentration was lower and the decline over the length of the element was limited.

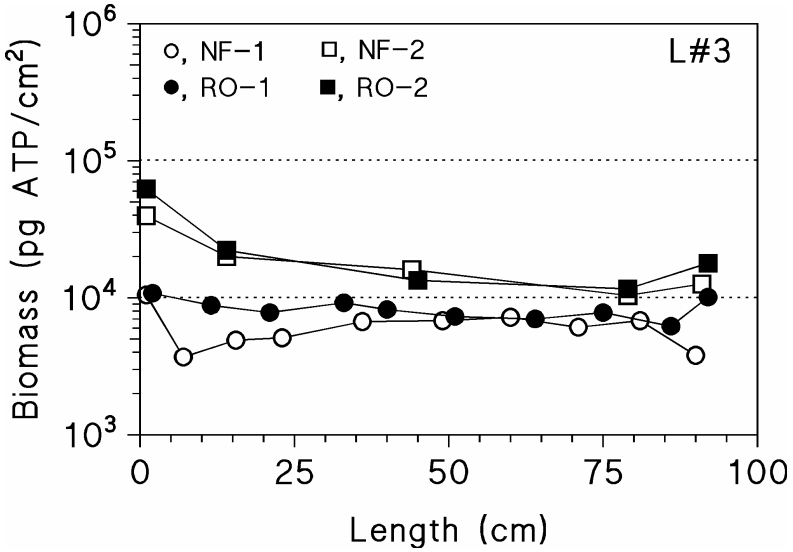

Fig. 7.5. Biomass concentrations in membrane elements at location 3. RO-1: RO membrane from experimental test unit; first experimental period; NF-1, NF membrane from experimental test unit, first experimental period; RO-2, NF-2, second experimental period.

7.5.2 Inorganic compounds

High concentrations of aluminum and manganese were observed on the membranes, In the first period, the concentrations on the NF membrane ranged from 1700 mg/m²

(inlet) to 65 mg/m² (outlet side) and on the RO membrane from 560 mg/m² (inlet) to 266 mg/m² (outlet side). In the second period, these concentrations were 494 -77 mg/m² (NF) and 1158-169 mg/m² (RO) respectively. Concentrations of iron, calcium and barium were all low (< 10 mg/m²). The high levels of Al and Mn may have contributed to the observed feed channel pressure drop.

7.6 Location 4

High biomass concentrations were observed in the membrane elements of the test unit supplied with feed water of the full-scale plant at location 4. Concentrations of inorganic element in the membrane elements were

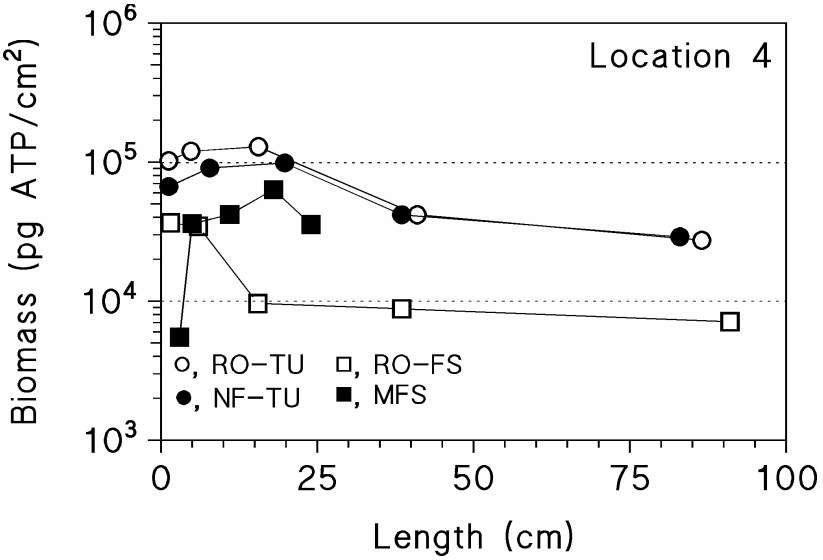

Fig. 7.6. Biomass concentrations in the membrane elements of the test unit at location 4. RO-TU: RO membrane of test unit; NF-TU, NF membrane of experimental test unit. RO-FS: membrane from full scale plant; MFS, membrane fouling simulator.

7.7 Location 5

Investigations not yet started

7.8 Discussion and conclusions

The discussion will follow when results about location 5 are available. This discussion will include the relationships between pressure drop and biomass/inorganic compounds in the membrane elements.

8 Cleaning procedures

Cleaning of membranes is conducted when a certain increase of feed channel pressure drop and/or flux decrease is observed. Efficient cleaning is needed to ensure reliable operation of the installation. Generally, cleaning is applied when a 15% increase of the normalized pressure drop is observed in the installation.

8.1 Survey of chemicals and experiences

The practical experiences in the Netherlands with cleaning have been described in a report (BTO 2005.028). The survey included a total of 15 NF and RO installations owned and operated by the water supply companies in the Netherlands. Cleaning frequencies depend on the type of feed water, but detailed information about the effects of cleaning is very limited. Also a report including a survey of chemicals and a review of the scientific literature on cleaning procedures has been completed (BTO 2005.060). However, water composition, operational conditions, cleaning procedures are poorly described in the scientific and technical literature. Mixtures of chemicals (complexing agents, detergents, and caustic) generally are most effective for biofouling reduction, but data to quantify these findings were scarce. It is concluded that a protocol is needed for testing and evaluating the effects of cleaning procedures in practice. An AwwaRF report on investigations conducted in the USA on the effects of cleaning agents has been received and discussed in the BTO-PG Biofouling.

8.2 Development of laboratory test procedure

Work has been conducted aiming at improving the methods for quantitative biomass analysis (see Stage 2). Also tests with membrane pieces in a batch test have been conducted. The results showed that biomass removal with the selected chemicals was very limited under the test conditions (batch with shaking). In this project stage a go-no go moment had been planned and the BTO-PG Biofouling had decided to continue the work on the further development of a test procedure. Experiments are in progress aiming at developing a protocol for the assessment of hydraulic conditions on biofilms. For this purpose biofilms developed in several materials, including plasticized PVC and polyethylene are used. When a reliable approach is available, effects of selected chemicals will be tested under laboratory conditions. The approach has been presented at the AWWA Membrane Technology Conference at Tampa (March 2007) and is included in this Progress Report (Appendix III).

Further experiment are in progress aiming at defining hydraulic conditions which can be used in a test procedure for assessing the effect of chemicals on the removal of attached biomass.

9 Evaluation of costs and effects

9.1 Evaluation of costs and effects

This (limited) activity will be conducted in the final phase (reporting) of the project.

10 Program preparation and communication

10.1 Joint project

10.1.1 Communication and workshop preparation

The workshop was conducted as agreed.

10.1.2 Workshop

Results of the workshop have been incorporated in the adapted project description. Agreement has been signed.

10.1.3 PAC Meeting/periodic report

This is the Fifth Periodic Progress Report.

10.1.4 Workshop 2007

Abstracts for presentations at the AWWA Membrane Technology Conference have been submitted. A meeting with PAC members during or directly after the conference was possible. It is proposed to organize a separate workshop early 2008.

10.1.5 Final report

The draft will become available in 2007. It is proposed to discuss this draft early 2008, in combination with a workshop and subsequently, make the final report.

10.2 Further developments

In the second half of 2005, Kiwa Water Research has contributed to a research proposal aiming at obtaining additional budget for research on membrane filtration in the Sixth Framework Programme of the European Community. This activity, which was initiated by research institutes in Europe, has a focus on desalination using membranes and includes investigations on biofouling control. This proposal has been accepted and the project will start officially in October 2006 Hence, additional funds will become available at the end of 2006. The consequences of this development will be discussed in the next BTO Projectgroup on Biofouling in December 2006.

An other development concerns preliminary investigations conducted at Kiwa Water Research on the use of air for biofouling control. These investigations were conducted in another project with limited budget and discussions with water supply companies are conducted to obtain additional funds for continuation. The results of this study have been published (BTO 2006.037) and .

11 Evaluation

In general, the project follows the intended schedule, Also few issues appear to be more complex and time consuming than anticipated (literature review, cleaning methods). The oxygen consumption method is not effective and a membrane fouling simulator has been developed. The investigations at full scale plants are conducted with a membrane test installation and with the membrane fouling simulator (MFS). These investigations are all laborious, partly due to changing conditions at these locations and many operation problems must be solved when conducting experimental work in practical situations. Collecting information about cleaning methods in practice did not yield detailed information. The work on developing a test method for evaluating cleaning procedures/chemicals has been continued.
The initial planning of completing the report in September 2007 is not realistic, because experimental work will continue in the summer period. It is proposed to prepare a draft report per 31 December 2007. This report can be discussed at a workshop to be organized in early 2008.

12 Reports and references

BTO 2005.028. NF- en RO-installations managed by water supply companies in The Netherlands (79 pp. *in Dutch*). Emile Cornelissen.

BTO 2005.060. Membrane cleaning in NF/RO-installations. A literature review (57 pp., *in Dutch*). Emile Cornelissen.

BTO 2006. 004. Achieving Q21 quality of drinking water prepared from anaerobic groundwater. Pilot plant investigations with ultrafiltration and nanofiltration at treatment plant Spannenburg (105 pp., *in Dutch*). Erwin Beerendonk et al.

BTO 2006.017. Oxygen consumpotion as a measure for biofouling of spiral wound membranes (62 pp., *in Dutch*). Joost Kappelhof.

BTO 2006. 0.30. The biological stability of the feed water of the RO installations at Baanhoek in relation to biofouling (40 pp. *in Dutch*). W.A.M. Hijnen et al.

Vrouwenvelder, J.S., J.A.M. van Paassen, L.P. Wessels, A.F. van Dam and S.M. Bakker (2006). The membrane Fouling Simulator: a practical tool for fouling prediction and control. J. Mem. Sci. 281, 316-324.

BTO 2007.007(s). (Draft). Relationship between feed water quality and membrane fouing at the RO plant of Water Supply Company in Veendam (33 pp. *in Dutch*). W.A. Hijnen et al.

I Project description

Project name: Elucidation and control of biofouling processes in high-pressure spiral-wound membranes used in water treatment

Background
The steadily increasing variety of organic contaminants observed in surface water and in ground water in industrialized and densely populated countries is a continuing concern for the water supply companies. Water scarcity in some areas amplifies these quality problems. Consumers expect the water supply companies to deliver safe drinking water meeting all quality standards related to health and also aesthetic aspects such as color. turbidity and taste and odor. The water supply companies in the Netherlands have initiated a comprehensive research program aiming at assuring the production and distribution of drinking water with a high quality (Q21). The application of low- pressure membrane filtration (microfiltration. MF; ultrafiltration. UF). and/or high-pressure membrane filtration (nanofiltration. NF; reverse osmosis RO) in water treatment. in combination with other treatment processes (e.g. UV and advanced oxidation). offers possibilities to meet with this quality goal. Also in the USA membrane filtration is considered a promising technique in water treatment.

The application of high-pressure membrane filtration in water treatment is hampered by membrane fouling. A specific type of fouling is caused by the accumulation of biomass in the membrane elements. resulting in a pressure drop and/or a reduced flux (MTC) value. Elucidation of factors contributing to biofouling and assessment of effects of cleaning techniques and strategies will enable to define conditions required for optimal use of membranes processes in water treatment.

Water treatment practices in the USA and in the Netherlands show some distinctive differences. such as the use of multiple barriers (storage reservoirs. soil passage) in surface water treatment with restricted application of chemical disinfection in the Netherlands and the use of conventional treatment (disinfection. coagulation/sedimentation/filtration) in the USA. These differences in approach affect the fouling problems arising from the application of high-pressure membrane filtration in water treatment.

This project proposal defines the objectives and deliverables of a Kiwa-AwwaRF partnership project on controlling biofouling in high-pressure membrane processes.

Objectives
The main objective of this research project is to identify effective biofouling control strategies for high pressure membrane systems based on defining conditions for feed water quality (i.e. pretreatment) in combination with cleaning strategies which enable optimal control (prevention/cure). For achievement of this main project objective the following research objectives have been identified:

- Collection and critical evaluation of information about biofouling in the scientific literature;
- Optimization of methods for the assessment of the biofouling potential of water;

- Optimization of methods for the quantification and characterization of biomass accumulating in the membrane elements
- Assessment of the relationship between selected water quality parameters (biofouling potential) and the rate and extent of biofouling in spiral-wound membranes;
- Elucidation of pretreatment effects on (water quality parameters affecting) biofouling;
- Development of tools for real-time monitoring (and early warning) of biofouling;
- Evaluation of cleaning techniques and protocols for the removal of biomass from spiral-wound membranes;
- Defining pretreatment in combination with cleaning strategies for a cost-effective control of biofouling in spiral-wound membranes in water treatment.

Investigations to achieve these research objectives will be completed by 31 September 2007. The project includes experiments at the laboratory facilities of Kiwa Water Research and investigations in pilot plants at selected locations (water treatment plants). Involved researchers include specialists in the fields of microbiology. water treatment and chemistry. The Biofouling project is closely linked to the Q21 water quality project in the Joint Research Program (BTO) of the Water Supply Companies in The Netherlands. This Q21 project (with a total budget of about 4 Mauro) also includes desk studies on Water Quality Goals. Integral Treatment Concepts and experimental studies with pilot plants on effects of membrane types and process conditions on water quality and a study on the interactions between high quality water and surfaces in distribution systems. Costs for pilot plants (construction and operation) are shared and decisions about the selection of the locations for pilot plant research are based on considerations valid for the entire Q21 project.

The outcome of several stages of the investigation is difficult to predict. The ensure optimal spending of the available budget. results will be discussed with the representatives of the water supply companies participating in the project group (listed in attachment) and decisions regarding adapting the program. including go-no-go for certain aspects when necessary. will be taken. For example. a reduction of program for testing the cleaning effects of chemicals would enable intensifying the investigations on growth potential assessment or pretreatment effects. These decision moments are mentioned in the program and indicated in the time schedule.

Project description

Stage 1: Review of literature
Scientific literature about biofouling of high-pressure membrane systems will be evaluated to give the state of the art for biofouling processes and control. Relevant literature about biofilm formation processes and measures for biofilm removal not directly related with membrane fouling will also be included in this review.
Deliverable: report.

Stage 2: Selection and optimization of methods for quantification and characterization of biomass accumulated in membrane elements
Analysis of accumulated biomass includes assessment of the concentration of active microorganisms with ATP analysis. heterotrophic plate counts. microscopic analysis (total cell numbers. TDC). total organic carbon. and inorganic compounds (e.g. Fe. Mn. Ca). Molecular techniques will be applied to identify the predominant

microorganisms. In addition to these tests. chemical analysis will be conducted on the accumulated biomass to determine the presence of carbohydrates and proteins. These analyses enable a differentiation between accumulated active biomass. dead cells and inorganic compounds.
Deliverable: description and evaluation of biomass composition in membrane systems.

Stage 3. Optimization of methods for determining the biofouling potential of feed water.
A series of analytical tools. some of which have been developed at Kiwa Water Research. will be applied to assess the biofouling potential (biomass growth potential) of water. These tools include: AOC. Biomass Production Potential (BPP). biofilm formation rate (BFR) as determined with the biofilm monitor. total direct cell count (TDC). adenosinetriphosphate (ATP) and membrane fouling index (MFI) in addition to traditional water quality parameters (DOC. pH. Fe. Ca. turbidity). These parameters will be related to the accumulation of biomass on membranes as determined after autopsy and the increase of the feed channel pressure drop in pilot plant systems with NF (or RO) membranes.
Deliverable: data about biofouling potential of feed water at selected locations

Stage 4: Development of tools for direct monitoring of biofouling of the membrane system.
Real-time methods for the detection of membrane biofouling enable the application of corrective measures at an early stage of biofilm development when biofilms are most susceptible for chemicals. Oxygen consumption in a membrane element is related to biofouling. Accurate assessment of the rate of oxygen consumption at low biomass concentrations may enable early warning for biofouling. but requires specific adaptations of the membrane elements for oxygen monitoring. The investigations aim at developing a protocol enabling early and sensitive in situ detection of biofouling in spiral wound membrane elements.
Pressure drop monitoring offers another possibility for early detection of biofouling. For this purpose. sensitive devices for the detection of pressure changes will be installed on the membrane systems at selected locations. In addition a flat sheet model will be developed and tested for its potential to serve as an early warning monitor. Decisions about continuation with these monitoring systems will be taken based on results obtained by application at location 1 (see Table 2. Time schedule).

Deliverable: Evaluation of methods aiming at early detection of biofouling

Stage 5: Effect of pretreatment on the rate and extent of biofouling in spiral-wound membranes.
Membrane test systems including UF and NF membranes will be installed at least 4 water treatment plants to collect information about the effects of membrane filtration of a variety of water types for a period of at least 6 months. The selection of the 4 locations depends on specific aspects of raw water quality and treatment including the concentrations of organic contaminants and NOM. Pretreatment will include conventional processes (aeration. coagulation/sedimentation. filtration. and also membrane filtration (UF). The feed water will not contain a disinfectant. The membrane test system will be installed in or at the end of the existing treatment. Construction and operational costs of the pilot plants are shared with other parts of the Q21 project. Accumulation and composition of biomass in the membrane elements will be assessed after defined test periods using selected and optimized procedures (stage 2). Feed water quality will be analyzed with the selected and

optimized procedures (stage 3). Real-time monitoring of biofouling will be conducted with oxygen consumption and sensitive pressure drop analyses.
The observations at location 1 will be evaluated and used to define details of the approach for the second location. which in turn will affect the test program for the subsequent stage.
Deliverable: The obtained data will be used to derive relationships between water quality parameters and the rate and extent of biofouling and to evaluate the effects of water treatment processes on these parameters and biofouling.

Stage 6: Evaluation of cleaning techniques for the removal of biomass from spiral- wound membrane elements
Cleaning of membrane at a certain frequency may be inevitable. A survey of available chemicals and cleaning experiences in the Netherlands (and in the scientific literature) will be conducted. Subsequently. a laboratory test enabling quantification of the effects of cleaning chemicals on attached biomass will be optimized. A selection of available chemicals. including enzymes. will be tested with this system. Subsequently. a number of selected chemicals will be tested in pilot plant situations. Information about the (side)effects of cleaning methods (environmental aspects; membrane damaging properties) will be collected and evaluated.

The results of the laboratory test procedure will be used to decide about adaptation/continuation of the investigations on cleaning (more extended testing of chemicals in the laboratory and/or application on membranes of the pilot plant.
Deliverables: an evaluation of the effects of selected cleaning agents on biofouling

Stage 7: Cost-effective application of spiral wound membranes in water treatment
Based on the information obtained from the pilot plant studies and the relationship between water quality parameters and biofouling rate. pretreatment will be defined aiming at a certain cleaning frequency. The most desirable (cost-effective) combination of treatment and cleaning frequency may differ between different water types.
Deliverable: evaluation of cost-effective control of biofouling based on costs analysis in The Netherlands

Stage 8. Program preparation and communication
- The research conducted in the Netherlands will be discussed in the BTO Working Group (WG) Biofouling. This working group reports to the Program Advisory Committee (PBC) on Membrane Technology;
- To prepare a joint research project on biofouling. an AwwaRF-Kiwa workshop has been organized on October 11 2004 This workshop was attended by the WG members and representatives of AwwaRF (Kenan Ozekin. Chris Gabelich. Peter Huck);
- Project progress will be reported periodically (each 6 months) to the AwwaRF PAC;
- A second project workshop will be organized in 2007;
- The final project report will be available at the end of the project (31 September 2007).

Budgets

Table 1 Budgets in US dollars

	AwwaRF	BTO	Total
Project stage/activity	k$	k$	k$
Stage 1: Review of literature	32.1	6.4	38.5
Stage 2: Biomass analysis	25.6	6.4	32.1
- selection and implementation of methods			
- application of methods in autopsies (in stage 5)			
Stage 3: Growth potential feed waters		25.6	25.6
- optimization of methods			
- application of methods (in stage 5)			
Stage 4: On site (early warning) monitoring (O2. dP)	$19.2	205.1	224.4
- optimization oxygen monitoring/test protocol			
- application/testing (in stage 5)			
- optimization of dP method/protocol. including the use of a flatsheet			
- application of dP method (in stage 5)			
Stage 5 Pretreatment impacts/effects of water composition	$38.5	269.2	307.7
- location 1 (Spannenburg; treated anaerobic ground water)			
- location 2; to be selected			
- location 3; to be selected			
- location 4; to be selected			
Stage 6: Cleaning procedures	25.6	205.1	230.8
- survey of chemicals and experiences in the Netherlands/literature			
- survey of experiences in USA; pm			
- development of laboratory test procedure			
- testing of selected chemicals in laboratory			
- testing of selected chemicals in field (stage 5)			
Stage 7: Evaluation of costs and effects		51.3	51.3
Stage 8: Program preparation and communication			
- Workshop/adapted proposal for partnership project	32.1		32.1
- PAC Meetings/periodic reports	25.6		25.6
- Workshop 2007	19.2		19.2
- Final report	32.1		32.1
Total budget (excluding pilot plants and in kinds)	250.0	769.3	1019.3
- costs of pilot plant (PP) construction		192.3	
- further costs covered by the water supply companies (operation of PP)		128.2	
Total	250.0	1089.8	1339.8

Table 2 Time schedule

Partnership Project Biofouling															
	2004				2005				2006				2007		
Project stage/activity	*1*	*2*	*3*	*4*	*1*	*2*	*3*	*4*	*1*	*2*	*3*	*4*	*1*	*2*	*3*
Stage 1: Review of literature															
Stage 2: Biomass analysis															
- selection and implementation of methods															
- application of methods in autopsies (in stage 5)															
Stage 3: Growth potential of feed waters															
- optimisation of methods															
- application of methods (in stage 5)															
Stage 4: On site (early warning) monitoring (O2, dP)															
- optimisation oxygen monitoring/test protocol						gng									
- application/testing (in stage 5)															
- optimisation of dP method/protocol															
- application of dP method (in stage 5)						gng									
Stage 5 Pretreatment impacts/effects of water composition															
- location 1 (Spannenburg; treated anaerobic ground water)															
- location 2; to be selected															
- location 3; to be selected															
- location 4; to be selected															
Stage 6: Cleaning procedures															
- survey of chemicals and experiences in the Netherlands/literature															
- survey of experiences in USA; pm															
- development of laboratory test procedure						gng									
- testing of selected chemicals in laboratory															
- testing of selected chemicals in membrane elements (stage 5)															
Stage 7: Evaluation of costs and effects															
Stage 8: Program preparation and communication															
- communication and workshop preparation															
- Workshop/adapted proposal for partnership project															
- PAC Meetings/periodic reports															
- Workshop 2007															
- Final report															
gng, go-no-go; decision about adaptation/continuation of activity															

;

II Paper Tampa 2007: Elucidation of membrane biofouling processes using bioassays for assessing the microbial growth potential of feed water

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Sjack van Agtmaal, Water Supply Company Evides
Koos Baas, Aquacare Europe BV
Gilbert Galjaard, NV PWN Water Supply Company North Holland

Introduction

Membrane fouling causing increased feed channel pressure loss and flux reduction seriously hampers the application of spiral-wound RO and NF membranes for the production of water intended for human consumption or industrial purposes. In many cases accumulation of microbial biomass in the membrane elements (biofouling) is the main fouling process. The rate and extent of biofouling depend on the rate of multiplication of bacteria in the membrane elements, which in turn depends on the concentration of organic and inorganic nutrients in the feed water. The concentration and nature of growth-promoting (biodegradable) compounds is defined by (i) the nature of the raw water, (ii) the effects of treatment processes applied prior to membrane filtration (pretreatment) and (iii) the effects of chemicals added to the feed water. In many cases surface water serves as raw water, but also seawater and groundwater are used. Surface water contains biodegradable compounds originating from contamination with (treated) waste water. Furthermore, growth of algae or cyanobacteria leads to the production of easily biodegradable compounds in surface water and in seawater. Treatment may lead to a reduction of the concentration of biodegradable compounds by physicochemical processes, e.g. coagulation/sedimentation (CS) or ultrafiltration (UF) for the removal of large molecular-weight compounds and particles, including micro organisms and by biological processes, e.g. sand filtration or granular activated carbon filtration. Application of oxidative processes, e.g. ozonation, leads to the formation of easily biodegradable low molecular-weight compounds from refractory humic and fulvic acids. Furthermore, addition of chemicals for scaling prevention, including inorganic acids and organic antiscalants (AS) may increase the concentration of biodegradable compounds (Hiemstra et al. 1997; Van der Hoek et al. 2000). Consequently, different raw water types and different water treatment schemes, including additives, lead to a large range of feed water qualities with different growth-promoting properties, i.e. biofouling characteristics. Elucidation of the effects of water composition, water treatment and addition of chemicals is required to enable decisions regarding the prevention of biofouling. For this purpose, bioassays for characterization and quantification of the growth promoting properties of water in various stages can be used. A study on the growth-promoting properties of a number of AS types demonstrated that these chemicals differed strongly in the potential to produce biomass in batch tests or biofilms in a dynamic test (Vrouwenvelder et al. 2000). This report shows that AS dosage may also increase the concentration of available phosphorus (P).

Bioassays

A variety of techniques, initially developed for determining the biological stability of treated water, is available for determining the microbial growth potential (MGP) of the feed water. These techniques include:

(i) the assessment of the concentration of easily assimilable organic carbon (AOC), based on determining the growth of two pure cultures of bacteria in samples of pasteurised water (Van der Kooij, 1992);

(ii) the biomass production potential (BBP) test, based on measuring the maximum growth yield of the indigenous microbial population in water samples. This method, which has been introduced as alternative AOC method (Stanfield and Jago, 1985) was adapted by using glass containers identical to those used in the AOC test. The BBP test can also be used for determining the limitation of microbial growth by phosphorous (P). For this purpose, the effect of acetate addition on the maximum level of growth is measured;

(iii) the biofilm monitor enabling the determination of the biofilm formation rate (BFR).

The applied bioassays are listed in Table 1. Analysis of the concentration of adenosinetriphosphate (ATP) is used for measuring the concentration of biomass in the BPP test and in the biofilm monitor. This method is also applied to quantify the concentration of biomass in water in various stages of water treatment and in the membrane elements after autopsy. The use of this parameter provides a framework of data enabling a systematic assessment of the biological processes in water treatment and distribution, i.e. production of suspended and attached biomass (Van der Kooij et al. 2003).

Table 1. Selected bioassays

Test	Mode	Organisms	Biomass parameter	Reference
Easily assimilable organic carbon (AOC)	Batch	Two pure bacterial cultures	Plate count	Van der Kooij, 1992
Biomass Production Potential (BPP)*	Batch	Indigenous population	Adenosine triphosphate (ATP)	Stanfield and Jago (1987)
Biofilm formation rate (BFR)	Dynamic	Indigenous population	ATP	Van der Kooij et al. 1992

* originally presented as AOC method.

Locations

Investigations were conducted at two full scale plants, viz. the UF-RO water treatment facility Heemskerk of NV PWN Water Supply Company North Holland (location A) and the water treatment facility at Baanhoek (location B) of Water Supply Company Evides. At location A lake water is pretreated with CS, granular activated carbon (GAC) filtration, followed by UF. At location B, river water stored in open storage reservoirs is treated with microstraining, in line coagulation and UF. At both locations, acid and AS are added to the UF filtrate prior to RO treatment for conditioning of the RO process. The RO installation at location A is operated without biofouling problems, but the installation at location B frequent cleaning is applied.

Results

The AOC concentration of the feed water of the RO plant at location A was determined, as well as the BPP value (Table 1). The values are very low indicating a high degree of biological stability, i.e. a low biofouling potential. Addition of acetate (1 ppm C) to the water prior to AS dosage only caused a very small limited increase of the ATP concentration, indicating that growth was limited. Most likely, phosphorus (P) limitation occurred, because C (added) and N (nitrate) were both presence in excess. Addition of AS to the water samples, collected after acid dosage, at concentrations of 5 and 50 ppm in the presence of additional P and N (nitrate) did not increase the biomass production (Table 1). However, acetate dosage to feed water sampled after AS dosage gave increased growth, confirming that C was growth limiting in the presence of AS, and that AS addition had lifted the P limitation. Nevertheless, at location A the AOC concentration and the BPP value remained low after AS dosage, confirming that the applied AS did not contain increase the growth potential. Measurements with the biofilm monitor revealed that the BFR values of the feed water containing acid and AS were very low (< 2 pg ATP/cm².d). This observation confirmed that AS dosage did not affect the growth potential of the water at this location.

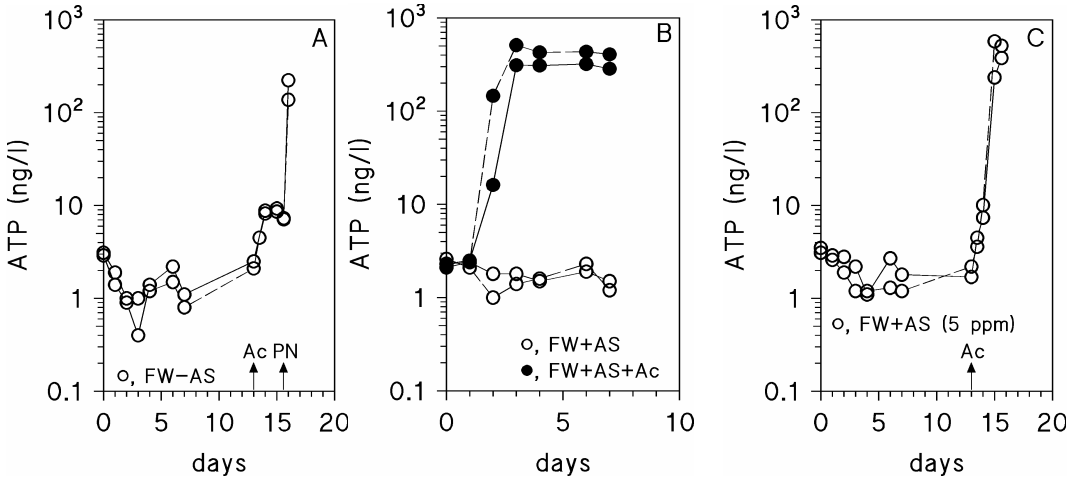

Fig. 1. A, Production of biomass (ATP) in batch tests with water sampled after ultrafiltration and acid dosage, supplemented with acetate (1 mg/l C) on day 13 and P+N on day 15; B, feed water sampled after AS dosage (0.9 mg/l), and supplemented with acetate (1 mg C/l) on day 0; C, Feed water after dosage of acid, supplemented with AS (5 mg/l) and P+N on day 0 and with acetate (1 mg C/l) on day 13.

Table 1. AOC and BPP values of feed water without and with dosages of antiscalant and acetate

Water type	Additions in test	AOC (µg C/l)	BPP (ng ATP/l)
Feed water*	None	5.6 ± 0.3	2.3 ± 0.3
Feed water*	acetate (1 mg /l C) on day 13	Not tested	9.0 ± 0.5
Feed water*	+ N+P on day 15	Not tested	> 180
Feed water	None	4.1 ± 0.0	2.1 ± 0.2
Feed water	acetate (1 mg/l C) at day 0	NT	416 ± 135
Feed water*	5 mg AS + N+P at day 0	7.0 ± 2.7	2.4 ± 0.3
Feed water*	50 ppm AS + N+P at day 0	9.8 ± 1.1	2.6 ± 0.8

* water sampled after acid dosage at plant A

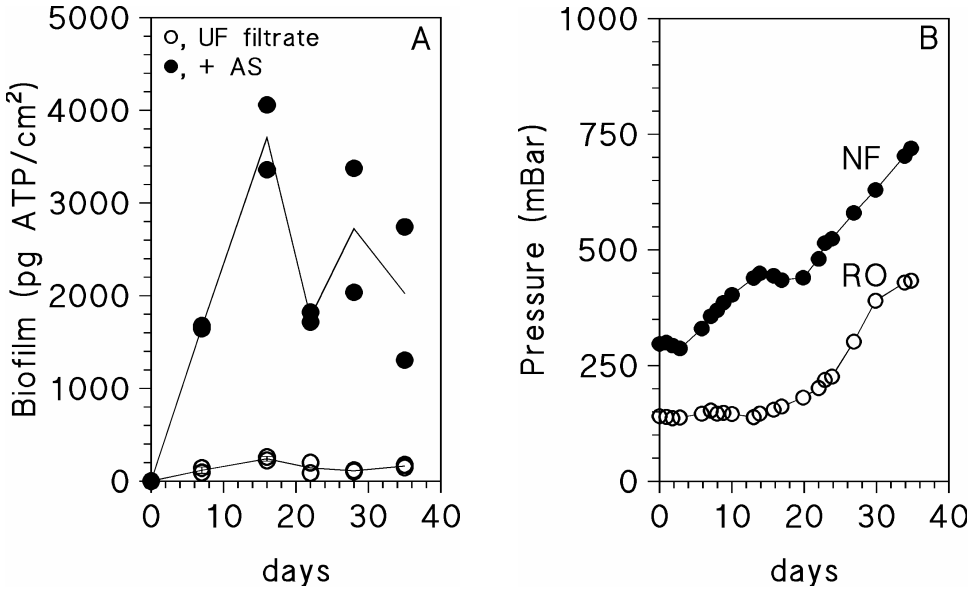

Fig. 2. A Biofilm formation in the biofilm monitor at location B supplied with water from open storage reservoirs, treated by coagulation/sedimentation and ultrafiltration. B. Feed channel pressure drop in bench scale membrane elements (RO and NF, 4") supplied with UF filtrate after AS dosage.

At location B the AOC concentration of the feed water (UF product) ranged from 8 - 25 µg C/l before AS dosage and from 21 to 34 µg C/l after AS dosage. BPP values ranged from 10 to 35 ng ATP/l and from 21 to 49 ng ATP/l, respectively. These observations show that AS dosage slightly increased the growth potential of the feed water, but do not give information about the growth kinetics. Addition of acetate to the feed water gave a higher yield in the BPP test, indicating the P was not growth limiting at the sampling dates. The application of the biofilm monitor at location B on the UF product prior to and after AS dosage revealed that AS dosage strongly increased the BFR value (Fig. 2A). Within a few weeks a biofilm concentration of more than 3000 pg ATP/cm² was attained and a BFR value of about 230 pg ATP/(cm².d) was calculated for the water after AS dosage. Prior to AS dosage, the BFR values was 15 pg ATP/(cm².d). Given the presence of sufficient N (nitrate), the effect of AS dosage may have been caused by the small increase of the growth potential, but an increase of the concentration of bioavailable P cannot be excluded. Observations in an experimental bench scale membrane system, with one NF and one RO membrane element (4") revealed a strong pressure drop increase within a few weeks (Fig. 2B). Membrane autopsies demonstrated that high concentrations of active biomass (16 ng ATP/cm²) were present at the feed side of both membrane elements. Concentrations of inorganic elements (Ca, Fe, Mn) were all low (<20 ppm/m²), confirming that accumulation of biomass had caused the pressure drop increase.

Discussion

The presented results show that AS dosage can promote the biofouling potential of water, confirming earlier observations (Van der Hoek et al. 2000; Vrouwenvelder et al. 2000). However, in these earlier studies, the effect on biofouling was attributed to the presence of biodegradable compounds in the AS. Tests with a variety of AS types demonstrated that several of these chemicals increased the AOC concentration and

also the BFR value. Lifting P-limitation however is another potential effect of AS dosage, which may occur in situations where the concentration of bioavailable P is limiting the utilization of the concentration of biodegradable compounds. At location A, the concentration of biodegradable compounds is very low, as may be derived from the low BPP value (< 5 ng ATP/l) in water supplemented with P and N. In this situation, addition of P does have an impact, as is demonstrated by the low BFR value (< 2 pg ATP/(cm^2.d) and by the low rate of biofouling in the plant, which operated without an increase of the feed channel pressure drop for several years (Kamp et al. 2000). Obviously, the application of CS followed by GAC filtration and UF effectively reduces the concentration of growth-promoting compounds. However, in a situation where in line coagulation is applied onto river water after storage in open reservoirs (location B), removal of biodegradable compounds is less efficient, but the concentration of P may be reduced by growth of algae and the pretreatment. The strong impact of AS dosage on the BFR value may have been caused by an increase of the AOC concentration, but also an increase of the concentration of bioavailable P may have occurred. The observed BFR value of about 230 pg ATP/(cm^2.d) is in agreement with the rapid rate of biofouling, causing 100% increase of the feed channel pressure drop within 30 days (Fig. 2B). Rapid biofouling at a high BFR rate has also been reported in a groundwater treatment, where AOC was present in the dosed acid (Hiemstra et al. 1997). A very low rate of biofouling was also observed in RO treatment of surface water pretreated by CS, rapid sand filtration, and slow sand filtration (Van der Hoek et al. 2000). Also here AS was added but the BFR values remained very low (<1 pg ATP/(cm^2.d) due to a far-reaching reduction of the AOC value (< 6 µg C/l) in this water type. In this situation, no cleaning was required in the test period of 11 months. These observations are in agreement with those at location A.

In conclusion, low AOC concentrations, and low BFR values are essential for biofouling prevention. Achieving these low values in surface water treatment requires the application of biological processes and the use of AS with a very low growth potential. The role of AS in lifting the P limitation needs further investigation.

Acknowledgement
Part of this study was conducted in the frame work of the Joint Research Programme (BTO) of the water supply companies in the Netherlands, with financial support from AwwaRF. NV PWN Water Supply Company North Holland, Aquacare BV and Water Supply Company Evides supported studies at locations A and B.

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III Paper Tampa 2007: Assessment of the efficiency of air-water flushing for the removal of biomass from surfaces in a laboratory test

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Introduction

The application of membrane filtration in the production of drinking and process water is steadily increasing. The use of spiral wound membranes for nanofiltration (NF) and reverse osmosis (RO) is often hampered by biofouling which leads to operational problems such as an increase in normalized pressure drop (NPD) and a decrease in production rate (Ridgway and Safarik, 1991). Biofouling can be limited by pretreatment of the feed water of the membrane installation, but this approach increases the total investment cost of the water treatment process. Another option is to use periodical cleaning in place (CIP) for biofouling control, in which the negative effects of biofouling are (temporarily) reversed.

For a cost-effective application of membrane filtration in practice, extensive knowledge is required of the influence of cleaning methods on biomass removal. Partly due to the complexity of biofouling the determination of the optimal CIP strategy is based on 'trial and error'. Furthermore, data from scientific literature in many cases gives incomplete information about of the interactions between the feed water quality, the type of membrane, the resulting type of membrane fouling, the cleaning method and the effect of membrane cleaning on the membrane process. An important step in elucidating the effect of membrane cleaning processes is to develop a protocol for a systematic analysis. Two approaches can be followed for evaluating the effects of a cleaning procedure: (i), the use of operational parameters (Graham et al, 1989) and (ii), the application of a test procedure under standardized conditions in the laboratory or in a pilot set up (Whittaker et al, 1981).

Indications of effective cleaning procedures for biofouling control were obtained from a systematic approach to evaluate CIP procedures from both literature and full-scale membrane plant experience. In some cases, biofouling was effectively controlled with mixtures of complexing agents, surface active components and denaturating agents. Apart from this, the effect of a hydraulic action, e.g. by using air-water flushing, proved to be very promising in biofouling control (Cornelissen et al, 2007). The biomass removal efficacy of the air-water flushing strategy was verified with a newly developed laboratory test procedure and described in this paper.

Test procedure under standardized conditions

A test procedure was developed on laboratory scale to investigate the effects of air-water flushing. For this purpose, experiments were conducted using pieces of plasticized polyvinyl chloride (PVC-P) tubing (Emergo) with a diameter of 1.2 cm and a length of 1.5 to 6 cm, on which a biofilm had been developed by exposure to a continuous flow of tapwater for three (and a half) weeks in a darkened cooled room at 16°C. After air-water flushing experiments were conducted on these PVC-P rings,

the biomass was collected by swabbing and the biomass concentration was determined by adenosinetriphosphate (ATP) measurement (Van Der Kooij et al., 2003). For each flushing condition four rings of 1.5 cm were used in order to investigate the reproducibility of the experiment. Air-water flushing experiments were carried out to determine the effects of hydraulic conditions, e.g. air flow rate, flow rate of water and air water ratio on biomass removal. The results of the air-water flushing experiments were compared to the PVC-P rings which has not been flushed.

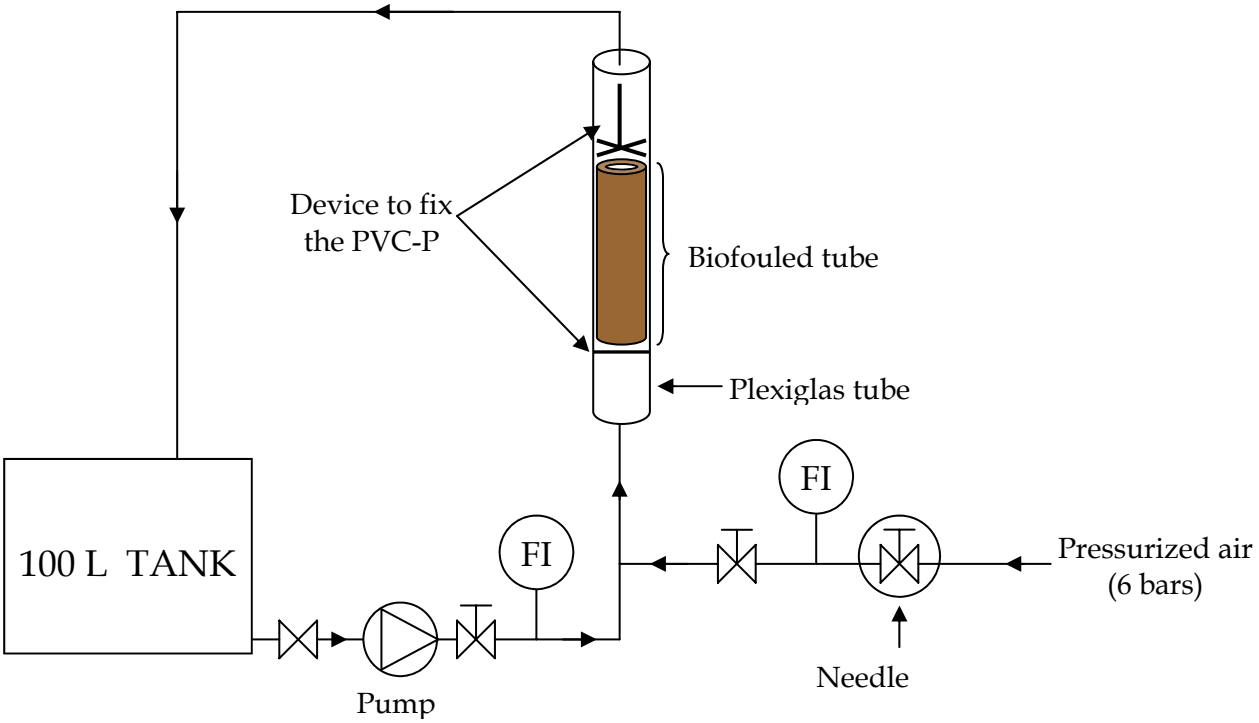

Figure 1: set-up used for assessment of the efficiency of flushing procedures using air/water.

Figure 1 show a schematic of the set-up for the assessment of flushing procedures using air-water flushing. Tap water (locally available without disinfectant residual) was used and mixed with pressurized air to introduce mechanical forces onto the biofouled PVC-P rings. A range of air and water flows can be introduced to the system, corresponding to a velocity range of respectively 0-7.4 m/s and 0.6-3.7 m/s. Also different air and water flow rates were investigated at a constant air water ratio of 2:1.

Results

Biomass removal from PVC-P rings was determined using air-water flushing at a constant air water ratio of 2:1 (figure 2). The blank value of 210,000 pg ATP/cm^2 indicated a strong biomass formation onto PVC-P rings after three weeks (21 days) of exposure to flowing tapwater. When using air-water flushing at a constant air-water ratio of 2:1, an average removal of biomass from the PVC-P rings was observed of more than 50% depending on the air-water flushing period. On the basis of this experiment a standard flushing time was selected of 10 minutes for further experiments.

The effect of increased flow rates on biomass removal from PVC-P rings using a constant air water ratio of 2:1 is given in figure 3. A higher blank value of 560,000 pg ATP/cm^2 was obtained which was related to a biomass formation period of three

and a half weeks (26 days). Biomass removal of approximately 30% was obtained when a constant air water ratio was used of 2:1, independent of the flow rates. An exception was found at 2.5 m/s water flow and 4.9 m/s air flow, at which higher biomass levels were found of 770,000 pg ATP/cm². An explanation could be the variation of biomass of the original PVC-P rings before air-water flushing experiments.

Increasing the water flow while keeping the air flow constant at 2.5 m/s yielded a significant increase in biomass removal from the PVC-P rings measured by ATP measurement (in these experiments the air-water ratio was not constant). A 40% biomass removal was achieved by increasing the water flow to 3.7 m/s, resulting into a residual biomass level of 340,000 pg ATP/cm², compared to a blank value of 560,000 pg ATP/cm².

Increasing the air flow while keeping the water flow constant at 1.75 m/s also yielded a significant increase in biomass removal of PVC-P rings. A 50% biomass removal was achieved by increasing the air flow to 3.6 m/s. In this situation the remaining biomass levels were 340,000 pg ATP/cm², compared to a blank value of 560,000 pg ATP/cm².

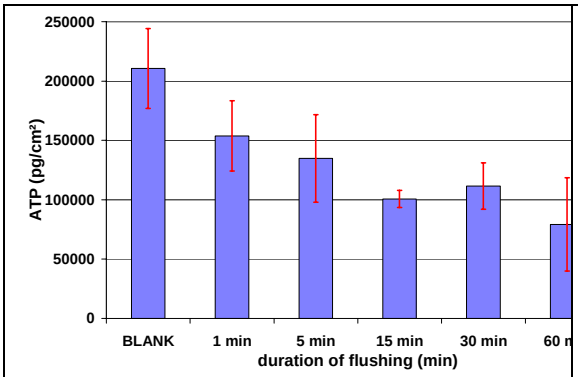

Figure 2: Biomass Biomass removal from PVC-P rings measured with ATP using different periods of air-water flushing at a constant air water ratio of 2:1 (n=4).

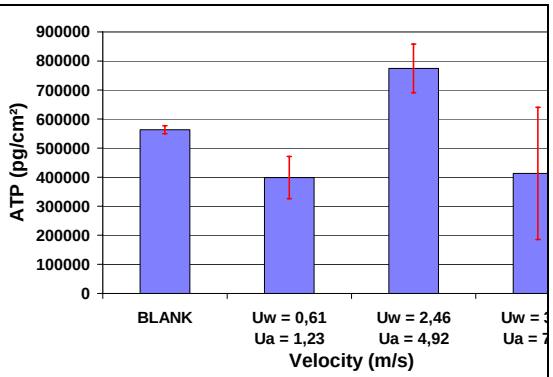

Figure 3: Biomass removal from PVC-P rings measured with ATP using different air flows and water flows at a constant air water ratio of 2:1 (n=4).

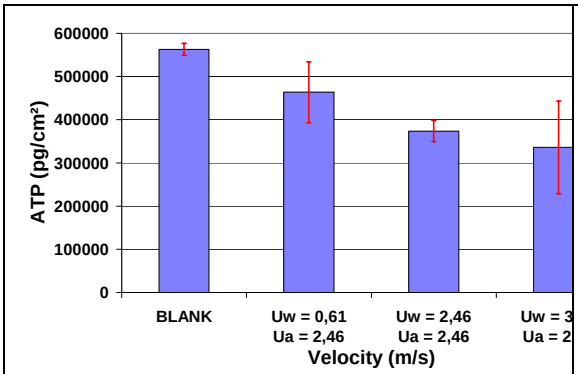

Figure 4: Biomass removal from PVC-P rings measured with ATP using different water flows at a constant air flow of 2.46 m/s (n=4).

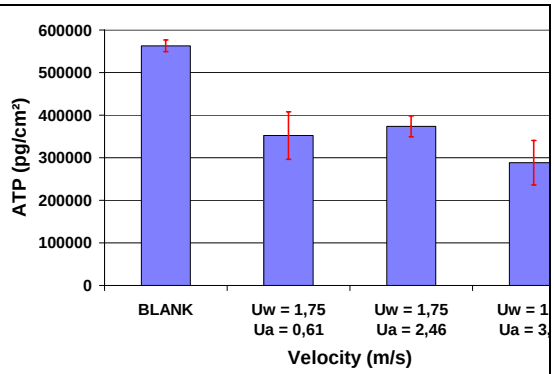

Figure 5: Biomass removal from PVC-P rings measured with ATP using different air flows at a constant water flow of 1.75 m/s (n=4).

Discussion

The presented results show that air-water flushing can only partly remove biomass from PVC-P rings. Removal efficiencies estimated by ATP-measurements were obtained ranging from 30-50% depending on flushing time and the actual air and water flows. An increase of flushing time, water flow and air flow increased the removal of biomass expressed by ATP, due to an increase in mechanical cleaning action (shear force). This was also found in applying air-water flushing in actual membrane elements (Cornelissen et al., 2007). The air and water velocities applied in the test system (Fig. 1) ranged respectively from 0-7.4 m/s and 0.6-3.7 m/s, which was much higher than velocities applied in spiral wound modules, in which average water velocity range from 0.1-0.2 m/s. Higher water velocities of 1.5-2 m/s gave more effective removal of membrane fouling (Bryers, 2000). Despite higher mechanical forces applied when removing biomass from PVC-P rings, biomass could not be removed by mechanical forces alone. The maximum removal of biomass from PVC-P rings was approximately 50% at 10 minutes despite considerable higher velocities applied in membrane systems. Furthermore, it has to be realized that the biofilm created in the PVC-P rings were only relatively young (less than three and half weeks). Older biofilms most likely are more difficult to remove from surfaces.

The test procedure for investigating the effects of air-water flushing will be further developed to enable comparison to air/water cleaning in membrane systems. Important current differences of the test procedure with actual membrane elements are the material which has been used (PVC-P), the flow pattern (tubular flow) and the type of biomass (relatively young biofilm). Furthermore, the flow pattern within spiral wound modules is turbulent due to the presence of a feed spacer and the flow within the PVC-P rings is turbulent due to the addition of air. The test protocol will be improved to enable assessment of the effect of chemical agents on biomass removal from PVC-P rings.

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IV Budget report

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