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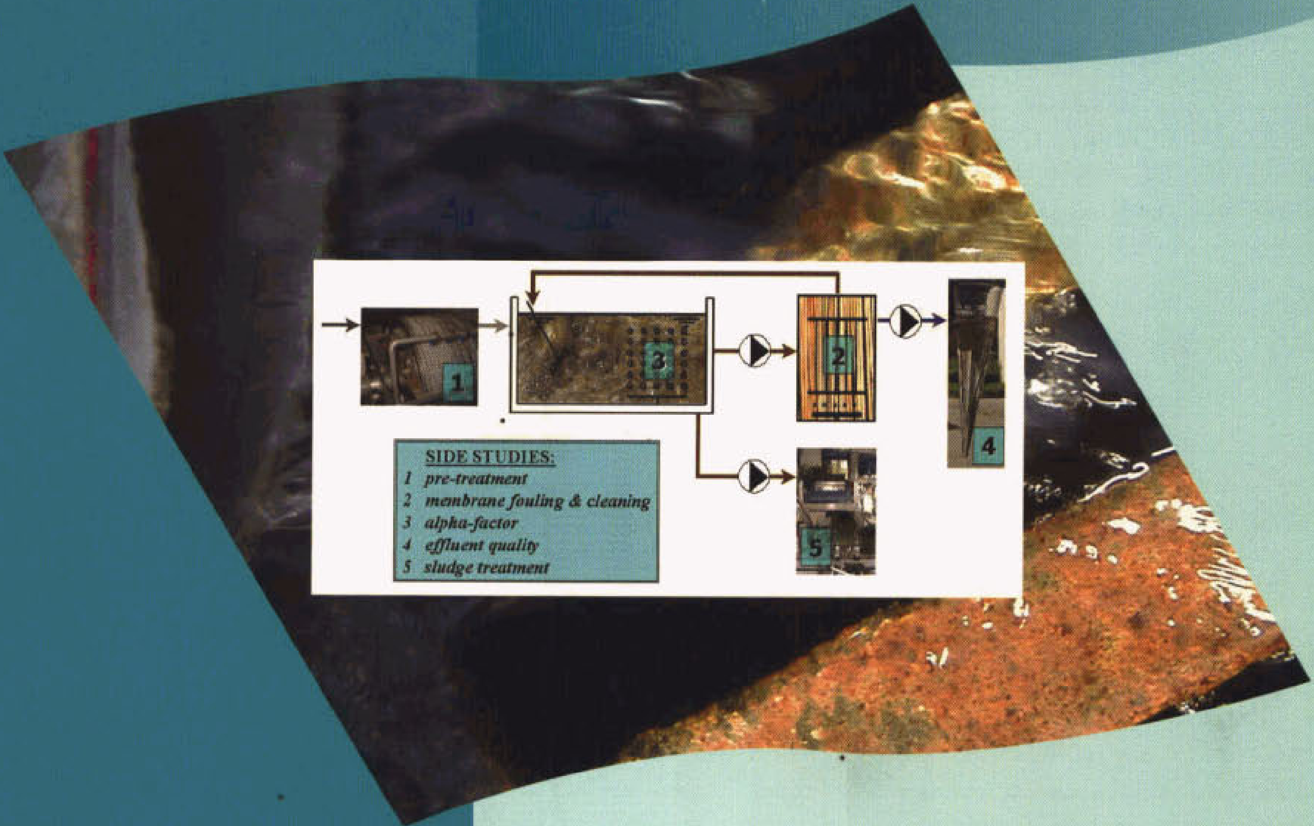
ichting Toegepast Onderzoek Waterbeheer

MBR for municipal wastewater treatment

Supplementary report with side studies



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MBR for municipal wastewater treatment

Supplementary report with side studies

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SIDE STUDIES

1 PRE-TREATMENT

2 FOULING AND CLEANING

3 ALPHA-FACTOR

4 EFFLUENT QUALITY

5 SLUDGE TREATMENT

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Stichting Toegepast Onderzoek Waterbeheer

Development MBR technology for large wwtp's

Pilot-research wwtp Beverwijk

Side study 1: Pre-treatment

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1 INTRODUCTION

1.1 The project

Since April 2000 four MBR pilot systems have been in operation at the Beverwijk WWTP. The goal of the research was to investigate the technical feasibility of the MBR system and to compare the four systems.

In the main STOWA report the experiences with the MBR pilot systems are described. Especially the biological performances and the membrane performances are mentioned for each system. Alongside the main report five more fundamental side studies were carried out.

The five side studies are described and summarised in the main report. The subjects of these side studies were:

1. Pre-treatment
2. Fouling and cleaning
3. α - factor
4. Effluent quality
5. Sludge treatment

In this report the objectives, set-up and results of side study 1 - Pre-treatment - are described.

1.2 Side study: Pre-treatment

Four different mechanical (fine) screens have been applied for pre-treatment, each are installed just before each MBR system. This results in the removal of solids (screenings) which otherwise may clog the membranes, possibly resulting in a decrease in flux and/or a shortage of life-time of the membranes.

The installations were tested for a period of four months, in which both pre-clarified influent (phase 2) and raw influent (phase 3) were used as feed for the pre-treatment installations. In both phases a 7.2 mm screen first screened the wastewater.

1.3 Reader

In chapter 2 the objectives of the study are described. Other experiences with fine screens in the field of water treatment are described in chapter 3. The set-up of the research, including all performed measurements and analyses are included in chapter 4. The results of each test phase are reported in chapter 5. In chapter 6 the design aspects for a fine screen are discussed. The report ends with conclusions and recommendations for further research (chapter 7).

2 OBJECTIVES

It is known that membrane systems can be sensitive to fouling of the membrane surface. Developments in membrane configuration, membrane material and ways of cleaning and operation have resulted in improvements towards reduced membrane fouling. Eventually, this would lead to a more stable operation of the MBR-system, less maintenance and prolongation in membrane life-time.

To prevent fouling as much as possible, pre-treatment of the wastewater is strongly advised. In most cases gravity settlement (e.g. sedimentation tanks) or mechanical equipment (i.e. grids, screens or sieves) or a combination of both are applied. The purpose is to remove solids (screenings) which are (likely to be) harmful for membranes, like:

- coarse (organic) solids, such as plastics, leaves, seeds, sand particles etc.;
- (mineral) oils and fats;
- hairs.

In this research four different types of mechanical pre-treatment installations are used. Each one was located just before one MBR-system (X-Flow, Kubota, Mitsubishi and Zenon). The objectives of the four month test with this equipment were:

- quantify the amount of suspended solids, COD, oil, fats retained by each pre-treatment installation and establish differences between them;
- determine long-term behaviour;
- obtain an impression of the required time for maintenance and cleaning;
- evaluate the results compared to these obtained by means of sedimentation;
- determine the compression behaviour of the retained screenings.

3 LITERATURE SURVEY

3.1 Introduction

The database Aqualine and Internet were used to search for information on (fine) screening, preferably in combination with a MBR system.
For the research in Aqualine keywords as 'screening', 'screen', 'MBR' and 'mechanical treatment' and a combination of these was used. The articles of the most relevant abstracts were applied for. It turned out that the amount of relevant information was rather limited.

3.2 Type of screens

Fine screens are generally classified as screens whose filter openings are less than 6 mm and may range to as low as 0.2 mm. Units with openings at the lower range of this spectrum are often able to reduce solids levels to primary treatment levels. Fine screens are used most commonly in wastewater treatment plants in applications that include:

- solids removal to protect downstream equipment and processes;
- primary treatment, instead of primary clarifiers;
- solids recovery in industrial process streams;
- sludge screening;
- scum de-watering;
- screenings or grit dewatering.

Screen head loss and the volume of solids removed increases exponentially as the size of the screen openings decrease. Therefore, the application of a fine screen necessitates a careful review of the plant hydraulics, the screenings handling system, and the sizing of downstream equipment.

Solids removal attributed to fine screens may result in a reduction of BOD levels by 5 to 25%, TSS by 15 to 30%, grease by 30 to 50% and up to 90% of all floatable material.

The various types of fine screens may be categorised and differentiated by the way that they are positioned relative to the incoming flow, the screening medium utilised, or the cleaning mechanism employed. One can distinguish [ref. 1]:

- **Filter screens (incl. belt and band screens)**
  In channel screening devices that consist of an endless cleaning grid or belt operating around the head-sprockets and foot-sprockets or lower curved guide rails. The screens are orientated perpendicular to the channel flow. The upstream face of the moving grid collects and retains debris, elevates it out of the flow, and discharges it into a suitable receptacle.
- **Static screens**
  Static screens use a stationary, inclined screen deck that acts as a sieve to remove solids. Static screens are also commonly referred to as "side hill" and "rundown" screens. Water flowing over the weir of the screen accelerated downward and passes over the inclined screen deck. As it cascades over the face of the screen, liquid is stripped away from the solids and falls through the screen openings into a filtrate chamber.
  A variation of the static screen is the vibrating screen. The screen deck is fabricated as part of a sub-frame that is mounted on shock absorbers so that vibrations are not transmitted to the main frame of the screen. Vibrating screens are much more effective than static screens in applications that require handling greasy or sticky solids.

- **Rotary fine screens**

  A rotary fine screen consists of a rotating screen cylinder fitted with a wedge wire or woven mesh screen to remove solids. Rotary screens may be internally or externally fed. The internally fed rotary screens utilises the inside surface of the cylinder rotating on a horizontal axis as its active screening surface. These screens are well suited for applications where the feed has a high fibre content (pulp and paper industry) and those where solids have a "heavy" consistency (e.q. meat, poultry).
- **Helical basket screen**

  The helical basket screen utilises a cylindrical screening basket mounted in a channel at an angle that may range from 30-50 degrees. The feed enters the lower open end of the basket and passes through the cylinder, while solids are retained on the interior of the wedge wire or perforated plate screen surface. The solids are then removed from the screen and conveyed up to the discharge point by a helical-type screw conveyor.

  These screens may be equipped with a screening dewatering and compacting system designed as an integral part of the screw conveyor used to transport debris to the discharge elevation.
- **Disc screens**

  A disc screen consists of a flat disc covered with screening media that rotates about a horizontal axis, perpendicular to the feed flow. Influent enters the submerged portion of the disc, and solids are retained by the screening media. The rotation of the disc lift the solids above the water surface where they are removed by a bank of spray nozzles.
- **Brush raked fine screen**

  Brush raked fine screens utilise revolving bristle brushes to remove solids from a curved stationary screen. The cleaning brush mechanism is mounted on a drive shaft that slowly rotates in a 360 degree circle about a horizontal axis. The rotation of the brush sweeps clean the upstream face of the screen and elevates solids to the top of the screen. The screening are by gravity discharged into a trough or container.
- **Drum screen**

  A drum screen is an in-channel screening device that consists of a series of (woven) wire mesh panels mounted on the periphery of a cylinder that (discontinuously) slowly rotates on a horizontal axis.

  Waste water enters the inside of the drum and flows through the wire mesh panels. Solids are retained on the inside surface of the wire mesh panels and elevated out of flow as the drum rotates. The solids are removed from the mesh into a trough at the top of the drum by a high-pressure spray wash system.

3.3 Experiences with screening

Severn Trent Water in England operates more than 1,000 wwtp's in England. Most utilise 6 mm coarse screens which retain a total of 46,000 m^3 screenings per year while treating 695 million m^3 of waste water [ref. 2]. Although the sludge incinerators are able to burn small quantities of screenings most of the material has to be landfilled. A typical composition of the screenings is (on dry basis):

- rag: 15-30 w.%;
- paper: 20-50 w.%;
- rubber: 0-5 w.%;
- plastic: 5-20 w.%;
- vegetable matter: 0-5 w.%;
- faecal matter: 0-5 w.%.

The main factor governing acceptability for transport and landfill is the dryness of the material. The standard that Severn Trent has adopted is that the material produced from the screenings handling equipment should contain at least 25% dry matter.
Some landfill operations require a maximum Quality factor which is defined as:

*Quality factor = BOD in the leachate / (packing density * dry solids fraction)*

Once the screenings have been removed from the sewage, they are usually washed into some form of screenings treatment device via a launder. Then, there are several options available:
The cheapest option is to drop the water bound material into a compaction device where the bulk of the water drains away by gravity and much of the remainder is squeezed from the screenings mechanically. The most common device of this type is the inclined reducing pitch screw. This produces an acceptable dry material, but typically the product from such an installation is brown and contains visible evidence of its sanitary origin.

A slightly more complicated system passes the screenings/water mixture through a washing stage. The screenings are washed by the turbulence of the mixing action, or washing can be accomplished trough a macerating pump. This produces an excellent product, but with increased capital and operating costs.
The final type of process relies on a maceration unit to reduce the material to such fine pieces that they can be returned to the sewage flow and removed from the plant with the sludge. This approach is sometimes not favoured as such units intends to lose efficiency quite quickly causing problems on bacteria beds, with sludge processing equipment and with the use of sludge on farmland.

At Aubergenville wwtp in France a 1 m^3 pilot MBR with hollow fibre ceramic membranes has been operated with municipal waste water [ref. 3]. The waste water is pumped into the MBR after coarse screening, sand removal, degreasing and filtration. The last pre-filtration with a 0.8 mm filter is carried out to protect the membranes. The average amount of suspended solids retained on the daily cleaned pre-filter is 25 g SS/day corresponding with 33 g SS/m^3.

In Japan a pilot MBR with polyethylene hollow fibre membranes has been tested with domestic wastewater [ref. 4]. Raw sewage was supplied into the aeration tank (21.4 m^3) after screening with a 1 mm bar screen. No further information about the screen is stated.

Two pilot-scale wastewater treatment systems, direct membrane separation and a membrane bioreactor, were tested in order to investigate the feasibility of membrane filtration technology for domestic wastewater treatment and water reuse [ref. 5]. A submerged-type hollow fibre micro-filtration membrane was used. A 0.5 mm sieve is applied before the membrane tank. No further information about the sieve is stated.

In case of Kubota membrane systems, bar screens with 1 to 2.5 mm slit is normally used as a fine screen. At the Porlock WWTP in the United Kingdom a 3 mm perforated screen has been used. According to Kubota the membrane system functions well without clogging [ref. 6].

4 SET-UP

4.1 Pre-treatment installations

For pre-treatment four different types of installations were applied. The installations were tested for four months, except for the Noggerath installation, which was only included in the research program for the last two months.
In table 1 the characteristics of each pre-treatment installation are described.

Table 1 - Characteristics pre-treatment installations

Configuration	internally fed rotary wedgewire screen	vibrating static screen	internally fed drumfilter	rotating brush raked screen
Supplier [1]	Noggerath	Reko	Hydrotech	Contec
Type	HRS 3648	600 VE	801	B4
Located for the MBR of:	Kubota	Mitsubishi	X-Flow	Zenon
Actual capacity MBR	7.8 m^3/h	6.4 m^3/h	1.8 m^3/h	7.6 m^3/h
Feed flow	continuously	on/off depending on water level in MBR	on/off depending on water level in MBR	continuously
Design capacity pre-treatment installation	200 m^3/h	40 m^3/h	14 m^3/h	8-10 m^3/h
Power of motor	0.37 kW	2x 0.085 kW	0.25 kW	0.04 kW
Filter Mesh	0.25 mm	0.75 mm	0.5 mm	0.75 mm

1) It should be noted that the suppliers involved in this research may also supply other types of micro screens.

Wedge-wire screen
The Noggerath (Hycor Rotoshear) installation is an internally-fed rotary wedge-wire cylindrical screen. Wastewater enters trough the inlet and flows into a header box. The header box fills and the water cascades over the weirs and contacts the perforated rotating cylinder screen. The header aids distribution of the waters over the screen. The solids are caught inside the cylinder, and the water passes through the screen and is transported to the MBR system. Diverters on the inside of the cylinder screw the solids along the length of the screen to the discharge point.

The unit has two separate spray systems: an internal spray to clean the screening surface of the cylinder and an external spray to keep the screen openings clean. During the test only the external spray system was manually put into operation once in a week for 1-2 minutes.

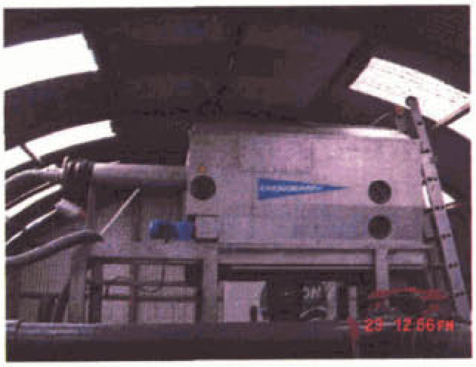

Figure 1 - Front view wedgewire screen

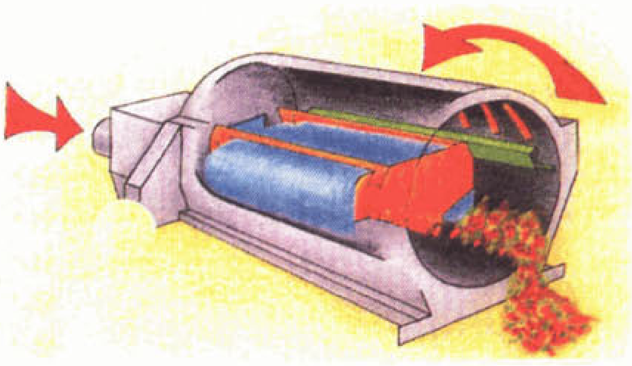

Figure 2 - Working principle

Vibrating static screen

The vibrating static screen installation is supplied by Reko. The feed wastewater pump is interlocked to the vibration motor so as the system requires feed the screen become active and the wastewater filtered accordingly. Filtered waters pass through the wedge wire openings and collected and discharged to the MBR system. The solids remain on the screen and are vibrated downwards and collected on a tray to be used for further analyses or discharge. An automatic cleaning device in the form of an oscillating spray bar was available as a standard option, but was not supplied for the Beverwijk installation.

Figure 3 - Front view vibrating screen

Figure 4 - Working principle

Drumfilter

The circular drum-filter is supplied by Hydrotech. The wastewater is fed inside the static drum and filtered on the inside peripheral mesh of the drum. The waters pass the mesh and fall into a small vessel before overflowing to the bioreactor. The retained solids which build up on the inside of the drum are periodically rinsed off the filter cloth by means of several spray nozzles located outside the drum. The rinse procedure is started automatically by means of a water level measurement in the drum, at the same time of the rinse the drum rotates slowly. The collected solids are washed from the mesh to a collection trough and then discharged.

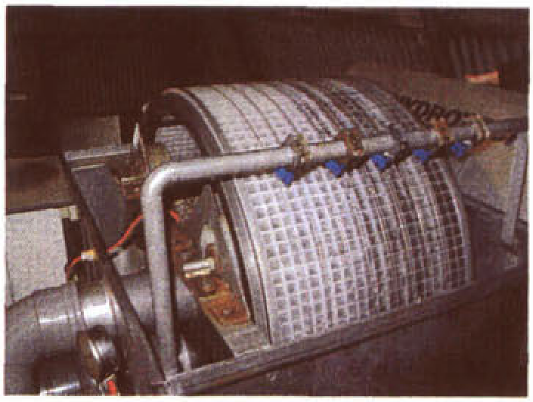

Figure 5 - Inside view drumfilter

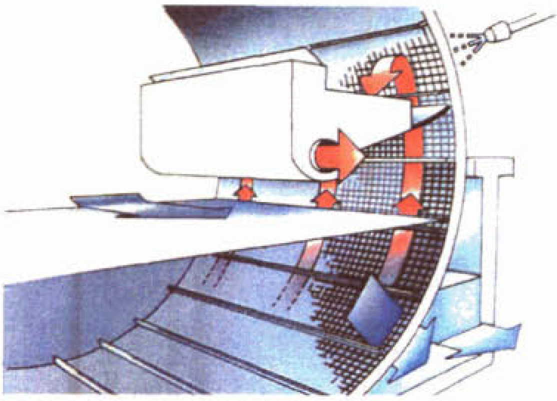

Figure 6 - Working principle

Rotating brush raked screen

The installation, supplied by Contec, is a horizontal located half cylindrical perforated screen. The feed is transported in a horizontal direction and distributed over the screen. The solids remain on the screen and are removed continuously by slowly rotating brushes. The treated water passes to the MBR system via gravity through the filter mesh.

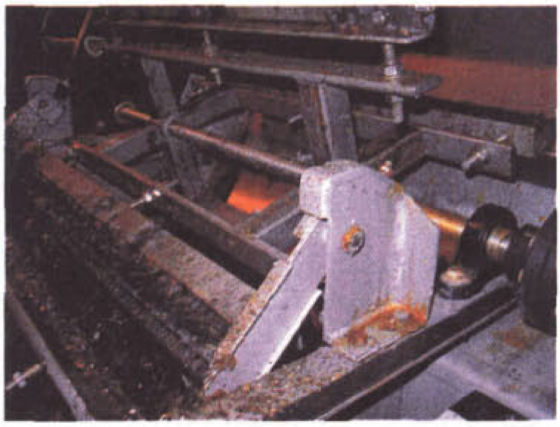

Figure 7 - Inside view brush raked screen

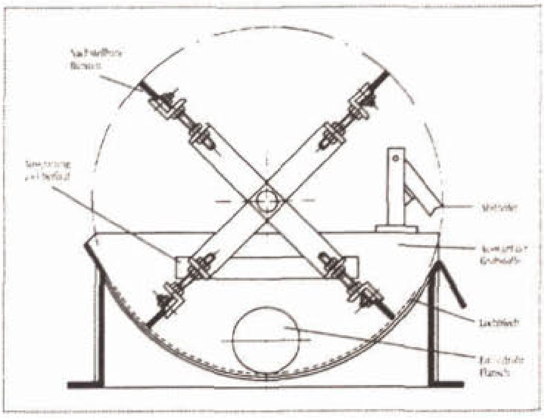

Figure 8 - Working principle

The pre-treatment installations are located just before the MBR installation. During the test period two phases could be distinguished:

- Phase 2: feed for the pre-treatment installations was wastewater which had passed a coarse (7.2 mm*) grid installation and primary sedimentation tanks;
- Phase 3: feed for the pre-treatment installations was 'raw' water which had only passed a coarse (7.2 mm*) grid installation.

*)original installed filter mesh was 6 mm.

4.2 Sampling and analysis

During the test, 2-3 times a week water samples were taken before and after the pre-treatment installation and every day a sample of the screenings was taken. In table 2 the sample and analysis program is shown.

Table 2 - Sampling and analysis program

Sampling location	Type of sample	Sampling frequency	Analysis
'raw' influent (phase 3)	time proportional	2-3x/week	COD, SS, mineral oils, fats
sedimented wastewater (phase 2&3)	time proportional	2-3x/week	COD, SS, mineral oils, fats
after pre-treatment installations	time proportional	2-3x/week	COD, SS, mineral oils, fats
screenings	grab	each time when collected screenings is disposed of	mass (kg) or volume (l), dry solids content, ash content, hair content, mineral oils, fats, density after compression, dry solids content after compression

The first month grab samples were taken. It seemed that the values obtained this way were not representative and sometimes improbable. For that reason automatic sampling devices were installed, which took a sample every thirty minutes.
At each MBR system the actual flow (in m^3/h) and the cumulative flow (in m^3) was measured. With the last value it is possible to relate the amount of retained solids to the volume of treated wastewater (in kg ds/m^3).

Total COD was measured by Dr. Lange test tubes (spectro-photometric method). Suspended solids were measured after filtration over a paper filter (Ø 110 mm S&S 589^2 white ribbon). Mineral oil was determined by means of infrared spectro-photography after extraction with TCE (tetra-chloroethene). Fats (the sum of animal and vegetable fats and mineral oils) were determined gravimetrically after extraction with petroleum ether and ethanol in an alkaline environment.

The dry solids content of the screenings was determined after drying at 105°C, the ash content of the dried solids was determined after exposure to 600°C.

During phase 2, the hair content was determined. This was done by dissociating an amount of screenings in a aerated beaker filled with water. Then the solids were washed out in a circular sieve with square 5.6 mm openings. All the solids passed the filter, except for hairs. After drying at 105°C, the amount of hair was related to the total dry solids content. During phase 3 it was no longer possible to separate hair from the remaining solids, caused by a strong increased quantity of retained solids and a change in particle size of these solids.

With a small filter press, compressibility tests were performed. A fixed amount of screenings was compressed for some minutes at a constant pressure of 7 bar. The filter cake was weighed and the thickness and surface area of the cake determined. With these values the density of the filter cake was calculated. After drying at 105°C, the dry solids content of the compressed filter cake was calculated.

5 RESULTS

5.1 Introduction

In this section the results of the analysis program are presented. A distinction have been made between the different phases:

- Phase 2: pre-sedimented wastewater as feed (7 November 2000 - 10 January 2001);
- Phase 3: 'raw' wastewater as feed (12 January 2001 - 14 March 2001).

For the evaluation of <u>water</u> analysis, only the data obtained from the automatic sampling devices are used. Because these devices were only functional after 30 December 2000, the data for phase 2 is rather limited. Obvious rogue data was not taken into account.
The wedge wire screen, located before the Kubota MBR, was operational since 29 Jan. 2001.

5.2 Screenings - quantity, composition and compression -

In tables 3 and 4 the characteristics of the retained screenings for each installation are presented. The first weeks (phase 2 and beginning of phase 3), the collected screenings of the drum-filter and brush raked screen were retained by the use of a round sieve which was attached to a plastic funnel (bag) which had the same filter mesh dimensions as that of the pre-treatment installation (see figure 9). In this case the amount of retained water on the screenings was measured. For the vibrating static screen this methodology was of no use, as this was the only pre-treatment installation located in the open-air (otherwise also rain will be included).
The sludge productions in the tables were derived from the main report of this project.

Table 3 - Screenings (phase 2)

phase 2	wedge-wire screen	vibrating static screen	drum-filter	brush raked screen
date	-	7 nov. - 10 jan.	7 nov. - 8 jan.	7 nov. - 8 jan.
treated wastewater (m^3)	-	2,955	501	4,691
retained screenings (kg ds)	-	not enough data	1.4	1.5
retained (g ds/m^3)	-		2.8	0.3
collected water (l)	-		$123^{(\text{till } 4/12)}$	697
collected (l/m^3)	-		0.50 (0.05%)	0.15 (0.015%)
dry solids (% ds)	-	10.1	$0.7^{(\text{from } 12/12)}$	11.7
ash content (% of ds)	-	15	31	17
hair (in % of ds)	-	5.6	0	2.6
dry solids after compression (% ds)	-	28.7	18.0	25.3
density filter cake (kg/m^3)	-	not enough data	1.07	1.04
extractable fats (mg/kg ds)	-	180,000	210,000	125,000
mineral oils (mg/kg ds)	-	8,600	8,600	8,000
sludge production in aeration tank (kg ds/kg COD removed)	0.45	0.41	0.32	0.43

During phase 3 it was not possible to separate hairs from the screenings anymore. Therefore the presence of hairs is described qualitatively.

In phase 3 the screenings of the drum-filter and brush raked screen had a very low dry solids content. For that reason these samples are treated as 'water samples' by the laboratory. However the outcome of the mineral oil analysis did not yield reliable data for these samples. For that reason the results are not included in table 3.

Since 30 March, the 0.25 mm rotating drum of the wedge-wire screen was replaced by a drum with a filter mesh of 1.0 mm. In table 3, between brackets, some average values from the period 30 March-8 May are included.

Figure 9 - Separation of attached water

Table 4 - Screenings (phase 3)

phase 3	wedge-wire screen	vibrating screen	drum-filter	brush raked screen
date	6 feb.-14 march	23 jan.-14 march	12 jan.-14 march	12 jan.-14 march
treated wastewater (m^3)	2,503	1,417	338	2,812
retained screenings (kg ds)	85 (8.4)	19	32	65
retained (g ds/m^3)	34 (4.1)	14	94	23
collected water (l)	-	-	-	193 (till 19/1)
collected (l/m^3)	-	-	-	0.72
dry solids (% ds)	8.4 (14.2)	12.7	1.1	4.0*
ash content (% of ds)	17 (14)	17	28	16
hair 2)	++ (+++)	+++	---	++
dry solids after compression (% ds)	43.2	43.4	34.2	39.7
density filter cake (kg/m^3)	1.04	1.03	0.95	0.93
extractable fats (mg/kg ds)	60,000	77,000	115,000	84,000
mineral oils (mg/kg ds)	4,000	4,000	-	-
sludge production in aeration tank (kg ds/kg COD removed)	0.49	0.41	0.28	0.42

*) 13.2 % ds (12/01-23/01), 1.4% ds (23/01-14/03): mixture of screenings and water

2) - = less hair, + more hair (relatively compared to the other screens)

5.3 Removal of COD, SS, fats and mineral oils

COD

The COD inlet and outlet concentrations of the pre-treatment installations and sedimentation tank are depicted in figure 10. In phase 2, pre-sedimented wastewater was used as feed. In phase 3, pre-sedimented wastewater was still analysed to compare the performance of full sclae sedimentation process to that of the performance of screening.

In table 5 the COD removal efficiencies are calculated during the two phases and as an average for the whole test period.

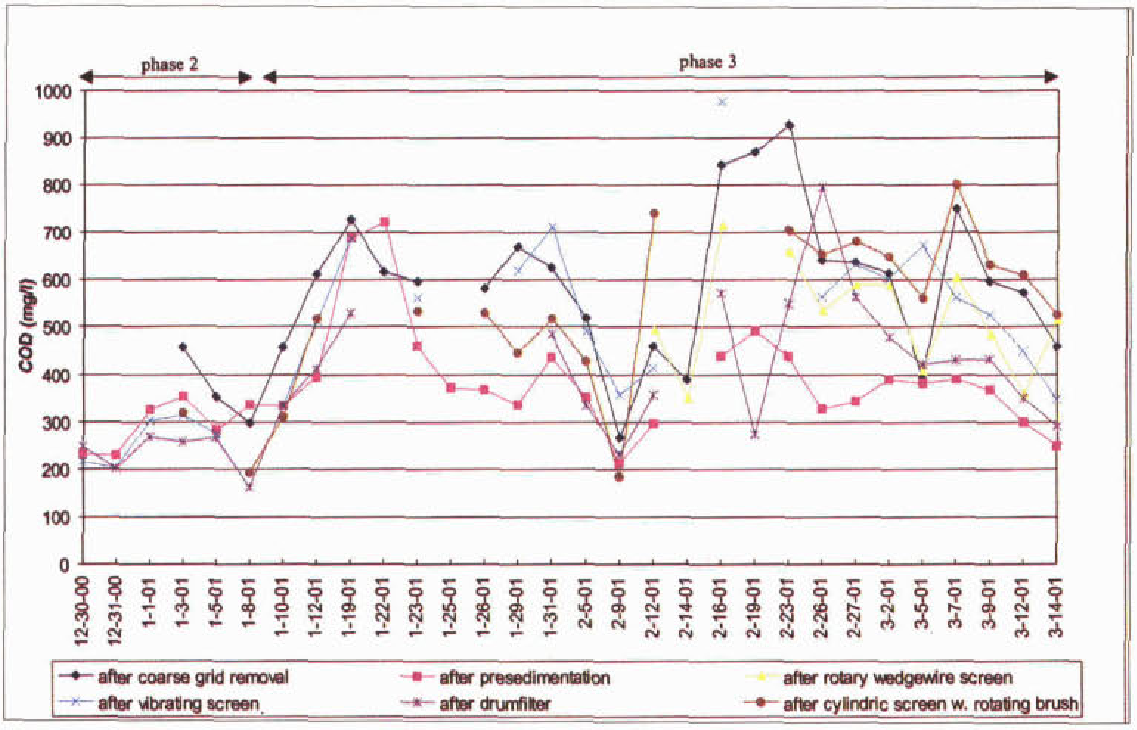

Figure 10 - COD removal

Table 5 - COD removal

	phase 2		phase 3		phase 2&3	
location	COD (mg/l)	removal efficiency (%)	COD (mg/l)	removal efficiency (%)	COD (mg/l)	removal efficiency (%)
after coarse grid removal	390	-	607	-	574	-
after pre-sedimentation	261	23%[1]	370	39%	362	37%
after wedge-wire screen	-	-	528	13%	499	13%
after vibrating screen	248	5%	534	12%	522	9%
after drum-filter	206	21%	431	29%	413	28%
after brush raked screen	209	20%	552	9%	511	11%

[1] removal efficiency based on waste water after coarse grid

Suspended solids

The suspended solids inlet and outlet concentrations of the pre-treatment installations and sedimentation tank are depicted in figure 11. In table 6 the SS removal efficiencies are calculated during the two phases, and as an average for the whole test period.

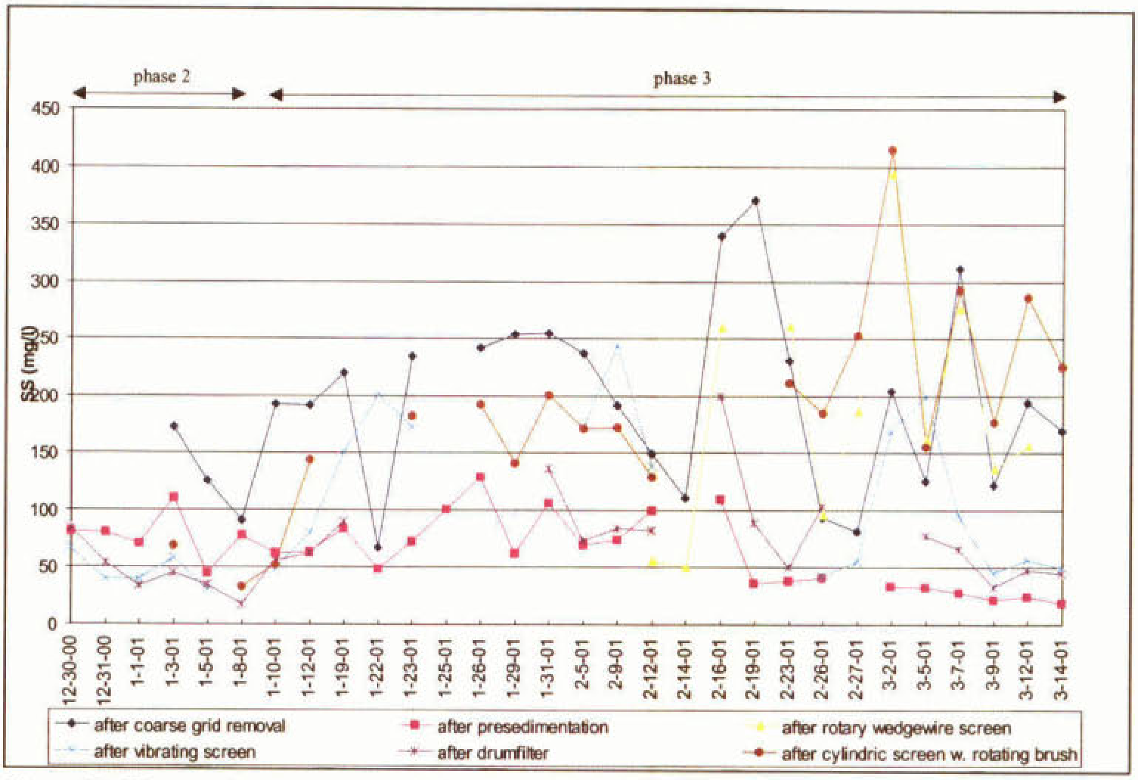

Figure 11 - SS removal

Table 6 - SS removal

	phase 2		phase 3		phase 2&3	
location	SS (mg/l)	removed (%)	SS (mg/l)	removed (%)	SS (mg/l)	removed (%)
after coarse grid removal	145	-	200	-	192	-
after pre-sedimentation	78	46%[1]	62	69%	67	65%
after wedge-wire screen	-	-	144	28%	138	28%
after vibrating screen	51	35%	112	44%	111	42%
after drum-filter	44	43%	74	63%	81	58%
after brush raked screen	48	38%	160	20%	146	24%

[1] removal efficiency based on waste water after coarse grid

Extractable fats

The (extractable) fats inlet and outlet concentrations of the pre-treatment installations and sedimentation tank are depicted in figure 12.

In table 7 the fats removal efficiencies are calculated for phase 3. The averages for phase 2 are not included as insufficient reliable data was established.

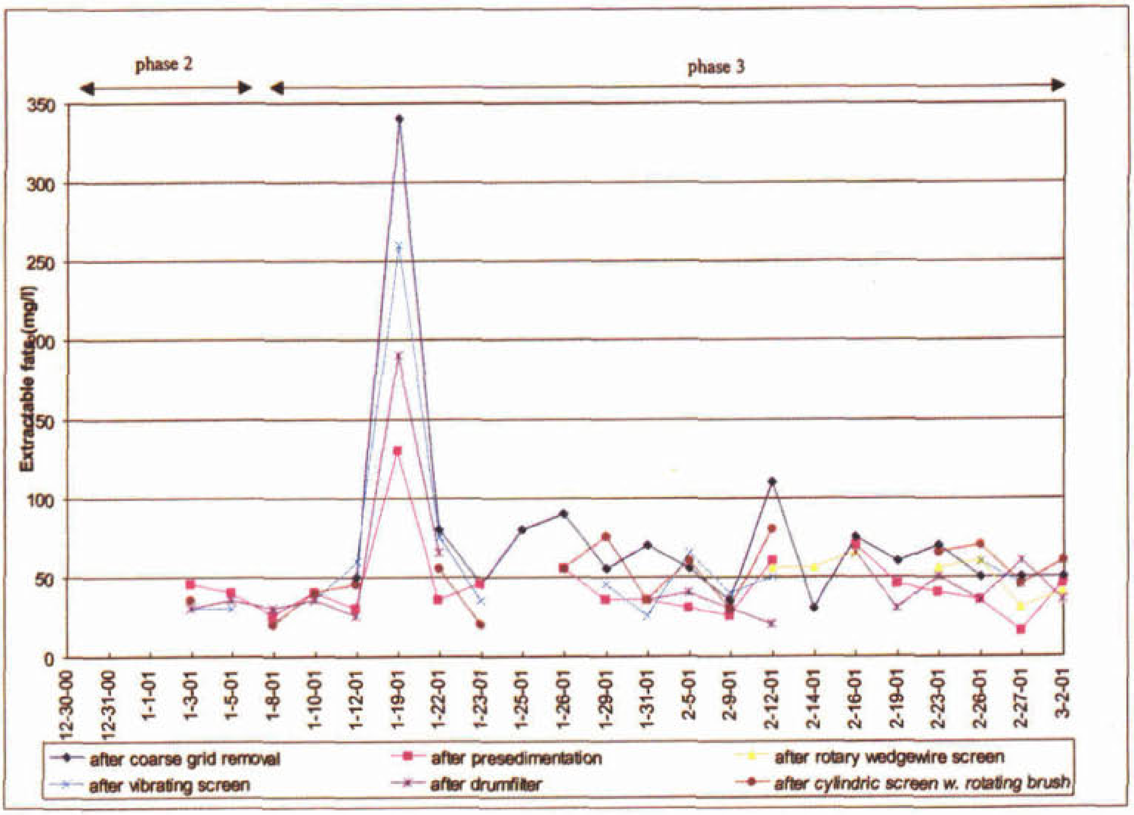

Figure 12 - Fats removal

Table 7 - Fats removal

	phase 3	
location	Fats (mg/l)	removal efficiency (%)
after coarse grid removal	78	-
after presedimentation	49	37%
after wedgewire screen	56	28%
after vibrating screen	45	42%
after drumfilter	41	58%
after brush raked screen	59	24%

Mineral oils

The (mineral) oils inlet and outlet concentrations of the pre-treatment installations and sedimentation tank are depicted in figure 13.

In table 8 the mineral oils removal efficiencies are calculated for phase 3. The averages for phase 2 are not included because insufficient reliable data was established.

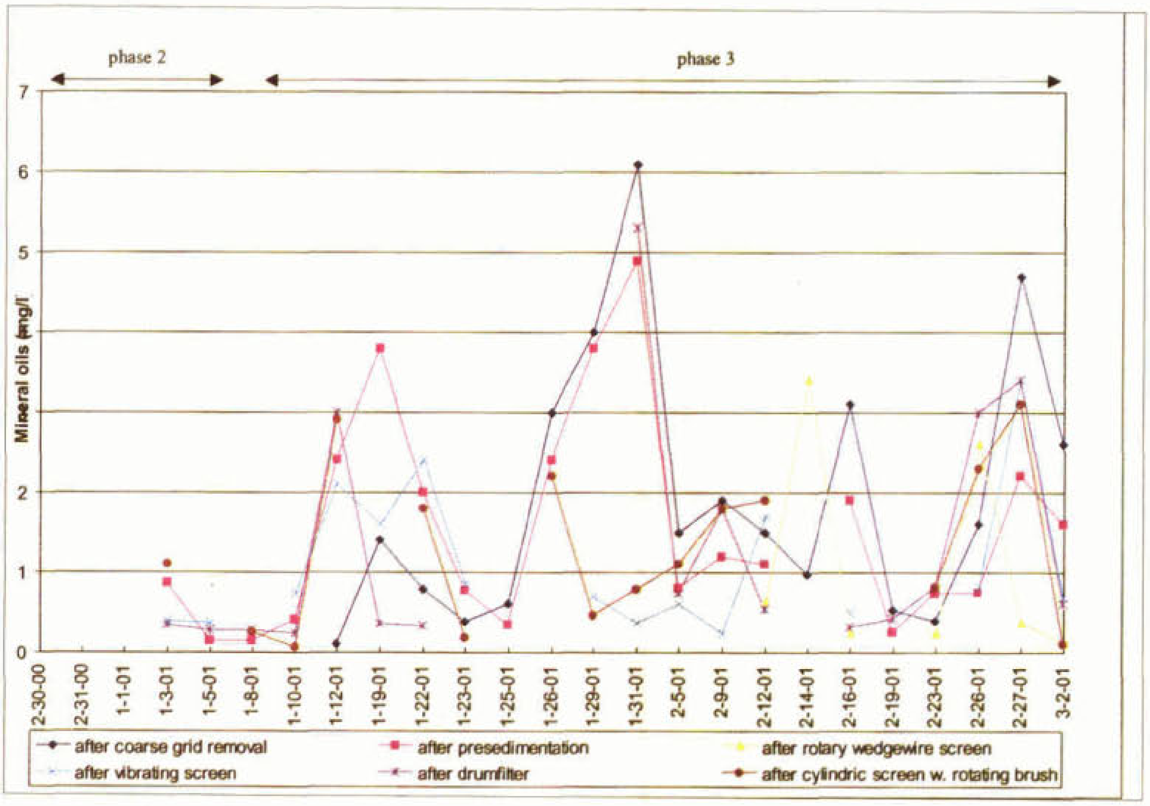

Figure 13 - Mineral oil removal

Table 8 - Mineral oil removal

	phase 3	
location	Oil (mg/l)	removal efficiency (%)
after coarse grid removal	1.95	-
after presedimentation	1.25	36%
after wedgewire screen	0.47	76%
after vibrating screen	0.62	68%
after drumfilter	0.99	49%
after brush raked screen	0.86	56%

5.4 Operation and Maintenance

Operation

All screens operated automatically and did not require special attention for normal operation. The rinse water system for the drum-filter was started automatically, for the wedge-wire screen it was started manually (once a week).

On 19 January the rinse water system of the drum-filter was switched off by accident. This has resulted in unfiltered wastewater entering the X-Flow MBR system. After three days the MBR system was automatically put out of operation due to clogging of the membranes. An extensive off-site cleaning of the membranes was necessary.

From 12 February, at irregular intervals, sludge was dumped in the splitting chamber (after the coarse grid installation). This lead to temporary peaks in COD and SS concentration in the inlet water of the pre-treatment installations (see also figures 10 and 11). However this situation did not seem to significantly influence the removal efficiencies for the pre-treatment installations.

Maintenance

The wedge-wire screen was cleaned for two times in about 1.5 month. Solids were accumulating in and at the top of the header box (see figure 14). This led to an unequal water distribution in the rotating cylinder (preferred flows), resulting in a severe water loss at the (screenings) discharge point.

Figure 14 - Accumulation of screenings

Figure 15 - Clogging of vibrating screen

The vibrating static screen was cleaned nine times (four times in phase 2, five times in phase 3). The small openings between the screen clogged up with fine (organic) material. This hampered the water throughput through the openings and at the end a (significant) part of the feed was not entering the MBR, but left the installation at the lower end of the vibrating static screen (figure 15). The screen was cleaned by powerful brushing for about five minutes. Concerning the clogging of the vibrating static screen it should be noted that:

- the screen was located in the open air (all the others were located inside a building);
- an automatic cleaning device is available as a standard option, but was not available at the pilot plant;
- the micro screen was fed discontinuously, which increases the risk of clogging.

The screen was frozen in January for almost two weeks, because it was located in the open-air. Then, most of the feed left the installation and did not enter the MBR. To prevent freezing of the screen surface, the feed pump was switched on/off more frequently by adjusting the level set points of the MBR.

The drum-filter did not require any maintenance during phase 2. During phase 3, three times a clogged rinse nozzle has been cleaned (figure 16). The drum-filter was also opened on three occasions to manually remove accumulated screenings ('clay like' structure) which were stuck to the tray inside the filter drum (figure 17). This required about 15 minutes per cleaning cycle.

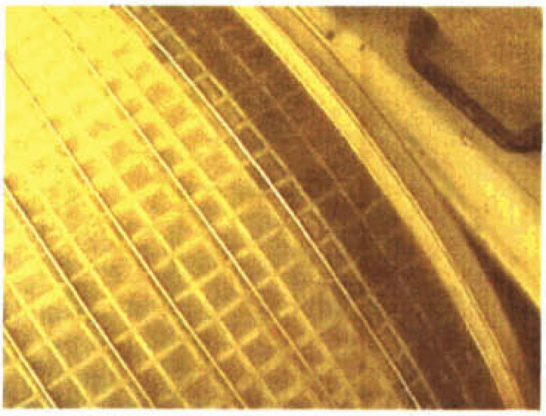

Figure 16 - Result clogging of rinse nozzle

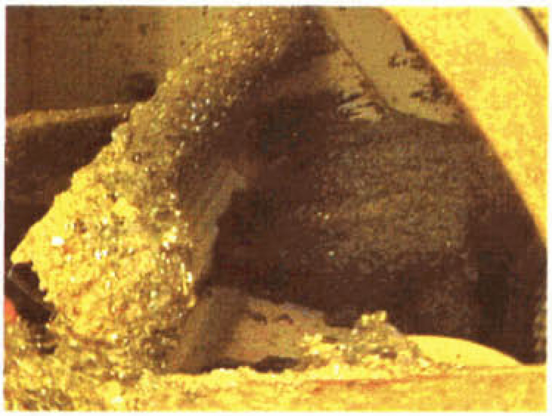

Figure 17 - Accumulation of screenings

The brush raked screen did not require any maintenance in phase 2. In phase 3 the installation needed to be hosed monthly to remove biological fouling (biofilms) on the brushes and the screen. This biofouling mainly occurred after a period of hydraulic peak loadings.

5.5 Evaluation removal by fine screens

Screenings - quantity and composition -

The highest specific quantity of screenings was retained by the 0.5 mm drum-filter (in both phases). In spite of the smaller mesh (0.25 mm) of the wedge-wire screen, this screen did not retain more screenings. Very likely, this was caused by the operation and filtration behaviour of the drum-filter. Due to the discontinuous rinsing procedure, the inside of the drum (filter cloth) is gradually covered with a thin sludge layer during operation. This likely improves retaining (filtration) of the screenings (similar to pre-coating).

Possibly this phenomena was also relevant for, but in less extent, for the vibrating static screen whereby the openings of the screen were gradually clogging up. The smallest specific quantity of retained screenings for this screen may be due to rinsing out of suspended solids in the collected screenings, because the screen was located in the open air.

The wedge-wire screen was strongly oversized, the maximum capacity was 200 m^3/h, while the maximum feed flow was 8 m^3/h. This results in a relatively long screenings residence time in the rotating drum, which may adversely effect the removal of (fine) suspended solids.
The quantity of retained screenings was drastically reduced when the 0.25 mm drum of the wedge-wire screen was replaced by a drum with a filter mesh of 1.0 mm.

Visually the composition of the screenings of the wedge-wire screen, the vibrating static screen and the brush raked screen was comparable: coarse organic material (leaves, seeds) and hairs are present. Also the dry solids content of the retained screenings and the ash content were almost the same. However the retained screenings of the drum-filter appeared different: a sludge (clay) like structure, while no coarse organic materials and hairs were noticed. This visual difference was confirmed by a much higher ash content of the retained screenings, indicating that relatively a lot of primary sludge was retained.

The compression behaviour of these screenings was also different compared to the other three types: the dry solids content for the drum-filter screenings was significantly lower compared to that of the other screens.
There was no plausible explanation for the difference in composition and behaviour of the screenings from the drum filter compared to the other three types.
The content of extractable fats and mineral oil in the screenings was in the same order of magnitude with the highest values for the screenings from the drum filter. This implied that the screen with the highest specific quantity of screenings also removes most of the fats and oils.

As expected, the specific amount of retained screenings enormously increases (30-70x) after treating raw wastewater in stead of pre-sedimented wastewater.

COD

The highest COD removal efficiency over the whole testing period with the screens was obtained with the drum filter (20-30%), followed by the wedge-wire screen (15%), the vibrating static screen and the brush raked screen (10%). These removal efficiencies show a relation with a finer (effective) filter mesh of the screens.

In comparison to primary sedimentation this is relatively low. During phase 3 about 35-40% of the COD was removed, which was higher than any of the screens.

Suspended solids

The highest SS removal efficiency over the whole testing period with the screens was obtained with the drum filter (60%), followed by the vibrating static screen (40-45%), the wedge-wire screen (30%) and the brush raked screen (20-25%).
The SS removal obtained by means of pre-sedimentation was higher. During phase 3 about 65% of the SS was removed.

The measured biological sludge productions for the MBR installations (see table 3 and 4) corresponded proportionally and inversely to the SS removal efficiencies for the different pre-treatment installations. During phase 3 the sludge production for the X-Flow pilot (drum filter) was by far the lowest, followed by the Mitsubishi pilot (vibrating static screen), the Zenon pilot (brush raked screen) and the Kubota pilot (wedge-wire screen). It should be noted that the above mentioned relation is also influenced by the lower biological loading of the X-Flow and the Mitsubishi pilot plant.

Extractable fats

The highest fats removal efficiency with the screens during phase 3 was obtained with the drum filter (about 60%), followed by the vibrating static screen (about 40%). The removal efficiencies for the other two screens were almost the same (25-30%).

The fats removal efficiency by means of pre-sedimentation was about 40%, which was lower than the removal of the drum filter.

Mineral oils

The removal efficiencies of mineral oil fluctuated greatly but largely due to erroneous data. During phase 3, the highest oil removal efficiency over the whole testing period with the screens was obtained with the wedge-wire screen (75%), followed by the vibrating static screen (70%), the brush raked screen (55%) and the drum filter (50%).

The oil removal efficiency by means of pre-sedimentation was about 35%, which was lower than any of the screens.

5.6 Coarse grid removal

The quantity of discharged grid retained by the 7.2 mm coarse grid installation was measured during both phases (see table 9).

Table 9 - Coarse grid removal (by a 7.2 mm grid installation)

	phase 2	phase 3
date	16/11-03/01	16/01-23/02
discharged grid (tonne)	10.6	9.5
treated waste water in this period (m^3)	3,710,000	2,490,000
assumed dry solids content (%)	15	15
specific solids removal (g ds/m^3)	**0.43**	**0.57**

If one compares these calculated values with the specific solids removal of the fine screens (see table 3 and 4), it can be concluded that a fine screen during phase 3 removes about 25-60 times (depending on the type of fine screen, excluding the drum filter) more solids compared to the 7.2 mm grid. As expected, during phase 2 this was much lower and the removal by the brush raked screen was lower than by the 7.2 mm screen.

5.7 Basket filters

From the first start of the MBR pilot research, pre-sedimented waste water was used as feed and no pre-treatment precautions were installed before the MBR systems (except for the Mitsubishi MBR, which was equipped with the vibrating static screen from the beginning).

In the feed lines of the three other MBR installations, small basket filters were applied to prevent clogging of the membranes. In spite of the fact that pre-sedimented water was used as feed, these basket filters rapidly clogged up and had to be frequently cleaned. The filter mesh of the basket filters and the average cleaning frequencies were as follows:

MBR	filter mesh	cleaning frequency (once per ...)
X-Flow	1 mm	1-2 days
Zenon	2 mm	1-2 days
Kubota	3 mm	2-3 days

5.8 Mass balance

Based on the results, the average COD and SS removal efficiencies and concentrations are made visual in figure 18 for both phases.
For the removal efficiency of the screen, the drum filter is used as reference (= the screen with the highest removal efficiency). For phase 3, also the effluent of the pre-sedimentation tank is included in the figure.

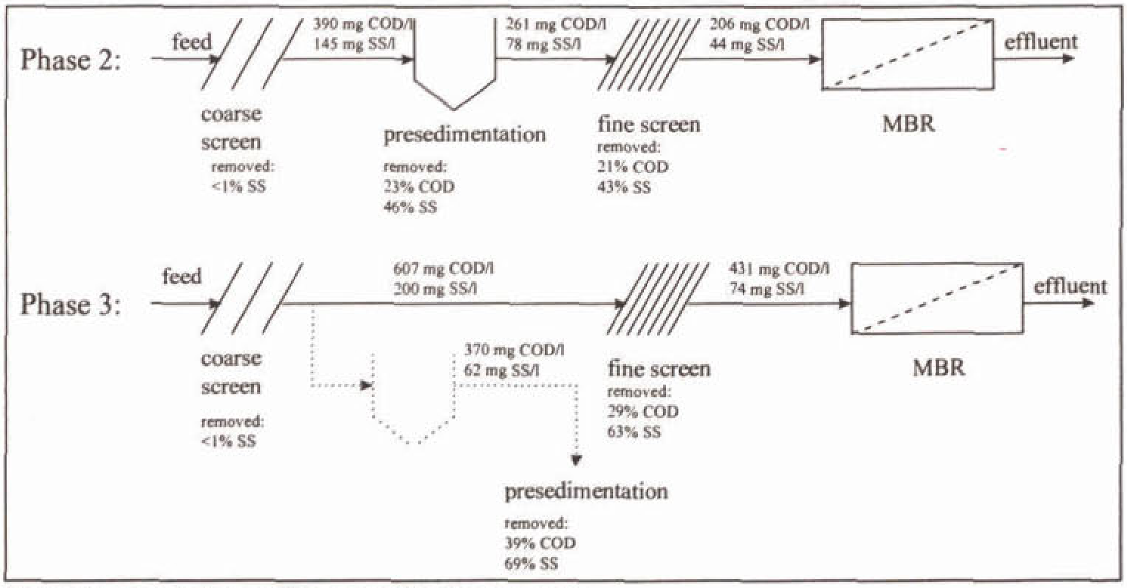

Figure 18 - Mass balance for COD and SS (phase 2 and 3)

During phase 2 21% COD and 43% SS are removed by the fine screen, corresponding to 55 mg COD/l and 34 mg SS/l. During phase 3 about 29% COD and 63% SS are removed by the fine screen, corresponding to 176 mg COD/l and 126 mg SS/l. The removal efficiencies of the presedimentation tanks are 39% COD and 69% SS, corresponding to 237 mg COD/l and 138 mg SS/l.

In general from these measurements, it seems that the COD removal efficiencies of the fine screens were limited (10-15%) and the SS removal was somewhat higher (20-40%). Except for the drum filter which had a much higher efficiency, as presented in the figure above.

6 DESIGN ASPECTS

6.1 Characteristics full scale installations

The described pre-treatment installations are available for different capacities. Not only the flow (m^3/h) is of importance, but also the type of wastewater, mainly caused by the nature and concentration of the suspended solids present. Dependent on the kind of application and effluent requirements, this also determines the required filter mesh of the pre-treatment installation.

In table 10 the characteristics of the tested pre-treatment installations are included for full-scale applications.

Table 10 - Characteristics full scale pre-treatment installations (Source: Technical Product Information)

Configuration	internally fed rotary wedge-wire screen	vibrating static screen	internally fed drum-filter	rotating brush raked screen
Supplier	Noggerath	Reko	Hydrotech	Contec
Types	HRS2448-80160	VE 600-1800	501-2007	B, C or D
Range of capacities (m^3/h)	102-2,955[1]	2-200[1]	40- 1,900[3]	7-540[2]
Power of motor (kW)	0.37-2.2	0.13	0.18-1.1	0.04-0.75
Mesh (mm)	0.25-2.5	0.15-1.5	0.01-3	0.75-10
Head loss by screen (m) [4]	0.3-0.8	approx. 2.0	0.1-0.3	0 (type C)- 0.25 (type B/D)
Dimensions (lxwxh in m)				
- minimum capacity	2.36x1.04x0.84	0.95x0.95x1.94	0.66x0.67x0.79	0.85x0.83x0.68
- maximum capacity	6.29x2.72x2.55	2.15x0.95x2.12	3.90x2.36x2.25	5.46x2.1x2.2
Rinse water flow (m^3/h)	± 2 (at 3 bar)	not applicable	0.7-7.6 (at 8 bar)	not applicable

1) depending on filter mesh

2) *mainly used for domestic wastewater*

3) depending on filter mesh and SS concentration: in this case intake water with < 10 mg SS/l and 60 µm filter mesh

4) effective head loss at the screen (difference between inflow and outflow level), the required head loss in a design will be higher and depends on the system configuration and the location of the screen

6.2 Influence of filter mesh

The filter mesh is an important design parameter which determines the suspended solids particle fraction which will be removed. The smaller the filter mesh, the higher the removal efficiency for suspended solids achieved.

However, also the working principle of the pre-treatment installation has an influence on the removal of solids: for example the inside of the drum filter was slowly covered by a sludge layer, resulting in a better filtration behaviour due to an artificially obtained finer filter pre-coat. This was caused by the discontinuous rinsing procedure of this screen.

On the other hand, a smaller filter mesh results in a decrease in the hydraulic flow capacity for the same size of installation.

During the test with pre-treatment installations, all MBR installations showed no problems with clogged or damaged membranes. Based on this, one can conclude that a screen with a filter mesh ≤ 0.75 mm should be sufficient to protect the membranes.

For some of the membrane systems, the optimal filter mesh may be larger, due to the membrane configuration and characteristics. Based on the test results it is not possible to draw further conclusions on this subject.
A much smaller (effective) filter mesh results in a (much) higher removal of SS and COD. The latter can just be disadvantageous for the de-nitrification process.

6.3 Use of pre-sedimentation

Pre-sedimentation, of course, has a large influence on the removal of COD and SS. During phase 3, the effluent of the pre-sedimentation tank has still been analysed, in spite of the fact that 'raw' wastewater was used as feed for the MBR installations.
Based on the results in this phase, it can be concluded that pre-sedimentation results in a higher removal efficiency for COD and SS than any of the tested screens. However one can not compare pre-sedimentation with screening when the aim is predominately the protection of membranes. The main function of pre-sedimentation is the removal of these compounds to diminish the organic load to the biological waste water treatment system.

Before the pre-treatment installations were installed, basket filters (1-3 mm) were applied in the feed line and pre-sedimented waste water was used as feed for the MBR installations. The cleaning frequency of the basket filters was high, especially at rain weather flow. If the cleaning procedure was neglected, the MBR feed pump shut down due to a (too) high pressure drop in the feed line. Of course, one must prevent this situation.

In case of no pre-sedimentation, a pre-treatment installation before a MBR system is definitely necessary. Clear indications for that are the huge increase of retained screenings in the case of 'raw' waste water. Also the fact that an off-site cleaning of the membranes of the X-Flow MBR turned out to be necessary after accidentally switching off the rinse water system necessitated the use of a fine screen.

6.4 Redundancy

A fine screen must be designed on the (maximum) rain weather flow entering the MBR system. At rain weather conditions the amount of screenings is high, especially after a (long) dry period. This is caused by the release of suspended solids from the interior wall of the sewers.
At dry weather flow conditions, one can consider:

- redundancy of operation one of more screens (if more than one screen is installed);
- slowly re-circulating the contents of the MBR system over the screens which can be put out of operation.

  Even if a fine screen is installed before a MBR system, it is possible that (fine) solids which pass the screen can agglomerate to larger particles in the MBR system. It is likely that these agglomerates are situated at the bottom of a MBR system and difficult to discharge. To prevent accumulation of these particles, re-circulation of the contents of the MBR system can be considered. Of course this is only possible if the 'normal' sludge flocs can pass the screen unhindered.

6.5 Energy consumption

The energy consumption for a pre-treatment installation is at least ascribed to the power of the motor for:

- vibrating of the screen (vibrating static screen);
- (dis)continuous rotation of the drum (drum-filter, wedge-wire screen) or rotation of brushes (brush raked screen);
- rinse water/spray system (drum-filter, wedge-wire screen).

The specific energy consumption for the motor can be calculated from table 10 and is very low: < 1 Wh/m^3 wastewater. The specific energy consumption for temporary rinsing is very low and therefore neglected.

The required pressure head to pass the screen is the sum of the required height to transport the water to the inlet of the screen and to overcome the resistance of the screen. Most screens have a very low resistance and theoretically these can be operated with wastewater which is transported at free decay (of course, if the available water height is sufficient to reach the inlet of the screen).

The energy consumption for a feed pump (if necessary) can be calculated by:

$$\mathbf{P\ (in\ W) = Q * (\rho \times g \times h)/\eta}$$

Example:
For a pump capacity of 1,000 m^3/h (Q) and a head (h) of 3 m (assumption), the energy consumption equals: (1,000/3,600) x 1,000 (ρ) x 9.81 (g) x 3 /0.7 (η) = 11.7 kWh = 11.7 W/m^3.

So, the total specific energy consumption is calculated at <15 W/m^3 which is relatively low, taken into account the specific energy consumption for the MBR installation itself (typically ≤ 1 kWh/m^3).

6.6 Treatment of screenings

The retained screenings are normally compressed in order to reduce the volume to be discharged. Based on the results of the compression tests, a dry solids content of about 40% can be reached.

For treatment of these screenings, one can consider:

- combined treatment with the coarse screenings, originating from a coarse grid installation. Of course the capacity must be adequate to handle the total quantity;
- separate treatment of the screenings. For the fine (organic) screenings digestion or incineration might be considered.

The characteristics of a combined treatment will be:

- the grid from a coarse screen (mainly plastics, papers, rags, sanitary towels) are treated together with fine screenings (mainly organic materials). Likely this will affect the compression behaviour of the combined solids. This is not investigated during this research;
- based on the measured SS removal efficiencies of the fine screens and of the coarse grid, the combined solids will primarily be of organic nature. However the presence of inorganic material (from the coarse grid) may restrict certain waste disposal routes.

7 EVALUATION AND RECOMMENDATIONS

7.1 Evaluation

During four months, four different screens were tested which were used as a pre-treatment for the MBR installations. The screens differ in working (filtration) principle and filter mesh; a vibrating static screen (0.75 mm), a rotating brush raked screen (0.75 mm), a drum-filter (0.5 mm) and a rotary wedge-wire screen (0.25 mm, in operation from 29 January) have been applied. Based on a short literature survey this was a representative selection of type of screens and filter mesh used in MBR systems.

The screens were located just before the MBR installation. During the test period two phases could be distinguished:

- phase 2 (until 10 January): feed for the pre-treatment installations was wastewater which has passed a coarse (7.2 mm) grid installation and primary sedimentation tanks;
- phase 3 (from 12 January): feed for the pre-treatment installations was 'raw' water which only has passed a coarse (7.2 mm) grid installation.

Time-proportional water samples were taken before and after the screen to establish removal efficiencies for COD, SS, mineral oils and fats.

The retained screenings were collected, weighed and analysed for dry solids content, ash content, hair content, mineral oils and fats. The screenings were compressed in a small filter press, in order to determine the density and dry solids content after compression.

Retained compounds

Established removal efficiencies for the water compounds are included in table 11. The data in phase 2 were rather limited and are therefore not included.

Table 11 - Removal efficiencies water analysis (phase 3)

	rotary wedgewire screen	vibrating static screen	drumfilter	rotating brush raked screen	presedimentation
Filter mesh	0.25 mm	0.75 mm	0.5 mm	0.75 mm	-
COD	13%	12%	29%	9%	39%
SS	28%	44%	63%	20%	69%
Fats	28%	42%	58%	24%	37%
Mineral Oils	76%	68%	49%	56%	36%

From the research, it can be concluded that:

- dependant on the type of screen, a significant part of SS, COD, fats and oils was removed;
- not only the used filter mesh has an influence on the removal effiency, but also the working principle of the pre-treatment installation. For example the inside of the drum filter was slowly covered by a sludge layer, resulting in a better filtration behaviour due to an artificial obtained finer filter medium (pre-coat). This was caused by the discontinuous rinse procedure of this screen.

  The removal efficiencies seems to be more or less correlated to the effective filter medium (except for mineral oils).
- pre-sedimentation was very efficient in removing particularly SS and COD. In the case of pre-sedimentation followed by (fine) screening (phase 2), the SS and COD concentrations were only slightly further reduced by the screens.

The results of the tests and analysis of the screenings for both phases are included in table 12.

Table 12 - Screenings (phase 3, and phase 2 between brackets, if data available)

	rotary wedge-wire screen	vibrating static screen	drum-filter	rotating brush raked screen
Filter mesh	0.25 mm [2]	0.75 mm	0.5 mm	0.75 mm
retained screenings (g ds/m^3)	34 (0.3)	14	94 (2.8)	23
dry solids content (%)	8.4	12.7 (10.1)	1.1 (0.7)	4.0 [1] (11.7)
ash content (% of ds)	17	17 (15)	28 (31)	16 (17)
hair in screenings [3] (qualitative)	++	+++	---	++
ds after compression (%)	43.2	43.4 (28.7)	34.2 (18.0)	39.7 (25.3)
density filter cake (kg/m^3)	1.04	1.03	0.95 (1.07)	0.93 (1.04)
Fats (mg/kg ds)	60,000	77,000 (180,000)	115,000 (210,000)	84,000 (125,000)
Oils (mg/kg ds)	4,000 (-)	4,000 (8,600)	- (8,600)	- (8,000)

1) 13.2 % ds (12/01-23/01), 1.4% ds (23/01-14/03): mixture of screenings and water

2) after using a 1.0 mm filter mesh these average values were obtained: 4.1 g ds/m^3; 14.2% ds; 13.9% ash

3) - = less hair, + more hair (relatively compared to the other screens)

The drum-filter retained the highest amount of fats and solids, the latter also corresponded to the highest removal efficiency of SS. The specific amount of retained screenings enormously increased after treating 'raw' wastewater in place of pre-sedimented wastewater.

The quantity of retained screenings was drastically reduced when the 0.25 mm drum of the wedge-wire screen was replaced by a drum with a filter mesh of 1.0 mm.

Visually the composition of the screenings of the wedge-wire screen, the vibrating static screen and the rotating brush raked screen were comparable: coarse organic material (leaves, seeds) and hairs were present. Also the dry solids content of the retained screenings and the ash content were almost the same.

The retained screenings of the drum-filter appeared different: a sludge (clay) like structure, while no coarse organic materials and hairs were noticed. This visual difference was confirmed by a much higher ash content of the retained screenings, indicating that relatively a lot of primary sludge is retained.

There was no plausible explanation for the difference in composition and behaviour of the screenings from the drum filter compared to the other three types.

The compression behaviour of these screenings was also different compared to the other three types: the dry solids content for the drum-filter screenings was significantly lower compared to the other screens. The retained screenings were more easily compressed in the case where 'raw' wastewater was used as the feed source.

Operation and maintenance

All screens operated automatically and did not require special attention for a normal operation. On 19 January the rinse water system of the drum-filter was switched off by accident. This resulted in unfiltered wastewater entering the MBR system. After three days the MBR system was automatically put out of operation due to clogging of the membranes. An extensive off-site cleaning of the membranes turned out to be necessary: a well-functioning pre-treatment is essential for an undisturbed operation of the MBR.

During three months the screens also did not require extensive maintenance. The vibrating static screen sometimes had to be cleaned by powerful brushing to prevent severe clogging of the filter openings. A few times, the inside of the drum-filter had to be cleaned to remove accumulated screenings. It is likely that a more frequent or extended rinse procedure of the drum will prevent this situation. The inside of wedge-wire screen had to be cleaned two times; solids were accumulating in and at the top of the header box. The rotating brush raked screen with rotating brush did not require any maintenance at all.

Energy consumption

The energy consumption for a pre-treatment installation was solely due to the power of the motor for cleaning/vibrating of the screen or for (dis)continuous rotation of the drum/brushes.

The required pressure head to pass the screen is the sum of the required height to transport the water to the inlet of the screen and to overcome the resistance of the screen. Most screens have a very low resistance and theoretically these can be operated with wastewater which is transported under free fall.
The total specific energy consumption for a screen was estimated at <15 W/m^3 which is relatively low, taken into account the specific energy consumption for the MBR installation itself (typically around 1 kWh/m^3).

7.2 Recommendations

Based on the research the following recommendations can be derived.

Use of fine screen

In case 'raw'waste water is used as feed for a MBR installation, a fine screen is definitely necessary. If pre-sedimented waste water is used one can consider not to use screens, but small baskets filters before the MBR installation. In this case one must account with much more attention for maintenance due to rapid clogging of these filters. A too high pressure drop in the feed line will switch off the feed pump of the MBR system.
The fine screen type to be used depends on the size of the treatment plant, the waste water characteristics and the required efficiency. Based on the results and experiences presented in this report the system choice can be made.

Filter mesh

During the test with pre-treatment installations, all MBR installations yielded no problems (under normal circumstances) with clogged or damaged membranes. Based on this, one can conclude that a screen with a filter mesh ≤ 0.75 mm should be sufficient to protect the membranes. The optimal filter mesh may differ for each membrane system.
Some screens obtained an artificially much finer filter mesh by the building up of a sludge layer (pre-coat) at the inside of a drum or by partially clogging of the filter openings. This may result in a higher removal of SS and COD by retaining also primary sludge in stead of only coarse materials. This can just be disadvantageous for the de-nitrification process.

Redundancy

A fine screen must be designed on the (maximum) rain weather flow entering the MBR system. At rain weather conditions, the amount of screenings is high, especially after a (long) dry period.

At dry weather flow conditions, one can consider:

- redundant operation one of more screens (if more than one screen is installed);
- slowly re-circulate the contents of the MBR system over the screens which can be put out of operation.

With the second option, these particles are retained, which in first instance have passed the fine screen and which have agglomerated to larger particles in the MBR system. This prevents an accumulation of (large) solids in the MBR.

Further research

At Beverwijk wwtp a coarse (7.2 mm) screen is used as a first mechanical treatment, followed by pre-sedimentation. Pre-sedimentation is very effective in the removal of (suspended) solids and COD. Nevertheless, some coarse materials pass the sedimentation tanks and are (partially) retained by basket filters (which differ in filter mesh from 1-3 mm). This necessitates a very frequent time-consuming cleaning procedure of these filters.

This suggests a process configuration where (only) a medium fine screen (2-3 mm) is used as a first treatment step in stead of coarse screening, followed by pre-sedimentation before the water enters the MBR system. Covering of pre-sedimentation tanks will prevent intake of light (organic) material (like leaves and seeds). In that case it may not necessary to include coarse screens in the design of a new wwtp.

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stowa

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Development MBR technology for large wwtp's

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1 INTRODUCTION

1.1 The project

Since April 2000 four MBR pilot systems have been in operation at the Beverwijk WWTP. The goal of the research was to investigate the technical feasibility of the MBR system and to compare the four systems.

In the main STOWA report the experiences with the MBR pilot systems are described. Especially the biological performances and the membrane performances are mentioned for each system. Alongside the main report five more fundamental side studies were carried out.

The five side studies are described and summarised in the main report. The subjects of these side studies were:

1. Pre-treatment
2. Fouling and cleaning
3. α - factor
4. Effluent quality
5. Sludge dewatering

This report describes the investigation of the fouling and cleaning of MBR systems (side study 2).

1.2 Side study: Fouling and cleaning

MBR technology has several advantages compared to traditional activated sludge processes, e.g. high effluent quality, limited space requirements and modular set up. However, one of the main disadvantages is the necessity to routinely clean the membranes. Cleaning of the membranes, irrespective of the procedure used has a knock on effect to the membrane life-expectancy and there after operational replacement costs. Additionally the chemical usage required for cleaning purposes impacts a toxic shock on the biological system, as well as a concentrated corrosive shock for the membrane material of construction.

It was of tantamount importance to undertake an investigation into the mechanics behind the membrane operation, the types of fouling that can promote membrane performance decline, and methods to clean the membranes in the most optimal manner, both from an environmental and economical point of view. Once investigated an optimised operating window could be defined for all relevant circumstances involved with MBR membrane operation [ref. 3].

Fouling within MBR systems applicable to the treatment of municipal wastewater is a complex phenomenon, mainly due to the problematic and variable composition of the raw wastewater and the suspension requiring filtration. The biological suspension (activated sludge) not only contains biological flocs, formed by the conglomeration of micro-organisms within a floc matrix, but also a whole range of soluble, insoluble and colloidal compounds, either bought in by the influent to be treated or resulting from bacterial metabolism [ref. 2].

The above problem definition suggested that the fouling of a membrane within the MBR would be difficult to compare with the typical fouling seen in other membrane applications. The water-sludge mixture within the MBR as well as the numerous by-products of biological oxidation and precipitation reactions could conspire to decrease membrane filtration efficiency and thus define the limitations of the MBR technology. The configuration of the membranes and their materials of construction would also play a major role in defining the type of fouling and cleaning mechanisms, as well as chemical selection and applied cleaning procedures. Not only the membrane characteristics, but also the location of the membranes in the biological process would yield minor localised changes in the sludge quality that could facilitate accelerated fouling and permeability decline.

The above paragraphs have enlightened the reader about the immense depth and diversity of membrane fouling, the causes, and the cures. Where the theory falters is in the real practical experience. At wwtp Beverwijk the possibility to research working MBR systems from several suppliers all open to achieving the optimal performance was available. In collaboration with several external bodies, this, the most important aspect of MBR - Fouling and Cleaning could be adequately studied and reported.

In simple terms the objective of this side study was to bring the fouling and cleaning methodology under control within defined safe operational parameters. The pilots were already protected against hair, debris and coarse material, which are known to be detrimental to membrane integrity. As the latter had been documented on numerous full scale installation. This in mind, the pre-treatment to the installations was also studied under side study 1. It was important to this study item that the most common cause of membrane performance deterioration be categorically eliminated. The only fouling permitted within the MBR configurations was that related to the biological process and the permeate extraction. This basis was the foundation to develop optimised operating criteria.

Other important aspects of this side study were to:

1. investigate the leading fouling mechanisms in MBR applications in theory and practice
2. investigate cleaning mechanisms in theory and practice
3. compare and evaluate the four different systems towards fouling and cleaning
4. investigate the most relevant design, operational and cleaning parameters
5. define further investigations into fouling and cleaning

1.3 Reader

In chapter 2 the set up of the study (Fouling and cleaning in MBR systems) is defined. In chapter 3, firstly the theory of fouling is discussed followed by the practical experiences based on the pilot test at WWTP Beverwijk.

Chapter 4 describes the theory of cleaning linked to brainstorming sessions with the suppliers. In chapter 5 an operating window (guidelines) for the operation of the different MBR systems and the cleaning of the systems is suggested.

In chapter 6 the main conclusions are drawn and recommendations are given. Also topics for further investigation are stated.

2 SET UP OF SIDE STUDY

2.1 *Organisation of side study*

From section 1, it was clear that this side study would require utmost commitment from all involved parties. This extended to the protection of very sensitive supplier information regarding membrane structure, morphology, and possible manufacture. Due to the sensitive nature of the resultant information, this project was split into three sub-categories:

1. Fouling - Carried out by TNO
2. Cleaning - Carried out by the respective suppliers
3. Practice/Operation - DHV

The communication links were structured according to the diagram below, as to protect sensitive supplier information.

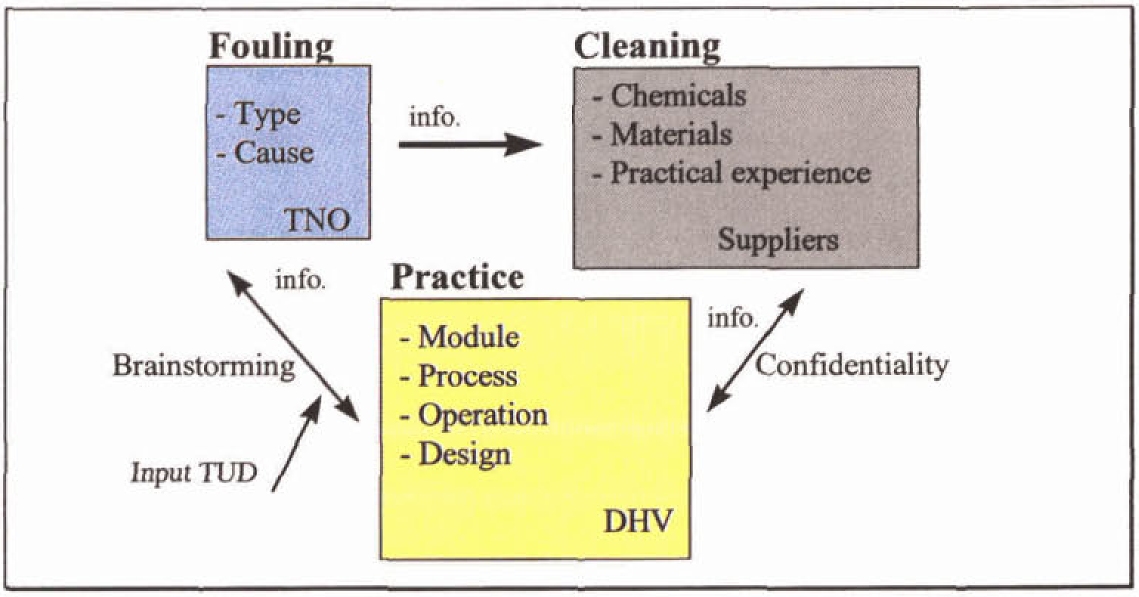

Figure 1 - Three main pillars of side study 'Fouling and Cleaning'

For each category several organisations were used, namely TNO-MEP, Delft University of Technology (TUD), University of Aachen, DHV and all suppliers and their representatives.

2.2 Fouling

The difficulty in defining membrane fouling can be investigated by ascertaining which type of fouling is taking place on the various membrane types and module configurations. This study item was carried out by TNO-MEP in discussion with DHV. The study included membrane autopsy utilising various microscopic, scanning techniques and cleaning tests of membrane samples taken before and after cleaning of the membranes. This study required permission from each supplier, due to the delicate nature of the autopsy. Three suppliers agreed to the specified proposal, and Mitsubishi repeated and extrapolated the study in Japan on their own accord to confirm the results. Zenon opted to carry out the autopsy using The University of Aachen, Germany.

In a number of brainstorming sessions between DHV and TNO-MEP, DHV and Mitsubishi, and DHV and Zenon the results of the autopsy and the cleaning tests were presented. The goal of these sessions was to define the main principles of fouling for specific membranes in specific MBR systems, and define cleaning procedures to maintain high levels of permeability under all operational circumstances.

2.3 Cleaning

The possibility to clean membranes is largely dependent on the membranes material resistance to potential cleaning chemicals and the membrane location/orientation in the module itself. In several meetings with the suppliers and their representatives the fouling experiences of the suppliers and their eventual cleaning procedures were discussed openly. Based on these discussions, guidelines were drawn up to improve operation of the various pilots at wwtp Beverwijk.

The membrane suppliers had several options regarding so called standard cleaning procedures and were often executed automatically as part of the pilots software or as a manually controlled procedure. To summaries the various ideas regarding cleaning a list was drawn up, and all suppliers fell into a number of the categories or combinations of the categories (See section 4.2.1 Cleaning Theory - Types of cleaning).

At the onset of the pilot study the pilots were cleaned as and when required, according to basic cleaning procedures specified by the supplier. These procedures were based on previous experiences with MBRs in municipal and industrial wastewaters.

2.4 Operational experience

Through the practical experience obtained on the four MBR pilot installation at wwtp Beverwijk it became clear that not only the operational aspects of the membranes themselves, but also the biological configuration and biological performance played a major role in the overall membrane system performance regarding fouling. The results from side study 1 and 2 were combined to formulate a 'safe feed' regime, suitable to protect the membranes from 'coarse fouling', the finding were coupled with the brainstorming sessions to better enhance the fouling and cleaning results. From the brainstorming sessions it was expected that:

- the complete relationship between what causes fouling and how to subsequently clean the membranes would come to light. Thereafter, based on the results, the pilot installations would be run in such a way as to re-enforce these findings. The latter would extend into a follow up research programme (phase 2 of side study 2).
- the formulation of short and long term R&D, where on one hand important questions regarding risk for full scale wwtp could be answered, and on the other hand, where fundamental research could be driven on the longer term.

Alongside the brainstorming sessions separate discussions were held with the suppliers in order to feedback the findings. The results of these findings could then be used to help further develop the membrane or module configuration itself. Thus producing a better product suitable for the municipal wastewater market as a whole. The latter required utmost commitment from all parties as it involved the delicate matter of membrane/module optimisation for the MBR market. The latter was also taken in consideration for the necessary cleaning requirements of the membrane which too, could be enhanced and optimised.

3 FOULING

3.1 Introduction

This chapter describes the theoretical mechanisms regarding membrane fouling. Thereafter the main results of the investigation by TNO are presented and finally the results and mechanisms are prioritised according to the findings at wwtp Beverwijk.

3.2 Fouling theory

A major limiting factor in the utilisation of membrane technology is the fouling of the membrane. Fouling manifests itself as a decline in permeability and higher Trans-membrane Pressures (TMP).

However, a lower permeability is not necessarily caused by fouling. Other causes could be:

- Changes in membrane properties during operation. These can occur as a result of physical or chemical deterioration of the membrane.
- Changes in feed properties, e.g. viscosity, or concentration of suspended solids.

As a basic rule, membrane fouling is caused by the deposition and accumulation of feed components on the membrane surface and/or within the pores of the membrane. Almost all feed components will foul the membranes to a certain extent.

The photographs used in this paragraph are only for illustration. A relation between the membrane type and the fouling type is not intended. Not all photos are from Beverwijk.

3.2.1 Mechanisms of fouling

In common, six fouling mechanisms can occur in MBR micro- and ultra-filtration applications, and can be split into two sub-categories of micro-fouling and macro-fouling:

Micro-fouling	Macro-fouling
1. Scaling 2. Bio-fouling 3. Organic fouling/adsorption 4. Pore blocking	5. Cake formation on the membrane surface 6. Feed debris, grease balls, plastic, hair, paper, etc

1. Micro - Scaling

Scaling is predominately the precipitation of inorganic salt crystals on the membrane surface and/or inside the pores of the membrane. Precipitation can only occur when the solubility index for a certain salt is exceeded or an active precipitation site is present.

The salt concentration is the highest near the membrane surface due to the de-watering (permeate production) of the concentrate stream adjacent to the membrane, in this hypothetical layer concentration polarisation occurs thus promoting potential scaling in this layer.

Figure 2 - Extreme Calcium Carbonate (chalk) scaling in an industrial MBR

Scaling is commonly a fouling mechanism in nano-filtration and reverse osmosis systems, because in these systems the salts are rejected by the membrane and as a result rapidly concentrated to saturation levels.

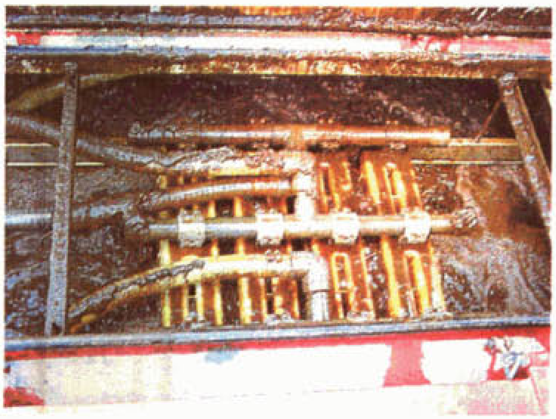

Figure 3 - An industrial MBR where chalk scaling predominates and is controlled

In micro- and ultra-filtration applications however, this rejection of salts is vastly reduced or limited to some divalent salts, heavy metals or complexes, or where the feed water is supersaturated itself. For example calcium, and magnesium salt scaling in MBR applications is quite common.

In MBR applications with simultaneous precipitation of phosphate with iron, there arises the possibility that iron-salts could be precipitated on or in the membrane surface.

Not only the membranes are at risk for scaling, but all process equipement and tankage faces similar problems.

2. Micro - Biofouling

Membrane performance can be negatively influenced by the formation of a bio-film on the surface of the membrane, the pores are effectively blocked, thus reducing the available filtration area of the membrane. A bio-film is a deposition of bacteria and extracellular polymeric substances (EPS) on or in the membrane surface. The bacteria can also excrete so-called Soluble Microbial Products (SMP) and enzymes which can have a similar effect as EPS. These products and their interactions on the biological system are defined in more detail in Side study 3.

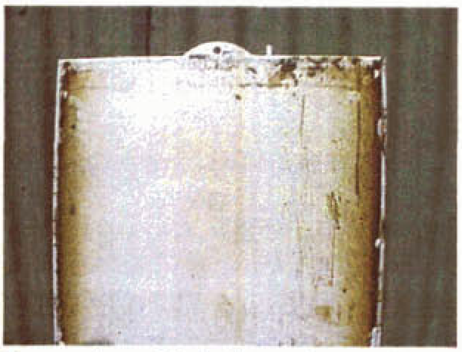

Figure 4 - Bio-fouling after software problems occurred in a Beverwijk Pilot

All the bio-film components are usually long molecules or complexes associated with the bacterial floc. These long chains or filaments can spread over the membrane surface or even penetrate the pores themselves. The resultant effect is the blocking of the filtration area, either by spreading over the membrane surface as a slime or by plugging the pore directly.

Figure 5 - Bio-fouling at microscopic level

3. Micro - Organic fouling/adsorption

Adsorption of organic matter is another known fouling mechanism. Sludge-membrane interactions that result in a physical adsorption of the solute by the membrane, whether on the surface or in the pores, will obviously cause a serious decrease of the membrane permeability as the membrane integrity is directly effected. The organic matter is difficult to remove from the membrane material and often leads to irreversible fouling of the membrane.

Since most modern membranes are single or combinations of organic polymers they are open to attack from other more aggressive organic molecules or solvents. When in the water or aqueous phase the solvents or organic molecules are rendered inert and have little effect on the membrane. If however these molecules are allowed to re-solute and effectively become free organics or solvents they can impinge serious damage on the membrane integrity. Such free solvents or organics (which are rarely found in municipal wastewater), could be ketones, Methyl Chloride, Benzene, oil-based solvents, and certain plastic or poly-electrolyte monomers.
Electron micro-graphs of this type of fouling show the surface of the membrane as being denatured or attacked. The fine pore configuration appears vague and smeared out as a sort of fixed slime across some of the membrane surface. The above should be compared to the new membrane. Both photos are at x 5000 magnification and originate from DHV archives.

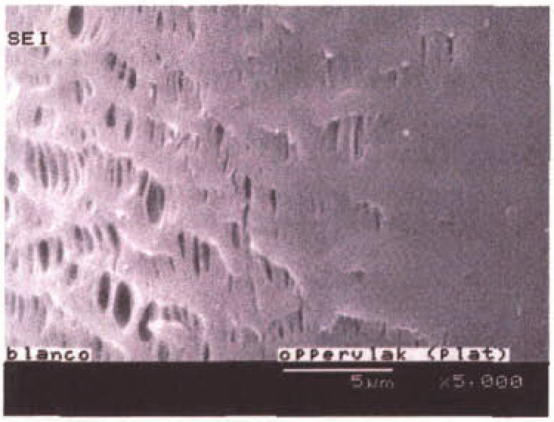

Figure 6 - Membrane with organic fouling

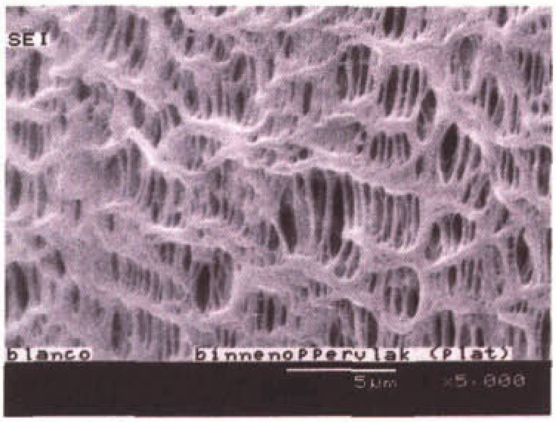

Figure 7 - New membrane

4. Micro - Pore blocking

This type of membrane fouling is actually self-explanatory. Micro- and ultra-filtration membranes have pores which can be seen under a low resolution microscope. Fine particles in the feed water in contact with the membranes can block the pores of the membranes and thus decrease the permeability. Pore blocking is often enhanced by organic fouling or scaling. Some references material suggested that fine powdered activated carbon could cause irreversible pore blocking, but was not investigated under the microscope.

5. Macro - Cake formation

The formation of a cake on the membrane surface is in many cases the most important fouling mechanism in micro- and ultra-filtration applications. In literature cake formation is commonly or mistakenly described as concentration polarisation. Cake formation occurs when hydrocolloids, macromolecules (such as proteins) and other relatively large solutes or particles are filtered. Several studies into MBR fouling indicate the predominant contribution of suspended solids and colloidal particles to membrane fouling [ref. 5, 7].

Figure 8 - Sludge on the membranes

In principle a porous cake is formed on the membrane's surface. The water must pass the cake before it can pass the membrane. If the applied pressure is too high the cake will be squashed thus increasing the resistance to water flow and thereafter a decrease in measured membrane permeability. Too achieve the required permeate flow the applied pressure must increase thus accelerating the cafe formation process.

The permeability of the cake/membrane will also decrease if too much material is transported to the membrane surface and the cake becomes too thick, therefore generating a higher resistance to water passage. In extreme cases sludging will occur.

The cake formed has a certain resistance to flow known as the trans- cake pressure (TCP) which is often much higher than the membrane's own resistance, the trans-membrane pressure (TMP). For those systems equipped with back washing procedures, if the permeability during back washing appears higher than during filtration, it is evident that cake filtration is the most important fouling mechanism. Systems utilising relaxation procedures can observe similar effects on membrane permeability if the relaxation time is too short between process modes - here the permeability will be seen to drop, rather than recover

Figure 9 - Sludge on the membranes due to an operational error

6. Macro - Debris collection

On some small scale industrial and municipal wastewater treatment plants the effect of debris build-up in the module is accepted as a fact of life and as a result is routinely removed. On several larger scale municipal treatment works the effect of debris has led to problems regarding throughput and eventual membrane damage.

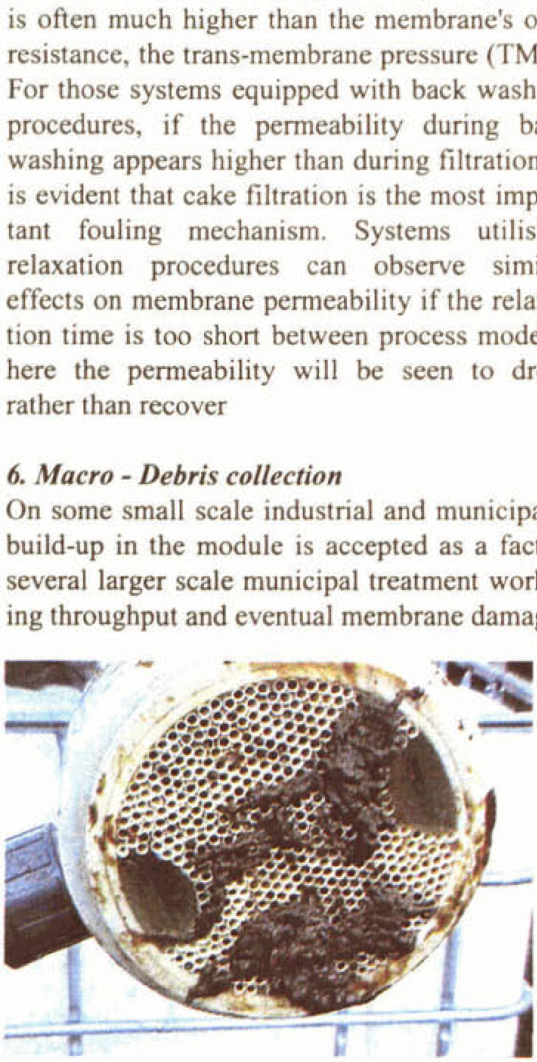

Figure 10 - Debris on the membranes

he effect of coarse debris on all membranes is uite devastating. In some cases the only course f action is to replace the module.

n principle coarse debris is simple to remove rom the wastewater stream, but in a treatment rocess such as for municipal wastewater all the rganic components are required in the feed tream to achieve the final effluent quality equirements. Based on this fact a fine screen uitable to remove debris would also remove aluable organic components as well.

In Japan several installations run with fine screens of 1mm. These screens work well at removing larger items, including fibrous material, but in the long term they still allow super fine fibres to pass into the MBR. These fine fibres recombine in the MBR and eventually get lodged between the membrane fibres. The latter is currently a problem more specific to Japan due to the type of clothes that are worn (a high percentage of man-made fibres).

Figure 11 - Fine fibres on the membranes

Figure 12 - Debris fouling

Despite the fundamental concern for this type of macro-fouling. It actually has relatively little effect on the filtration process itself.
However, the debris can cause localised restriction in membrane movement or air flow, thus allowing secondary fouling to occur. This fouling which has already been described above as micro and macro fouling numbers 1 through 5 will then predominate and accelerate.

If the feed streams are not correctly screened or the screen capacity is under-dimensioned serious problems will occur.

As already mentioned the debris can be easily removed, but here, the interaction with a manual procedure carried out by a man in direct contact with the membrane material asks for problems. These problems occur by short cutting the correct procedures. If a module fouls due to debris it is considered a calamity by the operators, who, under pressure to return the modules back to process mode, rush through the de-sludging procedure. These procedures are extreme and must be used with caution. Over-dosing of chemicals or the use of high pressure jet cleaners is faster, but unfortunately can destroy the membrane.

Side study 1 was used to test four separate fine screens suitable for scaling up to >1000 m3/hr flows. The goal of the study was to absolutely eliminate the possibility of debris from entering the MBR systems. This was achieved adequately (not reported here) and yielded a wastewater stream free of debris. The latter promoted a better working environment for the membranes and any fouling that took place would be associated to the primary 5 micro- and macro- fouling principles.

3.2.2 Factors affecting fouling

The nature and extent of membrane fouling is strongly influenced by the following factors:

1. The physical-chemical nature of the membrane
2. The physical-chemical nature of the solute
3. The configuration of the system and aeration

1. Membrane properties

The selection of membrane material should be not only based upon the desired permeate quality, but should also take into account the fouling characteristics of the membranes. The most important characteristics of the membrane affecting the fouling behaviour are discussed here.

Hydrophilic characteristics of membrane material

The hydrophilic characteristics of a material indicate to what extent a material is water attracting. In general a material is characterised as hydrophilic when it is compatible with or preferentially interacts with water, or as hydrophobic when it is incompatible with and cannot interact with water. One of the methods to measure the relative hydrophilic characteristics is to measure the contact angle of a water drop with the membrane surface (the smaller the angle suggests a more hydrophilic membrane) [ref. 8]. In Table 1 the hydrophilic characteristics of the most commonly used membrane materials are presented.

Table 1 - Hydrophilic characteristics of membrane materials

Hydrophobic	Hydrophilic
Polytetrafluorethylene (PFTE)	Cellulose esters
Polyvinylidene fluoride (PVDF)	Poly carbonate (PC)
Polypropylene (PP)	Polysulfone / polyethersulfone (PSF / PES)
Polyethylene (PE)	Polyimide / polyetherimide (PI / PEI)
	Aliphaticpolyamide (PA)
	Polyether etherketone (PEEK)

With aqueous feed streams, the ideal membrane should be hydrophilic. If the material is hydrophobic, it would adsorb components that are hydrophobic or amphoteric in nature, resulting in fouling. For example, many proteins have hydrophobic regions within their structure that can interact strongly with hydrophobic materials [ref. 8].

In literature the hydrophilic characteristics of the membrane is mentioned as a "key-factor" [ref. 5] in fouling of membranes in MBR applications.

Surface topography

The roughness of the surface of the membrane material is also of importance. In general, a smooth, homogenous membrane surface will have less fouling tendency than a rough, heterogeneous membrane. For example: polyamide thin-film composite membranes (PA) are more fouling sensitive than cellulose acetate membranes (CA), because of the protuberances on the surface, which can act as hooks for suspended matter [ref. 8].

Charge of the membrane

Most membranes have a net negative charge under normal process conditions. The charge on the membrane becomes important if charged particles are being filtered. For example, non or inefficiently aerated sludge can have a neutral or positive charge due to the onset of reduction reactions, whereas well aerated sludge is negatively charged due to the predominant oxidation reactions. A simple comparison can be made here by attempting to filter de-nitrification (anoxic) or anaerobic sludge through the same membrane as used in the aerated biology. The permeate flux may be a factor ten lower than under the optimal conditions.

In the case of simultaneous phosphorus removal flocculent such as Fe^{2+} and Al^{3+} are dosed to the bioreactor system, these ions are positively charged and could be attracted by the membrane surface and thereafter cause fouling.

Pore size

The relative pore size in relation with the size of the particles in the feed is very important. If the size of the particles are in the same range as the size of the pores, pore blocking can occur. In general it can be stated that although membranes with larger pores has a much higher clean water flux (less pressure drop in the pores), the operating flux can be much lower compared to the operating flux of a membrane with smaller pores because of the fouling (pore blocking) on the membrane.

Surface modification

A membrane surface can be modified to become more hydrophilic. This modification should be taken into account when fouling is related to the hydrophilicity of the membrane material. It should be noted that surface modified membranes may not be as tolerant to aggressive chemicals as the unmodified membranes.

2. Solute properties

The properties of the solution which influence fouling can be distinguished as: Sludge and water phase. These are closely related with the operation of the Bioreactor. In Side study 3 a description is given of biological aspects in relation to α-factor. In side study 3 a closer investigation is made of factors that influence the make-up of sludge and the various components present in the water phase.

In this side study only the main contributors are mentioned.

Sludge

The sludge flocs do not normally interact with the membrane. In this case the only fouling mechanism that may occur is cake filtration. The presence and the composition of the cake is mainly influenced by the floc size. In general: Larger flocs are less easily transported to the membrane surface and more easily back-transported to the main stream compared to smaller flocs.

In literature [ref. 5, 7] it is suggested that ideal sludge flocs are comfortable at a discreet size of 80 - 200 μm, whereas a bulky sludge is not desired due to the presence of Extra Polymeric Substances (EPS) and filamentous bacterial strains. Due to the presence of filamentous bacteria in bulky sludge the cake formed has a smaller porosity and therefore a higher cake resistance. However, when filamentous bacteria are present in an acclimatised sludge, caused by natural selection and related to the nutrients in the feed water, the filaments can be used to form larger flocs which is advantageous for the sludge filterability.

The appearance of EPS is reported to be responsible for dramatic flux/permeability declines in membrane systems [ref. 6, 4].

The extra-cellular matrix is suggested to effect the cake resistance by filling the pores in the cake, but on the other hand EPS can also interact directly with hydrophobic membrane surfaces, the result is the same.

It has been noted that foaming sludge with a high percentage of EPS can render a stronger adherence of floc particles to one another as well as to the membrane surface itself.

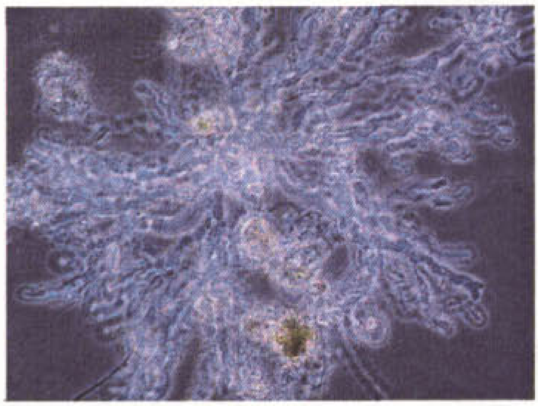

Figure 13 - Sludge containing EPS

Water phase

Besides the suspended solids, dissolved solids (e.g. salts) can be deposited on the membrane surface or in the membrane pores when super saturation is reached (scaling). Super saturation can be reached when pH is raised, or when the temperature changes.

Also organic matter in the feed water can cause fouling of the membrane by adsorption. Most commonly seen is the adsorption of humic acids. The latter is seen in the lower fluxes achieved in some leachate MBR installations as compared to municipal wastewater MBRs. Landfill leachate contains high inert COD fractions composed mainly of humic acid derivatives, these components are partial adsorbed by the membrane and as a result reduce the systems permeability. Here the balance between adsorption and de-sorption via cleaning is critical.

3. Configuration

In addition to the complicated physical-chemical interactions of feed components, process parameters such as temperature, hydrodynamics, pressure and overall equipment design have a great influence on membrane fouling.

Temperature

The effect of temperature on fouling is not too clear. In general a rise in temperature will result in a higher flux (lower viscosity). However, it could also result in a decrease in flux for feeds with high concentrations of salts e.g. calcium phosphate (solubility decreases with temperature increase). It is well known that the biological activity decreases by a factor of two for every 10°C decrease in temperature, and also increases by a factor of two for an increase of 10°C. At lower temperature it can be surmised that the bacteria would require more time to digest the food source available, if the time is not sufficient organic feed substrate will be present in the vicinity of the membranes, this could cause organic fouling. A correctly designed bioreactor configuration would avoid the latter.

Hydrodynamics

High shear rates generated at the membrane surface tend to shear off deposited material and thus reduce the hydraulic resistance of the fouling layer. At high fluxes, particles move to the membrane surface at much faster rate than their removal by shear, leading to greater fouling. The utilisation of cross-flow, aeration, back-pulsing etc. can be used to introduce extra shear for cake break-down.

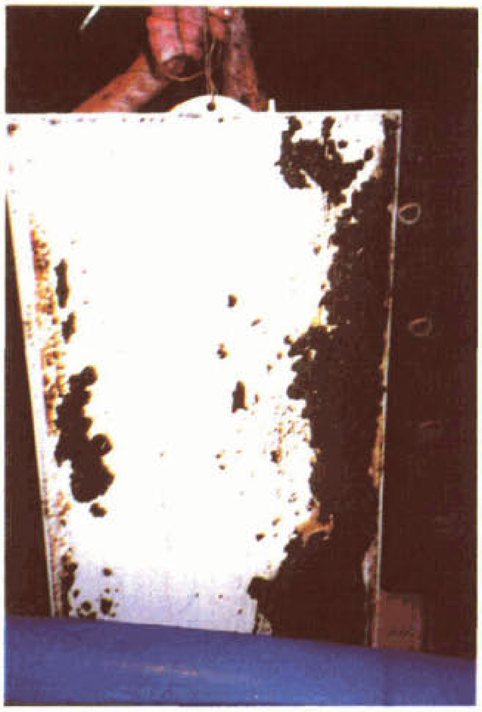

Figure 14 - Effect of a blocked aeration system

The design of an installation is also a factor that has to be taken into account. In some designs it is almost impossible to avoid "dead-zones" in the membrane module configuration. In these zones too little shear stress is introduced and as a result there is no possibility for cake break down. The cake layer will build up and eventually get so large that a blockage of the module occurs. This phenomenon is called "clogging" or "sludging". See section 3.2.1 Macro - cake formation.

The photo shows the effect of a blocked aeration system under the module. The left hand side of the plate was reasonably aerated whilst the right hand side was not. Clearly the membrane material itself is free of fouling (white colour) but was unable to permeate efficiently due to the "sludging" present. Mechanical cleaning was all that was required to return the system to normal operation.

Pressure

The Trans Membrane Pressure (TMP) is not of major importance in the range 0.01 to 0.1 bar. As the pressure increases, the flux also increases to a certain extent but due to the existence of a cake layer a further increase of TMP does not result in a further increase of flux. The flux becomes independent of pressure (so-called critical flux rate). However, at higher pressures, the fouling cake layer becomes compacted and less permeable.

3.3 Fouling in practice

3.3.1 Investigation by TNO and University Aachen

TNO and university Aachen have carried out their part of investigation as specified in Figure 1. Different technologies were used to achieve the information required and summarised under section 3.3.2 - results for each system.

3.3.1.1 Methodology

The following analytical procedures were used to access the membranes:

- SEM (EDX)
- Cryro-SEM
- CLSM

SEM

The Scanning Electron Microscope (SEM) analyses the sample by exposing the sample to an electron bundle. On impact the sample causes emissions of secondary electrons (reflection) which are detected and reformed into a computerised 3D-picture. The membrane samples are prepared by first drying the sample in air and depending on the resolution required are also sputtered with carbon or gold. This method is ideally used to assess the surface characteristics of a sample, but in some circumstances the drying of the membrane alters the morphology of the samples structure and can lead to erroneous interpretations, to avoid the latter the cryo-SEM is also used.

Cryo- SEM

To avoid the potential morphological changes in the sample preparation, a flat sample is taken and using a special type of glue is fixed in a sample holder. The sample is then placed in the SEM chamber (Jeol JSM-5600LV) on a cooling table. To prevent direct evaporation of the water in the sample the cooling table is set to -100°C. Thereafter the chamber is evacuated to approximately 50Pa. Once the microscope was stable at an acceleration voltage of 12kV the sample could be investigated. During the pressure transition to 50Pa in 35 minutes the temperature of the cooling table was slowly increased until the ice began to sublime. The sublimation was continued until the sample structure was visible. Thereafter the temperature was again dropped to -100°C.

For the preparation of the cross-sectional analyses, the membrane sample was first cut and mounted in a special sample holder. The sample was then exposed to liquid nitrogen and then broken or cut. The sample holder was then directly placed in the chamber of the SEM and the above preparation procedure followed.

CLSM

The apparatus used was a CLSM - confocal laser scanning microscope, 1-photon technique (Biorad 1024 CM).

Bacterial analyse.

Micro-organisms are coloured with acridine orange, a general DNA detection dye. Dependent on the colouring seen and the structures shown the bacteria can be separated from other materials in the sample.

Protein analyses

Proteins are coloured with Sypro red from Molecular Probes. This is a dye that is normally used in the colouring of proteins in gels. Unfortunately nucleotides and lipo-polysaccharides are not detected by Sypro red.

Analyses for EPS

Extra polymeric substances (EPS) are coloured using two different dyes, namely alcian blue and calcofluor white. Alcian blue is a dye that can stain mycopolysaccharides but also other interesting structures. Calcofluor white has the ability to stain cell walls of micro-organisms. EPS that is situated on the outside of the cell wall would shield the colouring of the cell wall, and the presence of EPS is often detected as a negative colouring around the micro-organism. The signal from the colouring decreases according to the presence of more EPS.

Table 2 - Investigation method and analysis technology used by TNO and University of Aachen

Investigation method	Analysis technology	Executor	Expectations	Sample
Analytical-morphological	SEM-EDX LM	TNO	character of fouling: organic or inorganic	Kubota, Mitsubishi, X-Flow
Analytical-morphological	SEM-Cryo (Low Vacuum)	TNO	type of fouling: - surface fouling (scaling, bio fouling) - pore fouling (adsorption, pore blocking)	Kubota, Mitsubishi, X-Flow
Analytical-morphological	CLSM	TNO	character of fouling: EPS, bacteria, proteins	Kubota,
Analytical-procedural	Chemical cleaning	TNO	character of fouling, relation: cleaning and permeability	Kubota
Analytical-morphological	REM-scan (technique for composition analyses)	University Aachen	type of fouling: - surface fouling (scaling, bio fouling) - pore fouling (adsorption, pore blocking)	Zenon
Analytical-morphological	EDX-analysis	University Aachen	character of fouling: organic or inorganic	Zenon

In the last column it can be seen which samples have been examined by a specific method and technology. Samples were taken just before a chemical cleaning and just after a chemical cleaning.

3.3.2 *Results of each system*

It must be stressed that at the time of membrane sampling the MBR pilots had already gone through extensive optimisation regarding cleaning procedures. The Kubota system had just been rebuilt to the double-decker configuration and was therefore partially cleaned as a precaution to start up, this suggested that the membrane samples taken would be relatively clean. Zenon had incorporated the so called maintenance clean (MC), and therefore fouling of the membrane was significantly reduced. The X-Flow membrane was also under going cleaning routines as part of flux optimisation, and the samples were taken from a side stream cross flow module (different operating parameters). Finally the samples taken from the Mitsubishi pilot were weakened due to prior overdosing of cleaning chemicals. In all cases the samples were taken before and after a cleaning procedure. Considering the amount of prior optimisation regarding cleaning, any result if found would be the basis of further fouling possibilities in the installations.

3.3.2.1 *Kubota*

TNO Results

Under a light microscope the outside of the membrane appeared clean with only 10% of the surface lightly fouled.

Only a few spots of fouling were visible after simple examination. These light brown/green areas were dried sludge flocs.

On further investigation using SEM and cryo-SEM the sludge side of the membrane yielded localised organic matter.

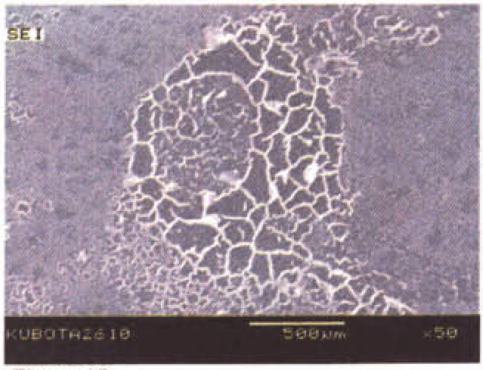

Figure 15

The fouling occurred as deposition in the lower parts of the membrane between the "backbones" of the non woven support fibres. Various organic and inorganic matters were detected:

- bacteria and proteins (CLSM)
- relatively many filaments (SEM-cryo)
- inorganic matter, in particularly Iron, Phosphate and Calcium (SEM-EDX)

Incidental mineral particles, sand and Aluminium Silicates (SEM-EDX)

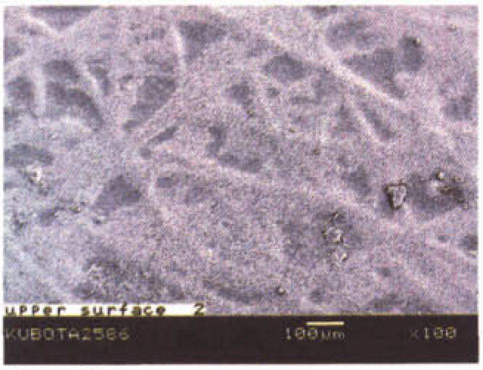

Figure 16

The thickness of the organic deposition was less than 1 µm (SEM-cryo). Thus the observed fouling was not caused by an extended bio-film.

The CLSM technique was used to detect EPS, proteins and DNA rich material through the membrane at a depth of 1 to 30µm in 1.4µm slices. It was found that the concentrations of proteins increased strongly through the membrane structure, even at depths on 10µm. These protein rich components were mainly detected in the pore structure rather than in the fouling layer. Deeper than 25µm was not possible with the detection technique but further results suggested that EPS was present throughout the pores of the membrane.

The permeate side of the membrane was also observed. No organic fouling was detected, but inorganic depositions of Iron salts, Phosphate and Calcium salts were detected.

A strict cleaning procedure carried out by TNO involving several discreet steps of NaOCl, NaOH, HNO_3, flushing, and back flushing were carried out on a membrane plate. After each part of the cleaning the permeability was measured. The results suggested that it was not possible to reach the permeability of a comparable unused membrane but this could have been caused by:

- fouling of the membrane matrix
- permeability of an unused membrane is not representative for operational permeability[1]

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[1] Same experience has been gained in filtration of surface water

The same tests were carried out on the membrane sample taken after chemical cleaning, here the membrane appeared the same as the non cleaned sample. The latter may have been caused by the pilot rebuilding to the Double-decker configuration and the preventative mild cleaning prior to starting up.

Pilot Beverwijk Results

The following observations have been recorded:

- Rapid cake formation at the onset of RWF (rain weather flow)
- Rapid cake formation followed by recovery
- Rapid cake formation followed by sludging caused by aeration system blockage. The aeration system was blocked with coarse debris that had passed a 2mm filter basket (replaced by 1mm rotating drum in Feb2001). The membranes themselves were not blocked with coarse debris, but the presence of debris in the system caused a major sludging problem.
- Surface fouling after several months of operation (no relaxation used), brown and slimy bio-film like layer, cleaned with NaOCl to yield a white membrane with localised orange areas, cleaned with oxalic acid to yield totally white membrane. Original process permeability obtained.
- Minor surface fouling after a further 6 months - cleaned due to new configuration of double-decker. Cleaning was not actually necessary for the optimal operation of the pilot.

When run at low TMPs the double-decker configuration may only require one chemical cleaning per year. The fouling seen was predominately cake formation, this caused by an inefficient air distribution under the modules or channelling of the air. The operational change from process without relaxation to a process with relaxation, greatly improved the membranes operability and stability, here the cake formation was under control, during process mode the cake was formed and during the relaxation mode the cake was removed. At lower fluxes of >10 $l/(m^2.h)$ relaxation is not strictly necessary as the cake formations and removal remain in balance. Above fluxes of 15 $l/(m^2.h)$ relaxation is mandatory.

3.3.2.2 Mitsubishi

TNO Results

Under the light microscope the membrane fibre even before cleaning appeared clean. Only local accumulation of sludge could be observed on the surface of the membrane fibre.

This sludge sometimes enclosed the whole fibre in some places. The thickness of this fouling varied from 20-80 μm, according to observations by SEM-cryo.

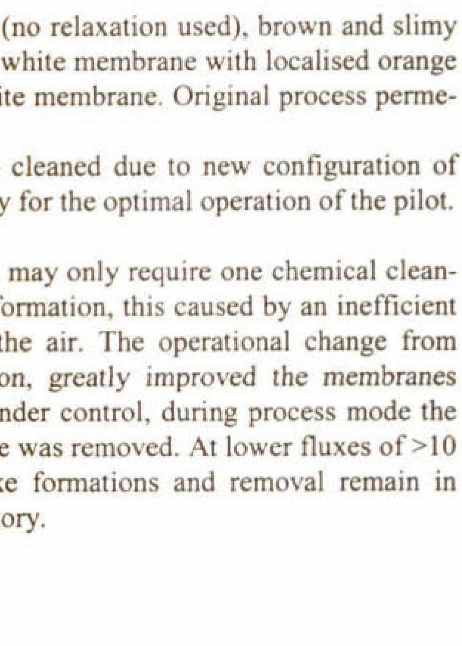

Figure 17

On a few localised places inorganic matter was deposited, in particular iron and phosphate (SEM-EDX). Also some textile fibres were detected (< 0,5 μm, SEM-cryo). Within the membrane matrix no obvious amounts of fouling were found (SEM-EDX). The comparison to a new fibre saw no noticeable difference, this suggested that the fouling if any took place solely on the outside surface of the membrane and not as a bio-film.

Below is the inside and outside of the fibres, both before and after cleaning.

BEFORE CLEANING (outside/inside) AFTER CLEANING (outside/inside)

Figure 18

Figure 19

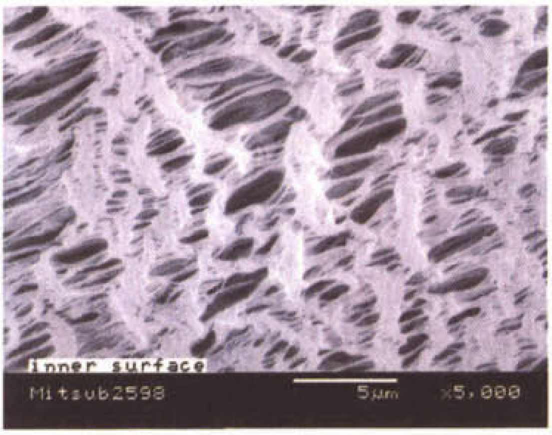

Figure 20

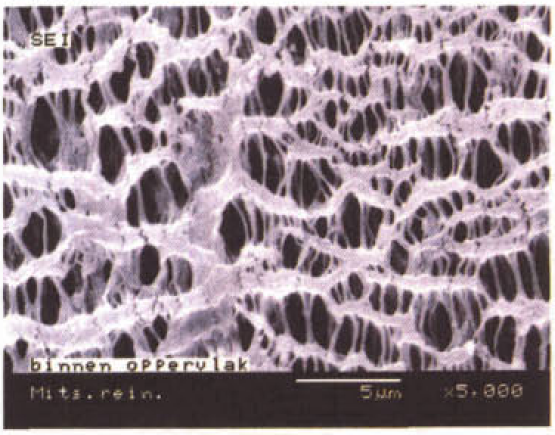

Figure 21

The membrane sample taken after chemical cleaning hardly differed from the sample before cleaning.

Results Mitsubishi

Similar work to that of TNO was carried out by Mitsubishi Japan, but the samples taken were after the module was seen to have structurally deteriorated. In Japan the pilot fibres were compared to new fibres, based on tensile strength. Results suggested that the module had been exposed to high concentrations of cleaning chemicals for a too long duration. This caused the polymeric structure of the membrane too weaken to the point of breakage. This was the first time that Mitsubishi had seen this phenomenon. Numerous tests were carried out to establish the relationship between chemical concentration, time and temperature - these results were incorporated into the pilot on a new module with success.

Under the electron microscope the actual membrane structure was intact (similar to micrographs of TNO), suggesting a good reason why the pilot had not seen break through of biomass. Only the structural strength of the fibre was diminished and not its integrity.

Pilot Beverwijk Results

The following observations have been recorded:

- Rapid cake formation at the onset of RWF (rain weather flow)
- Continuous slow cake formation causing linear permeability decline followed by minor recovery under all other conditions. Stable with MC procedures.

- Slow cake formation followed by sludging caused by aeration system stoppage. The aeration was stopped due to electrical problems but the membrane remained under permeation. Re-aeration for a several hours removed all sludging and the membrane returned to its original permeability trend.
- Surface fouling after long term operation, brown and slimy bio-film like layer, cleaned with NaOCl to yield a white membrane with localised orange areas, cleaned with citric acid to yield totally white membrane. Original process permeability obtained.
- Major fibre damage caused by high chemical exposure. Integrity of membrane was good but module ended up being replaced.

The fouling seen was predominately cake formation, usually caused by an inefficient air distribution under the modules or channelling of the air or by a too high required flux. In the beginning of the pilot trial the system suffered from electrical and software anomalies where continuous process operation became difficult - the effect here on the membrane was uncertain. Most process operation was aimed at maintaining a high permeability with the respective recovery after flux peaks, the latter goal was later replaced by the acceptance of a decreasing permeability followed by intermittent cleaning. Routine cleaning was incorporated with success and the predictable decline in permeability can be slowed down considerably.

3.3.2.3 X-Flow

TNO Results

The sample of the X-Flow module came from a 1 m element (in cross flow mode) and not from the 3 m module (in low pressure cross flow mode).

On the raw water side of the non cleaned membrane there was a clearly seen yellow/brown deposition using the light microscope (figure 22).

This deposition consisted of both organic and inorganic matter. Mineral particles were also observed (figure 23).

Under the cryo-SEM analysis the same fouling was observed as being <10µm thick, the fouling had a filamentous structure consistent with a biological background (figure 24).

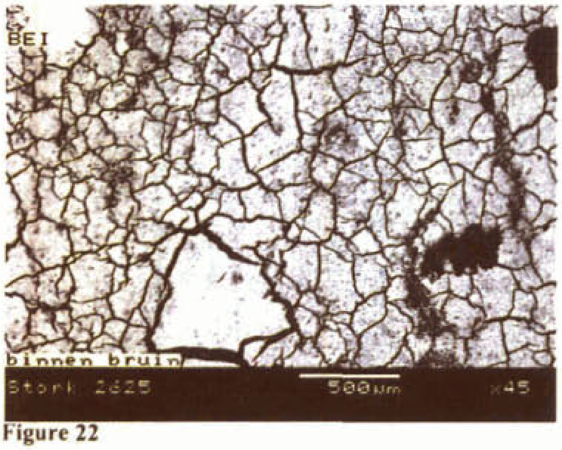

Figure 22

Figure 23

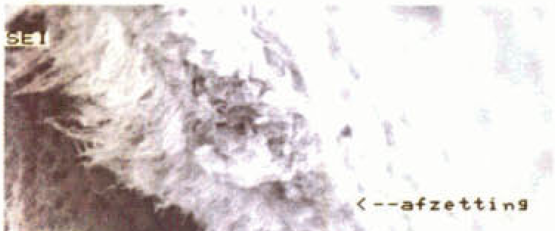

Figure 24

A cross-section of the membrane showed fouling of an organic nature was located on the sludge side of the membrane. On both sides of the membrane, as well as in the membrane matrix, crystals of iron and calcium were found (SEM-EDX). Using SEM-XRMA a large peak of oxygen was detected in the fouling layer, also stressing the presence of biological activity.

On the membrane sample after a chemical cleaning there was a significant difference between the top and bottom of the membrane. The fouling on the top of the membrane consisted mostly of inorganic elements (Fe, P, Al and Si) and some bacteria. At the bottom the same elements were found but in much lower concentrations. Overall the fouling appeared to get worst from the bottom to the top of the module with a distinct layer thickness increase. The latter can be explained by two arguments:

- The module used was set up for cross flow operation and was insufficiently cleaned after its continuous operation for 4 weeks. The fouling would be sever.
- The cross flow mode of operation may not be representative for the low presure cross flow configuration as tested in the pilot.

Despite the use of an external sample module the data points to a bio-fouling, that increases toward the top of the module, as well as cake formation.

Pilot Beverwijk Results

The following observations have been recorded:

- Extremely rapid cake formation at the onset of RWF (rain weather flow). System had to be set to continuous flow to enable some process stability.
- Low permeability during process mode compared to huge permeability (factor 5 higher) during back wash mode. Suggested very rapid cake formation during process mode. Permeability was stabilised with MC procedures.
- Catastrophic cake formation followed by sludging caused by insufficient turbulence in the module or too little feed sludge or too higher flux. On several occasions the module had to be removed to purge the tube-bundle of thickened sludge. On one occasion, caused by a safety device failure, the module could not be recovered and was thereafter replaced.
- Catastrophic cake formation via debris followed by sludging caused by failure of the pre-treatment filter (it overflowed to the bioreactor).
- Surface fouling after long term operation has not been seen, but the use of NaOCl and citric acid in the form of a MC procedure helps maintain a high permeability, even at high fluxes <35 $l/(m^2.h)$.

The fouling seen was predominately cake formation, caused by an inefficient turbulence in the tubes. Air distribution under the modules or channelling of the air or by a too high required flux are also issues requiring further investigation. Blocking of the tubes remains an issue.

3.3.2.4 Zenon

University of Aachen Results

The number and quality of the SEM and EDX/XMRA graphs was enormous. Every aspect of the fibres had been studied, new fibres, dirty fibres and cleaned fibres, all of which were analysed at 5 different magnifications and for the bottom, middle and top of each fibre sample. The EDX/XMRA scans were carried out for each location, and where anomalies were seen, each anomaly was separately analysed.

Despite the catalogue of data files produced the conclusions were rather tame:

- There was little difference between the new membrane and the used membrane.
- There was little to no biological fouling or scaling seen on the membrane surface of the used membrane.

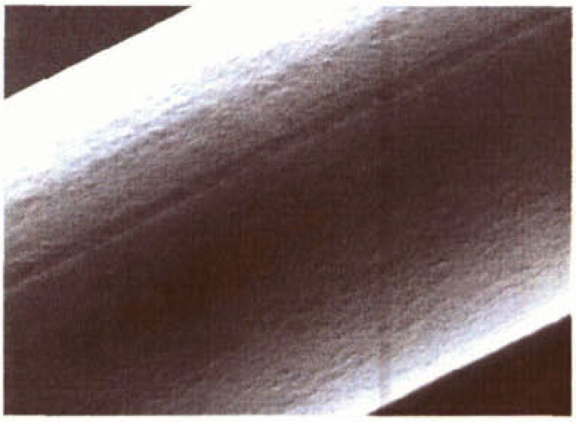

Figure 25 - New Zenon membrane

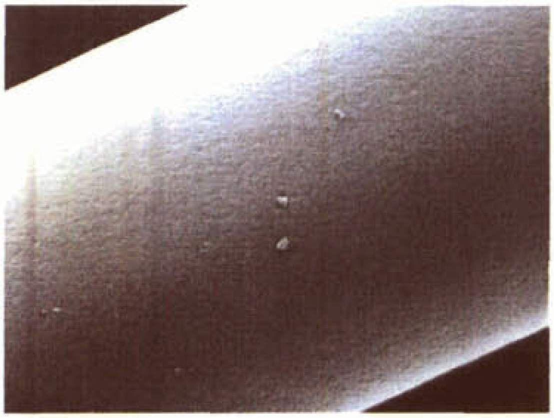

Figure 26 - Used Zenon membrane

The REM-scans yielded the same pictures (and structure) of the membrane surface for the new and used membrane.

The scans of the used membrane did show an almost negligible layer of "slime" on the membrane surface. Most likely the permeability of the membrane could have beem reduced by this layer. During a chemical cleaning the same layer is partly removed and the permeability (partially) recovered. The difference could be measured as 50-100 l/(m^2.bar) after each maintenance cleaning (MC) procedure (beverwijk data).

The conspicuous parts (3 to 5 per sample) on the clean membrane were examined in more detail by an EDX-scan. These parts are impurities originated from the membrane production process. The same impurities were found on all the fibres analysed and not found to hinder membrane integrity.
On one sample of the used membrane a larger particle was found. The EDX-analysis showed a high Silica content in the particle. Most likely this particle was a sand/clay particle stuck on the membrane surface (figure 27).

Figure 27

Further analyses of cross sectional SEM yielded no extra data, all samples appeared the same.

The results and conclusions were quite acceptable considering the incorporation of the MC procedures. The objective here was to maintain a high permeability irrespective of flux requirements or process conditions.

Pilot Beverwijk Results

The following observations have been recorded:

- Rapid cake formation at the onset of RWF (rain weather flow) on ZW500a module, new ZW500c module yielded negligible cake formation even at extremely high net fluxes of <60 l/(m^2.h).

- Rapid cake formation followed by rapid recovery due to back washing (ZW500a). ZW500c module permeability remains stable despite the onset of flux peaks (minimal cake formation).
- Rapid cake formation followed by sludging (ZW500a) caused by aeration system malfunction. The aeration system was only operated on two of the four modules, the two modules without air sludged. All coarse debris was removed by an inline filter (later changed to fine screen on the feed). Coarse sludge blocks were found under the modules (fallen out).
- Surface fouling after several months of operation, brown and slimy bio-film like layer, cleaned with NaOCl to yield a white membrane with localised orange areas, cleaned with citric acid to yield totally white membrane. Original process permeability obtained.

The fouling seen was predominately cake formation in the ZW500a module, usual caused by an inefficient air distribution or air/fibre penetration under the modules or channelling of the air. The new ZW500c with its modified air distribution and air/fibre penetration possibility almost negates cake formation. Re-circulation ratios of 2:1 have been tested combined with high net flux rates <60 $l/(m^2.h)$. Cake formation does occur and increases as the flux increases, but due to the open nature of the module the sludge falls free of the fibres and aeration system. The sludge instead of sludging the module (as with the ZW500a) falls to the bottom of the tank for collection and subsequent removal.

3.3.3 *Main conclusions (TNO)*

1. The researched membranes yielded no significant fouling on the membrane surface, with the exception of the X-Flow membrane where a cake/bio-film was detected at ca.10μm thick. In general this suggests that cake filtration was the most important fouling mechanism.
2. The examined membrane samples did not show thick cake layers or bio-films on the membrane surface, however small localised areas of bio-fouling were found.
3. A significant fouling of the membrane matrix (pores) under the SEM was not found. The cyro-SEM had a resolution of 30nm, a fouling layer in the pore of 30nm thick, if present, would have a significant effect on the permeability.
4. Visual examination suggested scattered spots of fouling of both organic and inorganic matter on some membranes. The organic fouling consisted of bacteria, proteins and filaments. The inorganic fouling consisted primarily of iron salts, calcium and Phosphate.
5. In the Kubota membrane, up to a depth of 25μm fragments of DNA and protein material was found using the CLSM technique.
6. For all researched membranes there were no visual differences in the membrane before and after the cleaning.

3.4 Correlations in fouling

From the previous sections it can be concluded that many different factors influence the type and amount of fouling of a membrane. The factors influencing fouling can be divided into four categories:

1. *Membrane properties*: hydrophilic characteristics, surface topography, charge of membrane, pore size, surface modification;
2. *Solute properties*: sludge (+EPS), water phase, debris;
3. *Configuration*: temperature, hydrodynamics/aeration, pressure, location;
4. *Operational properties*: maintenance cleaning and intensive cleaning MC/IC, process optimisation.

In the following table the type of fouling and occurrence are prioritised. Also the most important factors which influence the different types of fouling are presented. The table is drawn up based on the municipal wastewater feed quality seen at Beverwijk. The comparisons would appear different if a larger proportion of the wastewater was from industry or if the wastewater was predominately industrial. The latter is also noted in the table. The priority is defined as: 1= highest and 5=lowest, the percentage is a weighting on the priority value. The grey areas are those covered by the research at Beverwijk, the industrial column is based on literature and practical experience.

Type of fouling	**Priority**	**Priority**	**Priority**	**Factors of influence**	
	Municipal wastewater only	**Municipal + some industry**	**Largely industrial**	**Factor**	**(priority)**
Cake formation	**1**	**1**	1	Sludge	(1)
				Surface topography	(5)
	80%	**75%**	65%	Hydrodynamics/aeration	(2)
				Pressure	(3)
				Debris	(1)
				Location	(3)
				MC / IC	(2)
				Process optimisation	(2)
Bio-fouling	**2**	**3**	2	Hydrophilic characteristic	(3)
				Surface topography	(3)
	8%	**7%**	10%	Surface modification	(3)
				Sludge (EPS)	(1)
				Water phase	(3)
				Temperature	(5)
				MC / IC	(1)
				Process optimisation	(2)
				Hydrodynamics/aeration	(2)
Organic fouling / adsorption	**3**	**2**	4	Sludge (EPS)	(1)
				Hydrophilic characteristic	(2)
	7%	**8%**	8%	Surface topography	(2)
				Charge of membrane	(2)
				Surface modification	(3)
				Water phase	(1)
				Temperature	(3)
				Hydrodynamics/aeration	(3)
				MC / IC	(1)
Pore blocking	**4**	**5**	5	Pore size	(1)
	3%	**2%**	7%	Sludge / EPS	(2)
				Pressure	(3)
				MC / IC	(1)
Scaling	**5**	**4**	3	Pore size	(4)
	2%	**3%**	10%	Water phase	(1)
				Temperature	(3)
				MC / IC	(1)

It is appreciated that the wastewater at Beverwijk is not the same as all other wastewaters but the principles are clearly defined. One area which could effect the above presentation is a wastewater containing large concentrations of Calcium and Magnesium salts which could cause accelerated scaling of the MBR. In this situation the MC procedures could be weighted more on the acid side than the Chlorine side, thus affecting clean membranes.

3.4.1 Controlling influences and tools

In practice the most important fouling mechanism seen was cake formation. Other fouling mechanisms are of importance but remain under control via maintenance cleaning or process optimisation, these are discussed in the next chapter. To control fouling in MBR systems one has to focus on the control of cake formation.

Certain factors of influence are mentioned in the table with a high priority and tools must be found to bring these items under control. The most important factors associated with cake formation were:

- Debris
- Sludge
- Hydrodynamics/aeration
- MC / IC
- Process optimisation

Debris

As already mentioned debris is the real "membrane killer" and must be avoided at all times. Adequate pre-treatment is essential to protect the membranes. Much effort was put into side study 1 to establish the optimal pre-treatment, defined as the device that can remove all coarse material such as paper, hair, leaves, rubbish, etc but allow the passage of the fine suspended solids and dissolved organics. Four separate pre-treatment system were installed at Beverwijk with various separation efficiencies on suspended solids and dissolved organics, but one aspect of all four that was most outstanding was the fact that little to no coarse material entered the MBR pilots. After the pilots were equipped with the fine screens no debris was found in the membranes. On the one occasion that one fine screen blocked and overflowed due to operator error (spray system was switched off), the module was blocked within 6 hours of process operation.

There are no links between *debris* and the other factors as debris has a catastrophic effect to the MBR functionality and if present totally opens the membranes to all other types of fouling.

Sludge

Manipulation of the size and quality of the floc would result in less cake formation or could promote a more permeable cake. Ideally a floc should be created that is large, stable, with little external EPS filaments, low water retention and high dewaterability. The prevention of filamentous bacteria and excessive EPS around the sludge would be advantageous. A good control of the biological process is of utmost importance in this matter. This section on *sludge* has a strong link to *hydrodynamics/aeration* and *process optimisation*. The biological optimisation regarding sludge quality is described in side study 3.

Hydrodynamics/aeration

The formation of a cake on the membrane surface depends on two phenomena:

1. Cake formation
2. Cake break down

The cake formation is influenced by:

- *Flux rate.* At lower flux rates the cake formation is negligible and at higher flux rates the cake formation can reach a critical point. In practice an optimal flux range has to be found for the required process conditions. At higher flux rates the sludge/water mixture adjacent to the membrane surface is dewatered at a faster rate, the critical point of cake formation will occur when the dewatering process (permeate extraction) runs out of water and begins to pull sludge onto the membrane surface.
- *Solids Flux.* The solids flux is a hypothetical measurement of the speed of suspended solids in the direction of the membrane surface. The solids flux is directly related to the supply sludge flow and sludge concentration, and related to the flux. If the solids flux becomes too high the membrane will form a cake. In practise the solids flux can be directly related to and influenced by the sludge re-circulation stream over the membrane zone and its suspended solids content. The aeration of the module and the module configuration plays an important role in solids flux optimisation (see ZW500a to ZW500c comparison). Zenon and Kubota were operated at re-circulation rates of 5:1 based on net permeate flow (raw feed flow), this relates to a suspended solids increase of 20% in the filtration zone i.e. from 10g/l to 12.5g/l. At higher fluxes during rain weather conditions the re-circulation pump ramps up to its maximum flow (limitation), here the ratios can be as low as 3:1 with the resultant sludge concentration increasing to 15g/l. The solids flux also increases. The highest risk for cake formation is therefore during peak flow periods i.e. Rain.
- *Membrane permeability.* A higher membrane permeability is positive as the flow velocities in the pores of the membrane for a fixed flux remain low. A lower membrane permeability suggests that not all the available pores in the membrane are available for filtration (blinded or blocked), here the open pores need a faster velocity in the pore for the same overall membrane flux. The faster the local velocity around a pore the easier it is for sludge to be pulled onto the membrane surface. High permeability equates to lower cake formation also a more permeable membrane can be operated at a higher optimal flux. The links here with routine cleaning is clear.

The cake breakdown is influenced by:

- *The aeration.* The air is used to supply the necessary/maximum turbulence around the membrane surface. The turbulence in turn facilitates the sludge transportation to and from the membrane surface. The distribution of the air, the bubble size and the amount of air are all important, and have been intensely researched by the suppliers. The continuity of the air should also be considered. In general the air flow to the modules is fixed and depends on the number of modules installed, from experience there is very little flexibility in the volume requirements as this is limited by the supplied aeration system which is generally an integral part of the membrane module. Less air would be a benefit for energy consumption but would be weighted against extra membrane cleaning.
- *Packing density of the membranes.* If the packing density is too high the turbulence created via the aeration system and sludge supply may be inefficient at penetrating the membranes in order to refresh the sludge being filtered. Dead zones will be created which will rapidly cause cake formation and eventual sludging. It is therefore, from the operational point of view, not recommended to choose a high packing density. Other important issue on packing density is the actual membrane location in the module. Random fibre location will promote local high density packing zones - these will always sludge. A module with symmetrical uniform spacing would allow the best sludge/air penetration.

- *Relaxation and Back washing*: Relaxation and back washing are operational modes separated by production modes. An overall efficiency decrease will be seen on the module but this down time allows the sludge to be refreshed around the membrane surface and also promote the removal of any cake being formed. The choice of relaxation of back washing depends on the membrane being used and the required application. Extended relaxation periods during night time operation are common and are seen to help recover the membranes permeability from the previous days operation.

Maintenance Cleaning and Intensive Cleaning (MC / IC)
Maintenance cleaning helps maintain a continuous high permeability, it removes the less important fouling factors on a regular basis and oxidises cake on the surface which then falls to the bottom of the filtration zone. MC is an operational tool. The rule is routine. The intensive cleaning should only be required if the MC has proven to be ineffective.

Process optimisation
This item incubuses all the above mentioned factors and tools. The quality of the sludge is strongly dependent on the biological design as well as the hydraulic flow through the bioreactor system. The physical size of the floc can be influenced by the pumps used or bioreactor/filtration zone configuration. The manner in which the membranes are operated in streets must also be considered.

4 CLEANING

4.1 Introduction

In this chapter the theory and practise of cleaning is discussed. A theoretical outline of the different type of cleaning is given followed by the experience obtained the pilots at WWTP Beverwijk. In section 4.4 the main relation between theory and practise is presented.

4.2 Cleaning theory

Commonly a membrane is considered to be clean when a permeability is obtained of a comparable new membrane. Actually, it may not be possible to obtain the initial clean water permeability, as this permeability usually drops to a stable value after just a few runs. The importance of restoring the clean water permeability can be over emphasised, leading to an excessive (non-economical) cleaning frenzy. The most important criteria regarding whether a cleaning is successful or not should be that the previous (clean) process permeability is restored (first few runs after installation or previous cleaning).

Based on the fouling factors identified and isolated in the previous section the membranes were subjected to a number of cleaning procedures to ascertain the type and quantity of the fouling. It should be noted that the effectiveness of a particular cleaning procedure directly relates to the fouling occurring during normal processing.

As a rule the type of fouling determines the type of cleaning required.

4.2.1 Types of cleaning

Two main types of cleaning can be distinguished:
1. Chemical cleaning
2. Mechanical cleaning

1. Chemical cleaning

Chemical cleaning is essentially a physical-chemical reaction between the cleaning chemical and the foulant. During a chemical clean the fluid mechanics, temperature and contact should be considered.

Different chemicals are used for cleaning:
1. Oxidants and disinfectant, e.g. sodium hypo-chloride, hydrogen peroxide
2. Alkali, e.g. caustic soda
3. Acid, e.g. hydrochloric acid, sulphuric acid, phosphoric acid, citric acid, oxalic acid etc.
4. Soap (enzymatic cleaning)

1. Oxidants are used for disinfection and oxidation of organic matter. The organic matter is used as hydrogen donor.
2. Alkalis are particularly effective in combating fouling of organics and proteins. A high pH is preferred for protein fouling, not only because proteins are slightly more soluble at high pH, but also due to possible hydrolysis of the proteins [ref. 8].
3. Acids are primarily used to clean the membrane of inorganic salt depositions, like iron-salts. The pH of the acid should be measured during the cleaning to observe the cleaning dynamics and to ensure that it is within the recommended limits of the membrane.
4. Detergents (enzymatic cleaning) are used to aid the removal of biological and organic fouling. Detergents are commonly used in combination with other chemicals.

The chemicals mentioned are in a procedural order. To remove biological fouling an oxidant or alkaline is used. After this the inorganic matter and precipitated salts are removed by an acid cleaning. If the desired permeability is not reached an additional cleaning with detergent can be incorporated.

2. Mechanical cleaning

Mechanical cleaning is a term used for the physical removal of suspended solids from the membrane material. Mechanical cleaning is usually based on turbulence and fluid mechanics and in extreme cases manual participation.

Turbulence and fluid mechanical cleaning

- Circulation, based on a shear rate of sludge over membrane
- Air-flush/aeration, also based on a shear rate of an air-water mix
- Back-flush, a reversal of the filtrate flow
- Relaxation, shear rate at the outside of the membrane (by aeration) and no permeate production.

Commonly mechanical cleaning is a part of the automated operational window of a membrane system, e.g. a period of production is followed by a period of back flushing.

When pore blocking is one of the mechanisms, periodic back flushing of the membranes is very effective. When the back flush has little effect, pore blocking is most likely not the significant fouling mechanism. Circulation and aeration alone have no effect on pore blocking.

Extreme Mechanical cleaning

These procedures are only carried out when the process has failed in a major way, the chance that the membranes would be damaged is high. The procedure involves the removal of the membranes from their normal environment, and with the use of hose pipes, brushes, sponges etc the membrane surface is cleaned.

On the next page a table of all chemical and mechanical cleaning procedures used on the pilots is presented. Clearly from the table the potential mechanic options far out number the chemical options. This is normal as the more chemicals used by a membrane the greater the potential negative effect on membrane life-time. The chemical stock on the biology is rarely considered during membrane cleaning, but can give rise to micro-pollutants and complex organic compounds.

4.3 Cleaning in practice

The following section is composed of actual cleaning procedures tested on the pilots at Beverwijk. These procedures were optimised in the course of the study to their current status or operating window. The brainstorming sessions between DHV and the suppliers was used to further develop the procedures and feedback ideas to generate new chemical cleaning procedures for the future. The latter not only dealt with simple cleaning procedures but also covered areas of module improvements and membrane performance.

Type of procedure	Zenon	Kubota	X-Flow	Mitsubishi
(M) Mechanical aeration	cycled	continuous	continuous	continuous
(M) Air flow reduction	tested - no benefit	tested - no benefit	tested - no benefit	tested - no benefit
(M) Air flow increase	tested - inconclusive	tested - minor benefit	tested - negative	tested - minor benefit
(M) Process - relaxation cycled	tested - low flux only	Normal mode	tested - low flux only	Normal mode
(M) Night time relaxation	tested - minor benefit	Not tested	positive	positive
(M) Shortening of relaxation from 120sec to 60 sec	unknown	negative	negative	slight negative
(M) Lengthening of process time in process-relaxation configuration	unknown	not tested 80% eff% current	not tested	positive to 13 minutes max 85% eff% current
(M) Process - back wash cycled	Normal mode	Not relevant	Normal mode	Part of cleaning mode
(M) Shortening of back wash time	tested - possibility	not relevant	tested - positive at high BP flux	used only in cleaning mode
(M) Lengthening of process time in process-BP configuration	tested - possibility 85%eff current	not relevant	tested - not recommended 91% eff current	tested - possibility
(M) Re-circulation flow	variable 5:1	variable 5:1	constant 24m3/h/mod	variable 10:1
(M) Reduced re-circulation flow	tested to 2:1 - no process benefit	tested to 2:1- no process benefit	tested to 14m3/h/mod - negative	tested to 25g/l - no process benefit
(M) Increased re-circulation flow	positive	positive	positive	positive
(M) Sludge concentration	10g/l	10g/l	10g/l	10g/l
(M) Max sludge concentration tested	13g/l Br 20g/l mem	15g/l Br 25g/l mem	11g/l Br	13g/l Br 25g/l mem
(M) Increased sludge concentration effect on Biology and membrane	negative negative	negative inconclusive	negative	negative negative
(C+M) Chemical Maintenance clean	positive - normal	not tested	positive - normal	positive - normal
(C+M) Intensive cleaning	positive - as needed	positive - normal	positive - as needed	positive - as needed

4.3.1 Kubota

4.3.1.1 Philosophy

The philosophy of Kubota is to prevent the fouling, rather than to clean membranes. The latter is achieved by operating the membranes at conservative fluxes which in turn yield low trans-membrane pressures. The typical TMP range would be from 0.001 bar to 0.2 bar nominal with 0.4 bar as a maximum.

The mechanical cleaning method is continuous aeration of the membrane, with or without a relaxation mode between process modes.

The chemical cleaning is a fixed procedure based on volume, concentration and time per module. For the E150 module this is a 450 litre 5,000 mg/l NaOCl solution back soaked through the membrane and left to soak for 1 to 2 hours. The module is thereafter set back to process operation and the following day the second cleaning (if necessary) is carried out. The second chemical used is 450 litre of oxalic acid at 10,000 mg/l back soaked through the membrane and left to soak for 1 hour. The module is thereafter set back to process operation. The clean process permeability is then measured. The above procedure is carried out in-situ, in bioreactor or filtration zone - the sludge is not removed.

Kubota expect that cake formation would be the main fouling factor, adsorption was not expected.

Kubota were open for maintenance cleaning procedures but did not expect to have to use them. Optimisation of the chemical usage is an issue at Kubota and would be addressed.

4.3.1.2 Pilot experience

Operational permeability was high at 400 - 700 l/(m^2.h.bar) and it's decline was slow over a period of 12 months to the point of 250 - 300 l/(m^2.h.bar) where it required chemically cleaning. At the time of this side study only the double-decker configuration was available for analysis, but in hindsight the membrane performance had not changed from the single-deck to double-deck configuration. Only the balance point of the process flux had changed, from 50:50 in the single-deck system to 60:40 (top:bottom) in the double-deck system.

The predominant cleaning method for Kubota was relaxation and aeration. Up to fluxes of 15 l/(m^2.h) relaxation was not a necessity as the turbulence of the air over the membranes surface was sufficient to maintain a constant permeability. At these low fluxes the cake formation and cake removal processes were in equilibrium. Above 15 l/(m^2.h) the cake became more defined or compressed, here the relaxation mode of 2 minutes was adequate time to allow complete removal of the cake. Using the process-relaxation concept the membrane could achieve and maintain high fluxes without negatively effecting the overall permeability. During peak flows under rain weather conditions the permeability was seen to drop quite rapidly at the higher required net fluxes. The permeability dropped and eventually stabilised at a new, but lower permeability. After the peak flux was removed (dry weather) the permeability was seen to slowly and steadily return to its original permeability. The recovery could take up to two days after extremely long flux peaks but under normal conditions could recovery fully in 12 hours. The latter recovery was related to process temperature; summer conditions promoted fast recovery as a rule and winter conditions promoted a slower recovery. The normal yearly averaged permeability decline seen suggested a chemical cleaning once every 12 months.

The Kubota pilot was chemically cleaned on two occasions and mechanically cleaned on two occasions. The chemical cleaning procedure used was that stated by Kubota Corporation, each time the clean process permeability was established - the cleaning procedure worked with no evidence of long term irreversible fouling. The mechanical cleaning was required after sludging had occurred (aeration system blockage). The membrane plates were removed and scrubbed with soft brushes and water, all plates were successfully cleaned despite serious man handling. No long term damage could be inferred after the plates were put back to process. The membrane proved to be robust.

4.3.1.3 Cleaning mechanism

The NaOCl solution oxidises any bio-fouling and the cake layer directly in contact with the membrane. The high NaOCl concentration used would also cause a strong concentration gradient from inside to the outside of the membrane matrix, any organic material trapped in the matrix would be oxidised en route. Due to the continuous sludge/air mixture circulating over the membrane's surface the effective NaOCl concentration at the this surface is almost 0mg/l, but at the inside of the membrane there exists a concentration of 5.000mg/l, the diffusive force through the membrane therefore remains constant and high. Due to the continuous aeration the foulant's grip on the membrane would be weakened and carried away in the bulk sludge/air stream.

Once the membrane is organically 'clean' the inorganic fouling or scaling can be removed. The use of a weak organic acid in place of a strong inorganic based acid is twofold: The organic acid is better at removing iron, and metal complexes, and the ionic working of the acid is passive and slow, compared to a fast reduction reaction of a salt based acid. The preference to oxalic acid over citric acid was not clarified, but the use of the high acid concentration is for the same reason as for the NaOCl solution.

Method = Cleaning by diffusion in situ.

4.3.2 Mitsubishi

4.3.2.1 Philosophy

The philosophy of Mitsubishi is to prevent the fouling, rather than to clean membranes. The latter is achieved by operating the membranes at low fluxes which in turn yield low transmembrane pressures. The typical TMP range would be from 0.001 bar to 0.2 bar nominal with 0.4 bar as a maximum. A 0.3 bar TMP would initiate the requirement to chemical clean.

The mechanical cleaning method is continuous aeration of the membrane, with a relaxation mode between process modes.

The chemical cleaning is a flexible procedure based on the type of fouling and the quantity of fouling. The actual procedure follows the classic order of oxidising agent followed by acid and can be carried out in-situ, in empty tank, or as an intensive cleaning (IC). The contact time, concentration and temperature of the cleaning agent is specified by Mitsubishi. The latter suggests cleaning optimisation for a particular application, rather than the same procedure for all circumstances.

Mitsubishi expected that cake formation would be the main fouling factor.

Mitsubishi were open for maintenance cleaning but suggested that their normal cleaning procedure would have to be carried out once every 2-3 months as a sort MC procedure. They expected a slow decline in permeability within the 2-3 months to the onset of required cleaning. Optimisation of the chemical usage is an issue and would be addressed.

4.3.2.2 Pilot experience

Operational permeability was initially high at 400 - 700 l/(m^2.h.bar) for approximately 15 days, followed by a slow decline in 2-3 months to the onset of cleaning.

The predominant cleaning method for Mitsubishi was relaxation and aeration. At low fluxes of <10 l/(m^2.h) the cake formation and cake removal processes were in equilibrium, and yielded a slow permeability decline. Above 20 l/(m^2.h) the cake became more defined or compressed, here the relaxation mode of 2 minutes was just adequate to allow complete removal of the cake, but the decline in permeability accelerated. Using the process-relaxation concept the membrane could achieve and maintain operability without negatively effecting the overall permeability, however, it became clear that peak fluxes had a negative effect on the permeability, and as in Japan, the system was set to a continuous flux operation. Under continuous flux mode the system was further optimised as the parameters around the membranes operability were fixed. The membrane was eventually optimised for a maximum continuous flux, this optimisation included semi-routine MC procedures and the permeability was seen to stabilise at a workable high level.

Nightly relaxation for 4 to 6 hours, as a simulation for full scale treatment, recovered the permeability.

The Mitsubishi pilot was chemically cleaned on several occasions and never mechanically cleaned. The chemical cleaning procedure used was an intensive clean (IC) to start with, but under the constant flux mode was optimised to a MC. Since the module was replaced after the fibres were chemically weakened via overdosing during an IC, the MC procedure has been fine tuned to cope with increasing process fluxes. A routine MC in air appears to be a workable procedure that adequately maintains a high process permeability. This procedure uses 500 mg/l NaOCl followed by ~3g/l citric acid in a pH 2.5 solution. Each membrane module (x3) is in turn back washed with the solution and left to soak for a period of time. The general IC procedure recovered the permeability each time to the clean process permeability.

4.3.2.3 Cleaning mechanism

The latest MC optimisation of MC in air will be described here. The filtration tank is drained and the membranes are in contact with air. The membranes are back-flushed and soaked with a NaOCl solution. The NaOCl solution oxidises any bio-fouling and cake directly in contact with the membrane. As the solution passes through the membrane or soaks out, it slowly trickles over adjacent fibres, thus acting as a passive chemical flush on the outside. Since no sludge is present the concentrations can be kept low as the chemical is not lost to the sludge. The cleaning method is pure oxidation of organic fouling and since the chemical is inside and outside the fibre at the same concentration, diffusional forces do not play a role.

Once the membrane is organically 'clean' the inorganic fouling or scaling can be removed. The use of a weak organic acid which is acidified to pH2.5 in place of a strong inorganic based acid is twofold: The organic acid is better at removing iron, and metal complexes, and the ionic working of the organic acid is increased, compared to just an organic acid. The acid procedure is identical to the NaOCl procedure.

Further optimisation will help reduce chemical consumption.

Method = Classic, simple and in air.

4.3.3 X-Flow

4.3.3.1 Philosophy

The X-Flow philosophy regarding membrane fouling relies on two points: Optimise the biological process to avoid membrane fouling in the first place, and secondly clean the membranes when required. The typical TMP range would be from 0.01bar to 0.2 bar nominal with 0.6 bar as a maximum. A 0.3bar TMP would initiate the requirement to chemical clean. The Low Pressure Cross Flow (LPCF) principle installed at Beverwijk is one of the few pilots using this new principle and would require in depth investigation.

The mechanical cleaning method is continuous aeration of the membrane, with a back washing(+air shot) between process modes. Once per week routine standard MC.
Based on traditional cross-flow modules, the chemical cleaning is a flexible procedure based on the type of fouling and the quantity of fouling. The actual procedure follows the classic order of oxidising agent followed by acid and can be carried out as a MC or IC. Detergents could also be used with the NaOCl clean. The latter suggests cleaning optimisation for a particular application, rather than the same procedure for all circumstances.

X-flow expected that cake formation and bio-fouling would be the main fouling factors.

X-flow were open for maintenance cleaning but suggested that their normal cleaning procedure would only have to be fine tuned to the municipal wastewater application. Cleaning periods were unknown with the LPCF configuration. Optimisation of the chemical usage is an issue and would be addressed.

4.3.3.2 Pilot experience

Considerable development work was carried out on the LPCF configuration and as a result many attempted optimisation steps led to sludging of the module. Despite the sludging the standard IC cleaning procedure was always able to return the membranes permeability to the clean process mode permeability. It was established that variable fluxes were detrimental to the operability and permeability of the membrane. The system was set to a continuous flux mode to fix all parameters around the module, the cross-flow feed sludge was set at 24m3/h , the air was set at (10-12m3/h), the head loss was reduced to a bare minimum (0.02 bar) and the back flushing set to short and powerful (5-7 sec at 12-14m3/h). The latter enabled the membrane performance to be slowly increased from 60% to 91%.
Continuous net fluxes were slowly increased to approximately 40 l/(m^2.h), and the permeability kept constant at 250 - 400 l/(m^2.h,bar) utilising 1x/week modified MC procedure.

The predominant cleaning method for X-flow was back washing and aeration. At low fluxes of <20 l/(m^2.h) the cake formation and cake removal processes were in equilibrium, and yielded a stable high permeability. Between 25 and 40 l/(m^2.h) the cake became more defined or compressed, here the back washing mode was just adequate to facilitate complete removal of the cake, but the permeability decreased. The decrease was stopped through once per week MC procedures.

Nightly relaxation for 2 to 4 hours, as a simulation for full scale treatment, surprisingly recovered the permeability.

The X-flow pilot was chemically cleaned on several occasions and mechanically cleaned 4 times. The chemical cleaning procedure used was an intensive clean (IC) to start with, but under the constant flux mode was optimised to a MC. Since the module was replaced after the module was blocked with debris, the MC procedure has been fine tuned to cope with increasing process fluxes. A routine MC in permeate appears to be a workable procedure that adequately maintains a high process permeability. This procedure uses 500mg/l NaOCl followed by ~1.5g/l citric acid in a pH 2.5 solution. The module is taken off-line and back washed with permeate to purge the biomass out of the module, the NaOCl solution is then pumped into the module to fill the permeate and process side (aeration remains on) the solution and left to soak for a period of time. The solution is later purged out with permeate and the procedure repeated with citric acid. The procedure took 1.5 hours to complete, and recovered the module completely to the clean process permeability. Since the modified MC procedure has been incorporated the module has not required an IC clean.

4.3.3.3 Cleaning mechanism

The latest MC optimisation of MC in permeate will be described here. The filtration tank is drained and the membranes are in contact with air. The membranes are back-flushed and soaked with a NaOCl solution. The NaOCl solution oxidises any bio-fouling and cake directly in contact with the membrane. As the solution passes through the membrane or soaks out, it slowly trickles over adjacent fibres, thus acting as a passive chemical flush on the outside. Since no sludge is present the concentrations can be kept low as the chemical is not lost to the sludge. The cleaning method is pure oxidation of organic fouling and since the chemical is inside and outside the fibre at the same concentration, diffusional forces do not play a role.

Once the membrane is organically 'clean' the inorganic fouling or scaling can be removed. The use of a weak organic acid which is acidified to pH2.5 in place of a strong inorganic based acid is twofold: The organic acid is better at removing iron, and metal complexes, and the ionic working of the organic acid is increased, compared to just an organic acid. The acid procedure is identical to the NaOCl procedure.

The only difference between the MC and IC procedures is that the IC procedure circulates the cleaning solution around the CIP tank and at higher concentrations.

Further optimisation will help reduce chemical consumption. The procedure mentioned here has been incorporated into automation of the new 8 module pilot installation at Beverwijk.

Method = Classic, simple, semi-intensive..

4.3.4 Zenon

4.3.4.1 Philosophy

The Zenon philosophy regarding membrane fouling relies on two points: Optimise the biological process to avoid membrane fouling in the first place, and secondly clean the membranes when required. Later in the pilot trial the latter "cleaning as required" was replaced by a routine maintenance cleaning. The typical TMP range would be from 0.01 bar to 0.4 bar nominal with 0.6 bar as a maximum..

The mechanical cleaning method is continuous aeration of the membrane, with a back washing between process modes. Once per week routine standard MC.

The chemical cleaning is a flexible procedure based on the type of fouling and the quantity of fouling. The actual procedure follows the classic order of oxidising agent followed by acid and can be carried out in-situ, in empty tank, or as an intensive cleaning (IC). The contact time, concentration and temperature of the cleaning agent is specified by Zenon. The latter suggests cleaning optimisation for a particular application, rather than the same procedure for all circumstances.

Zenon expected that cake formation and bio-fouling would be the main fouling factors.

Initially the pilot was run without the MC concept, only IC was used as required. Zenon were open for maintenance cleaning and suggested that this procedure would be tested. The normal software allowed the MC and IC to be carried out, and only the frequency and concentrations had to be fine tuned to the municipal wastewater application. The expected frequency for IC was 2-4 times per year. Optimisation of the chemical usage is an issue and would be addressed.

4.3.4.2 Pilot experience

The operation with IC yielded variable permeability depending on the throughput required, however, the trend was always down. Process permeability ranged from 325 l/(m^2.h.bar) whilst clean down to 75 l/(m^2.h.bar) for the onset of IC. After peak fluxes the membranes were often seen to recovery, but never to the original permeability - a step wise loss of permeability was seen. No rain, suggested minimal peaks and minimal cleaning, but many successive peaks yielded a higher cleaning frequency. In December 2000 the MC procedure was incorporated and optimised, this proved most successful at maintaining a high operational permeability at all times. The incorporated MC procedure will be described further on the basis of the ZW500a module, the ZW500c module is briefly described.

The ZW500a operational permeability remained between 250 - 325 l/(m^2.h.bar) since the incorporation of the MC procedure. The MC procedure has eliminated the IC procedure or reduced it to a maximum of once per year. The ZW500c module showed a lower process permeability of 225 l/(m^2.h.bar) due to the one header configuration, but remained absolutely stable under all eventualities of flux.

The predominant cleaning method for Zenon was back washing and intermittent aeration. At low fluxes of <20 l/(m^2.h) the cake formation and cake removal processes were in equilibrium, and yielded a stable permeability. Between 25 and 42 l/(m^2.h) the cake became more defined or compressed, here the back washing mode was just adequate to facilitate removal of the cake and some recovery, but the permeability was seen to decrease stepwise. The latter decrease was caused by cake formation and eventual sludging in dead zones within the module. The decrease in permeability was stopped through the use of once per week MC procedures carried out in air. Here the sludging was 90% eliminated.
The ZW500c module was cleaned using the same MC procedure from new. This module has experienced no sludging of any kind even under the rigors of an extreme R&D programme. Fluxes in excess of 60 l/(m^2.h) have been tested, and sludge re-circulation rates of down to 2:1 have yielded no problems. Cake formation and sludging does occur in the module but the sludge is knocked out by the more efficient penetration of the air between the fibres..

Nightly relaxation for 30 to 60 minutes of the ZW500a often occurred during night time dry weather flow conditions. This was not detrimental to the membranes and yielded minimal permeability recovery.

The Zenon pilots had no IC or mechanical clean after the MC was incorporated. The IC procedure used (beginning of trial) was effective and followed the classical cleaning ideas, NaOCl at 1.000 mg/l followed by 3g/l citric acid at pH2.5, both overnight. Each time the permeability was adequately recovered. Lower concentrations and soaking periods were tested but were not successful.

A routine MC in air (empty tank) appeared to be a workable procedure that adequately maintained a high stable process permeability. This procedure used 500mg/l NaOCl in 6 short soaking steps followed by 2.5g/l citric acid in a pH 2.5 solution in 2 short soaking steps. The procedure took 1.5 hours to complete (automation), and recovered the module completely to the clean process permeability. Since the modified MC procedure has been incorporated the module has not required an IC clean. Further optimisation of the chemical concentrations are under investigation.

4.3.4.3 *Cleaning mechanism*

The latest MC optimisation of MC in air (empty tank) will be described here. The filtration tank is drained and the membranes are in contact with air. The membranes are back-flushed and soaked with a NaOCl solution. The NaOCl solution oxidises any bio-fouling and cake directly in contact with the membrane. As the solution passes through the membrane or soaks out, it slowly trickles over adjacent fibres, thus acting as a passive chemical flush on the outside. Since no sludge is present the concentrations can be kept low as the chemical is not lost to the sludge. The cleaning method is pure oxidation of organic fouling and since the chemical is inside and outside the fibre at the same concentration, diffusional forces do not play a role.
Once the membrane is organically 'clean' the inorganic fouling or scaling can be removed. The use of a weak organic acid which is acidified to pH 2.5 in place of a strong inorganic based acid is twofold: The organic acid is better at removing iron, and metal complexes, and the ionic working of the organic acid is increased, compared to just an organic acid. The acid procedure is identical to the NaOCl procedure.

Further optimisation will help reduce chemical consumption.

Method = Classic, simple and in air

4.4 Main relations in cleaning

From the previous two sections it can be concluded that every type of fouling that occurs on/in the membrane can be treated with simple chemicals and procedures under simple hydraulic conditions or procedures. Each chemical used can be, if necessary, substituted for other more specific cleaning chemicals compatible to the membrane requiring cleaning, e.g. detergents for removing oil, fat and grease. The following table suggests various fouling mechanisms and classic methods of cleaning.

Fouling mechanism	**Place of fouling**	**Matter**	**Cleaning**	**Effective?**
Scaling	on top / inside	inorganic e.g. Iron, Calcium, Phosphate, Sulphate	Chemical cleaning with acids e.g. hydrochloric acid, sulphuric acid, citric acid, oxalic acid	yes
Bio-fouling	on membrane	organic bacteria, proteins	Chemical cleaning with chlorine	yes
Organic fouling/adsorption	on / in membrane	organic (in relation to membrane material)	Chemical cleaning with caustic soda	not always
Pore blocking	inside pores	organic/inorganic	Hydraulic cleaning: back flush	yes
Cake formation	on membrane	suspended material	Hydraulic cleaning:	
			- sludge circulation	yes
			- air bubbling	yes
			- relaxation	yes
			- back flush	yes

In municipal MBR systems mainly bio-fouling, and cake formation occur. Bio-fouling can be treated with an NaOCl cleaning eventually followed by an acid cleaning. Cake formation can be treated hydraulically. Optimising the hydraulic cleaning is an important aspect to prevent fouling of membranes, and is directly related to the membrane configuration and process control. Considering the simplicity of the chemical and hydraulic procedures all forms of fouling for most types of wastewater can be tackled with the same degree of success as seen in the pilots.

The frequency of the IC or MC chemical cleanings are much lower than the frequency of the hydraulic cleanings. The most important aspect is to optimise the hydraulic cleaning and use the IC or MC as the back up procedure for process integrity.

5 EVALUATION OF MBR SYSTEMS

5.1 Introduction

In the previous chapters the theory and practical experience regarding fouling and cleaning were described. The membrane autopsies suggested that there was very little bio-fouling on the membranes and scaling and pore blockage was not seen. The main form of membrane fouling was cake filtration.

The most important aspect is the operation of the MBR to prevent the forming of a cake on the membranes, followed by the removal of the cake layer and the cleaning of the membranes with chemicals.

In section 5.2 the operating window for each optimised MBR is given. In section 5.3 the cleaning window for each membrane is described. Both based on the theory, practical experience with the (pilot) systems at WWTP Beverwijk and the brainstorm sessions with the membrane suppliers.

5.2 Operation window of MBR system

5.2.1 Optimal operation

Some basic rules must be defined to prevent cake formation on the membranes. These rules are:

- use a membrane with a high maintainable permeability; lower velocities to the membrane surface prevent cake formation.
- reduce dead zones in the membrane module/tank, and avoid a too high packing density of the membranes.
- select responsible operating fluxes, however, during peaks temporary higher fluxes can be maintained.
- generate larger sludge flocs to allow a more permeable cake layer on the membrane.
- install and maintain good biological conditions thus preventing the formation of EPS and filamentous organisms.

If a cake layer is formed some actions can be undertaken to remove the cake layer from the membrane. The most important tools to remove the cake layer are:

- high turbulence/re-circulation of the fluid in the membrane tank, but the sludge flocs must not be macerated or stressed (This will cause a less permeable cake layer on the membrane).
- temporally more air bubbling or intermittent air can break down the cake layer on the membrane. A high cross-flow along/through the membranes will also help.
- where possible, a back flush is effective, but will only help the membrane if the frequency is high. In the first 3 - 4 minutes of a process mode the main part of the cake layer is formed.
- relaxation of the membranes is very effective to remove the cake layer. Disadvantage is that the membrane system reduces productivity.

5.2.2 Operational recommendations of the systems

Based on the experience gained at WWTP Beverwijk, operating windows for all four pilots were made. This operation window is a guideline for the design of full scale MBR-systems.

Operation mode

A MBR-system can operate in two different modes:

- Peak-flow: at DWF the membrane operates at a low flux, at RWF the membranes are at a high (design) flux;
- Continuous: at DWF a part of the membrane area is in operation at a continuos flux, at RWF the total (design) membrane surface is in operation at the same flux.

Maximum total suspended solids

The bioreactor should operate within a range of TSS concentration of 10-12 g/l dry solids. The concentration of dry solids in the membrane zone depends on the maintained flux and circulation factor. This can be different for all four systems.

Kubota

The operation window of the Kubota system is defined below.

Operation	**Parameter**
Temperature	<5°C
Max total suspended solids bioreactor	10-12 g/l nominal, with max. of 15 g/l
Operation mode	Peak flow or continuous
Maximum net flux (peak)	41.7 $l/(m^2.h)$
Filtration	480 - 600 seconds
Relaxation	120 seconds (above certain minimum flux)
Airflow	0.48 $Nm^3/(h.m^2)$, Continuous
Long term relaxation during night	No
Chemical cleaning	1-2 times per year intensive chemical cleaning Maintenance cleaning under investigation

Mitsubishi

The operation window of the Mitsubishi system is defined below:

Operation	**Parameter**
Temperature	<5°C, above 10°C better
Max total suspended solids bio reactor	10-12 g/l
Operation mode	Continuous (minor peaks acceptable x 1.25 to x 1.5)
Maximum net flux (continuous)	20.0 l/(m2.h)
Filtration	480 - 720 seconds
Relaxation	120 seconds
Airflow	0.24 - 0.40 Nm3/(h.m2), Continuous
Long term relaxation during night	4 hours (full scale simulation only)
Chemical cleaning	4 - 6 times per year intensive chemical cleaning (original) using MC this may be reduced to 2-3 times/year

X-Flow

The operation window of the X-flow system is defined below.

Operation	**Parameter**
Temperature	<5°C above 15°C better performance
Max total suspended solids bio reactor	10 g/l
Operation mode	Continuous
Maximum net flux (continuous)	35.0 - 37.0 $l/(m^2.h)$
Filtration	300 seconds
Back flush	6 seconds at 414 $l/(m^2.h)$
Airflow	0.35 - 0.41 $Nm^3/(h.m^2)$, Continuous 5 seconds at 0.86 $Nm^3/(h.m^2)$ in bottom feed during Air Flush
Long term relaxation during night	4 hours (full scale simulation only)
Chemical cleaning	1 time per week maintenance cleaning
	with 1 time per week maintenance cleaning expected 1x/year intensive clean as general overhaul.

Zenon

The operation window of the Zenon system is defined below.

Operation	**Parameter**
Temperature	<5°C, above 10°C better performance
Max total suspended solids bio reactor	10-12 g/l
Operation mode	Peak flow
Maximum net flux (peak)	41.3 $l/(m^2.h)$ (for ZW500a), 50-60 $l/(m^2.h)$ (for ZW500c)
Filtration	200 seconds
Back flush	15 seconds at 125% of process flux
Airflow	0.54 $Nm^3/(h.m^2)$ (for ZW500a), 0.45 $Nm^3/(h.m^2)$ (for ZW500c) Cycled, 10 s on - 10 s off
Long term relaxation during night	No
Chemical cleaning	1 time per week maintenance cleaning expected 1x/year intensive clean as general overhaul.

5.3 Cleaning windows of MBR systems

5.3.1 Optimal cleaning

The cleaning of the membranes consist of two types of cleaning:

- Mechanical cleaning;
- Chemical cleaning.

Mechanical cleaning

Extreme mechanical cleaning is labour-intensive, can damage the membranes and must be eliminated. Only when absolutely necessary a mechanical cleaning should be carried out. Mechanical turbulence generated using sludge and air is the most important membrane cleaning tool.

Chemical cleaning

During the pilot test two types of cleaning are carried out:
- maintenance cleaning MC;
- intensive chemical cleaning IC.

A maintenance cleaning is carried out frequently (e.g. 1x per week) with low concentrations of chemicals. A maintenance cleaning is specific to remove the cake layer of the membrane. A intensive cleaning is carried out 1 - 2 times per year with high concentrations of chemicals and long soaking times. The intensive cleaning is specific to remove other types of fouling (if present).

In the following section, the four MBR-system's cleaning windows are presented. Only the chemical cleanings are described. The mechanical cleanings are site and membrane specific. Mechanical hydraulic cleaning (back pulse and relaxation) are described in the operation window of each MBR-system.

5.3.2 *Cleaning recommendations of the systems*

Kubota

The cleaning window of the Kubota system is defined below:

Operation	**Parameter**
Temperature during cleaning	Process temperature
Maintenance cleaning	
Frequency	none (further investigation)
Intensive cleaning	
Frequency	1 - 2 times per year (in situ)
Concentration NaOCl	5,000 mg/l
Soaking time	1-2 hours
Concentration oxalic acid	10,000 mg/l
Soaking time	1-2 hour

The intensive clean is executed "in situ" this means that the filtration tank is not drained before the cleaning. The procedure of the intensive cleaning is as follows:
- back flush (by gravity) membranes with NaOCl
- soaking time 2 - 4 hours
- normal production of approx. 24 hours
- back flush (by gravity) membranes with oxalic acid
- soaking time 2 - 4 hours
- back to normal operation

Mitsubishi

The cleaning window of the Mitsubishi system is defined below.

Operation	**Parameter**
Temperature during cleaning	Preferable 35°C for IC, MC is at process temperature
Maintenance cleaning (in air)	
Frequency	1 time per week (not optimised) in air
Concentration NaOCl	500 mg/l
Soaking time	60 minutes
Concentration citric acid	1,000 - 3,000 mg/l
Soaking time	60 minutes
Intensive cleaning	
Frequency	2 - 3 times per year in combination with MC (in solution)
Concentration NaOCl	1,000 mg/l (dependent on fouling degree)
Soaking time	4 - 6 hours
Concentration citric acid	3,000 mg/l to pH 2.5
Soaking time	4 - 6 hours

The maintenance clean is executed "in air", this involves draining the filtration zone, so the membranes are in contact with air. The procedure for the maintenance cleaning (in air) is as follows:

- drain filtration tank (off line)
- back flush membranes with NaOCl
- soaking time 60 minutes
- back flush of membranes with citric acid at pH2.5
- soaking time 60 minutes
- fill filtration tank with sludge
- back to normal operation

The procedure for the intensive cleaning (in water/chemical) is as follows:

- Drain filtration and fill with water at 35°C, air on
- back flush of membranes with NaOCl until whole solution at required concentration
- soaking time 4 - 6 hours
- Drain tank (recover chemical)
- Fill filtration tank with water at 35°C, air on
- back flush of membranes with citric acid at pH2.5
- soaking time 4 - 6 hours
- Drain tank (recover chemical)
- Fill tank with sludge
- back to normal production

X-Flow

The cleaning window of the X-flow system is defined below.

Operation	**Parameter**
Temperature during cleaning	process temperature
Maintenance cleaning	
Frequency	1 time per week in solution plus air
Concentration NaOCl	500 mg/l
Soaking time	1.5 hours
Concentration citric acid	1,500 mg/l
Soaking time	0,5 hours
Intensive cleaning	
Frequency	1 - 2 times per year (in solution/circulation CIP)
Concentration NaOCl	1,000 mg/l
Soaking time	4 - 6 hours
Concentration citric acid	3,000 mg/l
Soaking time	0,5 hours

The procedure of the maintenance cleaning ("in water") is as follows:

- stop circulation pump
- back flush of membranes with permeate/drinking water (sludge purge)
- back flush with NaOCl
- soaking time 1.5 hours
- back flush of membranes with permeate/drinking water (chemical solution purge)
- back flush of membranes with citric acid
- soaking time 30 minutes
- start circulation pump
- back to normal operation

The procedure for an intensive cleaning is the same as for a maintenance cleaning, only the concentrations and soaking times are adjusted. During IC procedures the cleaning solution could be circulated over the CIP (cleaning in place) tank, here if necessary the solution temperature could be raised to improve the cleaning solution effectiveness.

Zenon

The cleaning window of the Zenon system is defined below.

Operation	**Parameter**
Temperature during cleaning	process temperature (permeate), 30-40°C preferable
Maintenance cleaning	
Frequency	1 time per week in air (not optimised)
Concentration NaOCl	500 mg/l
Soaking time	36 minutes (in 6 steps)
Concentration citric acid	2,500 mg/l
Soaking time	12 minutes (in 2 steps)
Intensive cleaning	
Frequency	one time per year (in comb. with MC) (in solution plus air)
Concentration NaOCl	1,000 mg/l
Soaking time	4 - 6 hours (overnight)
Concentration citric acid	3,000 mg/l
Soaking time	4 - 6 hours (overnight)

The maintenance clean is executed "in air", this involves draining the filtration zone, so the membranes are in contact with air. The procedure for the maintenance cleaning (in air) is as follows:

- drain raw water tank
    - back flush of membranes with NaOCl for 1 minute
    - soaking time 5 minutes
- repeat previous 2 steps 5 times
    - back flush of membranes with Citric acid for 1 minute
    - soaking time 5 minutes
- repeat previous 2 steps 2 times
- fill raw water tank
- back to normal operation

The procedure for the intensive cleaning ("in solution") is as follows:

- drain filtration zone, refill and re-drain to remove sludge
- fill filtration tank with permeate/water
- back flush of membranes with NaOCl until filtration tank volume at required concentration
- soaking time 4 - 6 hours (overnight)
- drain filtration tank or recover chemicals, refill with water/permeate, drain, and refill
- back flush of membranes with Citric acid
- soaking time 4 - 6 hours (overnight)
- recovery chemicals if required
- fill tank with sludge
- back to normal production

6 CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

In the previous chapters a theoretical and practical frame work was sketched of fouling and cleaning. The following conclusions can be drawn based on the work carried out at wwtp Beverwijk and the separate research items regarding this study item.

- The main objective of this side study was to bring the fouling and cleaning methodology under control within defined safe operational parameters. This has been fully achieved after extensive membrane autopsy and operational procedural optimisation. The main fouling factors have been identified, carefully defined, and isolated through methodical implementation of optimised cleaning procedures.
- An investigation into the leading fouling and cleaning mechanisms in MBR applications in theory and practice was carried out and defined a strategy for the correct approach to MBR in municipal wastewater treatment.
- After the failure/break-through of the pre-treatment devices on two of the pilots, and the subsequent catastrophic sludging of the membranes within 12 hours. The absolute necessity for a 100% robust and reliable pre-treatment system was implicated. No failure at the pre-treatment stage could ever be tolerated at full scale. The aeration system under the modules must also be 100% reliable at all times, this can be achieved through flushing and routine maintenance.
- Fouling was found to be predominately cake formation followed by sludging of the module, and bio-fouling. One membrane did show some signs of adsorption. Scaling and pore fouling were not found in the study. The result of the cake formation was anticipated, but the absence of the other forms was surprising, but possibly due to the extensive maintenance cleaning procedure already incorporated into the pilots at the onset of side study 2.
- Fouling of the membrane can be suppressed via biological system performance optimisation. Larger floc lead to better filterability of the cake and an overall higher membrane permeability. Mechanical pump selection also played a role.
- The incorporation of maintenance cleaning in place of more rigorous intensive cleaning helped maintain a high stable membrane permeability that in turn generated a stable membrane operational performance. The higher the permeability the lower the required TMP, thus the lower the potential to foul.
- Maintenance cleaning yielded less toxic shock on the bioreactor systems as the chemical concentrations used were far lower than by intensive cleaning. Maintenance cleaning could also be made into a flexible procedure depending on the fouling conditions. The concept was simple, 'a little a lot of the time' compared to 'a lot for a little time'. MC procedure were also simple to automate.
- The most stable membrane operation was obtained at constant flux conditions. Here, all parameters around the functioning of the membrane could be fixed and thus fine tuned. Variable flux was not suitable for XFlow and Mitsubishi, and difficult to optimise for Kubota and Zenon.
- The flux sage, suggested that full scale systems should be built for constant flux in several compartments (thus optimised). More compartments would be brought into use as the flow pattern of the feed wastewater varied. Once all the compartments were at their ideal optimised flux, only then should the overall flux be forced up in the direction of the maximum peak flux design. The latter technique would reduce membrane fouling even further than seen in the pilot trial.

- Despite having tested 4 separate membranes at Beverwijk the fouling seen was consistent on all - cake formation, with minor bio-fouling. The way in which the cake was formed was different between the pilots but the methodology for mechanically maintaining the cake formation in equilibrium with cake removal was the same - Aeration of the membrane. The aeration technique for generating turbulence around the membrane surface is essential and successful.
- Both the use of relaxation and back washing proved to be effective at maintaining permeability, but only in combination with the aeration of the membrane. The super low TMP membranes (incidentally both MF membranes) leaned more towards relaxation. The mid to low TMP membranes (both UF membranes) leaned towards back washing, although night time relaxation did yield some benefits.

6.2 Recommendations

The following recommendations came to light from this side study:

- The operating windows defined in this report are a basis from which the MC and IC cleaning procedures can be further developed. However, less chemical is good, less energy is good, longer membrane life is good, and a reliable process is good. These items mentioned are all inter-linked with process performance, membrane development and membrane cleaning but unfortunately are all major long term study items.
- The operating windows are not dynamic - for instance, summer conditions will be advantageous to the biological and membrane processes. What is the effect of sudden process change (e.g. salt water), the recovery and membrane effect. The dynamics of the process and the membranes must be investigated and modelled.
- above all, the scale up effect is not truly defined. A single compartmentalised pilot can yield the principles. Only a real installation with the same input as the wwtp Beverwijk pilots would yield the definite information.

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Development MBR technology for large wwtp's

Pilot-research wwtp Beverwijk

Side study 3: Alpha-factor

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1 INTRODUCTION

1.1 The project

Since April 2000 four MBR pilot systems have been in operation at the Beverwijk WWTP. The goal of the research was to investigate the technical feasibility of the MBR system and to compare the four systems.

In the main STOWA report the experiences with the MBR pilot systems are described. Especially the biological performances and the membrane performances are mentioned for each system. Alongside the main report five more fundamental side studies were carried out.

The five side studies are described and summarised in the main report. The subjects of these side studies were:

1. Pre-treatment
2. Fouling and cleaning
3. α - factor
4. Effluent quality
5. Sludge treatment

This report describes the investigation of the α - factor in the MBR systems (side study 3).

1.2 Side study: α - factor

MBR technology has several advantages compared to traditional activated sludge processes, e.g. high effluent quality, limited space requirements and modular set up. However, one of the main disadvantages is the relatively high energy consumption of the MBR process as a whole. The energy requirement is mainly comprised of the energy for activated sludge aeration in which the α - factor plays a crucial role.
It is therefore of tantamount importance to undertake an investigation into the mechanics behind the α - factor and to possibly enhance the α - factor in the MBR process.

Lower α - factors are measured in the activated sludge of several existing MBR installations. The sludge often seemed viscous and difficult to mix, with the result that the required oxygen for oxidation and respiration was difficult to bring into solution. Little was known regarding the cause of the viscous character. It was primarily believed to be due to the high sludge concentration itself or microbial products excreted by bacteria which were subsequently retained in the system by the membrane.

The goal of this side study was therefore to examine the cause of the α-factor decrease and to translate the results in to practical solutions for operating the MBR at normal ($> 0,5$) α-factors.

1.3 Reader

In chapter 2 a lay out of the set up of the study is given. In chapter 3 first the theory of the α - factor and EPS is discussed. Chapter 4 presents the results of the pilot test at WWTP Beverwijk. Chapter 5 first discusses the results and gives an operating window (guidelines) for the operation of a MBR in relation to the α - factor. In chapter 6 the main conclusions are drawn and recommendations are presented. Also topics for further investigation are given.

2 SET UP

2.1 Organization of side study

The goal of the side study is mentioned in chapter 1. To reach this goal, the following steps were formulated:

1. Literature study on microbial factors influencing the α - factor.

The literature study was performed in co-operation with the BRCC-Milieugroep BV. Theory of α-factor and practical experience were brought in by DHV.

2. Brainstorm with knowledge centres.

A brainstorm with knowledgeable organisations and individuals was organised to bring the results of the literature study into a creative process in which experiments could be formulated to detect the cause of the lower α-factor.

Participants in the brainstorm were prof. Flemming (University of Duisburg), prof. M. van Loosdrecht (Delft University of Technology), drs. F.W. Horjus and ir. A.G. Zilverentant of DHV, drs. M. Keymel of BRCC-Milieugroep and dr. G.R. Zoutberg of Hoogheemraadschap Uitwaterende Sluizen.

The results of the literature study and brainstorm are presented in chapter 3.

3. Microscopic investigation of activated sludge from MBR-pilots.

Microscopic observations of the MBR activated sludge were performed to study the composition of the sludge and to compare the separate pilots. The microscopic observation was performed by DHV.

4. Experiments with activated sludge from MBR-pilots.

As a result of the brainstorm several experiments were performed to determine the cause of the lower α-factor. Analyses just as viscosity, α-factor and other sludge characteristics were performed frequently on the pilots. These results could be used to correlate the changing sludge characteristics to changing α-factors. The various measurements were carried out in parallel to avoid secondary effects caused by the proportional feed flow to the pilots.

The results of the microscopic observations, experiments and measurements on the pilots are presented in chapter 4.

2.2 Measurement program & measurement methods

2.2.1 Measurement program

In the period from February to April 2001 several α-factor and viscosity measurements were performed every two weeks. Microscopic sludge analyses were performed every week. SVI, maximal settling velocity, DSVI, Sludge DS%, mechanical thickening, inorganic content, CST and Y-flow were measured almost daily. For a description of these measurements see Appendix 1 in the supplementary report.

2.2.2 *Measurements methods*

α-factor:

The α-factor measurements were carried out in two separate experimental setups. One equipped with a surface aerator, the other with a diffused air aerator.

Surface aeration setup: 45,7 liter square tank (0,5m * 0,5m * 0,185m). Mixing at 150 rpm. The oxygen electrode placed on the bottom of the tank. See figure 1.

Diffused air aeration: 35,1 cylindrical tank (diameter 0,3m and height 0,51 meter). Bubble aeration placed on bottom of tank. Extra mixing capacity installed. Stable gas flow during aeration of 10 l/min. See figure 2.

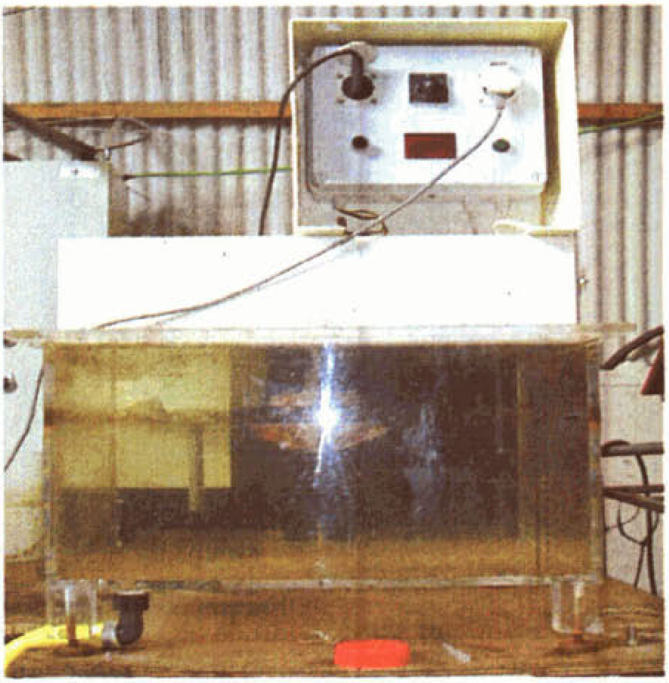

Figure 1 - Surface aeration setup

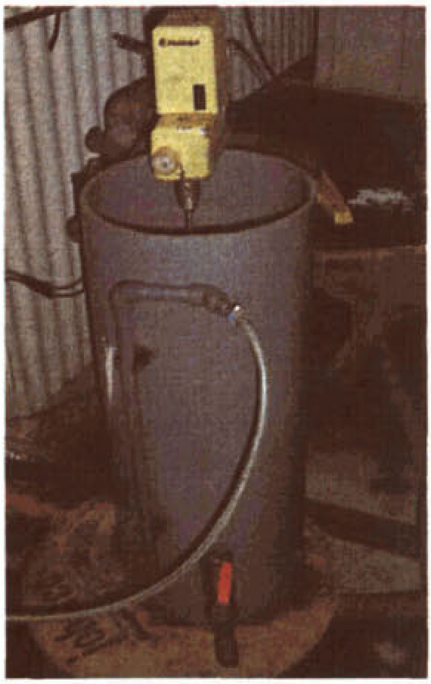

Figure 2 - Diffused air aeration setup

Measurement procedure:

The oxygen-input rate was first measured in drinking water. After this the water was deoxygenated with cobaltchloride and natriumsulfite. The drinking water was then replaced by undiluted activated sludge. The oxygen consumption rate was measured before commencement of aeration and checked afterwards. When the oxygen concentration reduced zero mg/l, the aeration was started and the oxygen input rate measured. The salt-concentration and temperature were measured during the experiment. With the collected data the α-factor was calculated.

Viscosity measurement

The viscosity was measured in a Haake viscosity apparatus, which was fitted with a VT 550 stirrer arrangement. The chamber in which the sample was added was temperature conditioned, and operated at the same temperature level as the sample origin. During the test, the shear rate was increased to 400 s^{-1}. Viscosity was measured during the run and the lowest and maximal values noted.

3 THEORY

3.1 Introduction

For a good understanding of the α-factor it was necessary to study the theoretical basis of the α-factor itself. When the mechanisms behind the α-factor were known, it became possible to search for microbial causes and effects on the α-factor. A summary of the theoretical basis is given in paragraph 3.2.
The outcomes of the literature study and brainstorm sessions were combined to yield the 'current knowledge status' available and subsequently used to produce an understanding into the microbial factors influencing the α-factor. The results of this exercise are given paragraph 3.3.

3.2 Factors influencing the α-factor

Prediction of oxygen-transfer rates in aeration systems is always based on an oxygen rate model as given in Eq. 3-1.

$$Rc = dC/dt = K_La\ (Cs-C) \qquad (3\text{-}1)$$

Where:

Rc = change in concentration [mg/(l.h)]
K_La = overall mass-transfer coefficient [s^{-1}]
Cs = saturation concentration of gas in solution [mg/l]
C = concentration of gas in solution [mg/l]

In this model K_La is the overall mass-transfer coefficient. A value which is a function of temperature, intensity of mixing (and hence the type of aeration device used and the geometry of the mixing chamber) and constituents in the water.

To predict the actual oxygen-transfer rate under field-operating conditions the following equation is commonly used.

$$OTR_f = SOTR\ ((Cs - Cw)/Cs_{20})\ \theta^{T-20}\ (\alpha) \qquad (3\text{-}2)$$

Where:

OTRf = actual oxygen-transfer rate under field-operating conditions in respiring system [kg O_2/kWh]
SOTR = standardized oxygen-transfer rate under test conditions at 20°C and zero dissolved oxygen [kg O_2/kWh]
Cs = oxygen saturation concentration for tap water at field-operating conditions [mg/l]
Cw = operating oxygen concentration in wastewater/activated sludge [mg/l]
Cs_{20} = oxygen saturation concentration for tap water at 20°C [mg/l]
θ = temperature correction factor, in range of 1.015 to 1.040 [-]
T = temperature [°C]
α = α-factor [-]

In equation 3-3 the calculation of the α-factor, which is the correction factor for aeration characteristics of the sludge/water mixture compared to tap water, is presented.

$$\alpha = K_La \text{ wastewater} / K_La \text{ tap water} \qquad (3\text{-}3)$$

The α-factor may vary between 0,2 and 2,0. This suggests that the α-factor can have a significant impact on the actual oxygen-transfer rate. The higher α-factor values are mainly measured in industrial sludges with high salt concentrations.

Since viscosity will influence the mixing characteristics of a solution, a highly viscous activated sludge sample will have a negative effect on the α-factor. This suggests that the actual α-factor will be determined by:

1. Reactor configuration and mixing/aeration device;
2. Sludge characteristics and sludge concentration;
3. Soluble compounds in the water-phase.

3.3 Microbiology and α-factor

The activated sludge in an aeration tank will influence the α-factor in several ways:

Sludge concentration:
With an increasing sludge concentration the amount of free water will decrease. As a result the sludge will be difficult to mix and therefor difficult to aerate. Such a relationship was established in the research of Günder [ref. 1] (see figure 4). A halving of the α-factor was observed at a sludge concentration of 8 g/l compared to the effluent.

Sludge characteristics:
The manner in which bacteria grow in activated sludge plants can be very different. They can grow as free bacteria but normally as flocs. This growth form is stimulated by oxygen.
Other growth forms are also seen:

1. Voluminous flocs.
2. Flocs with filamentous bacteria.

Figure 3 gives a overview of the different growth forms of bacteria in activated sludge and the factors influencing this growth.

Voluminous flocs
A sludge floc contains a certain amount of extra-cellular polymeric substances (EPS). EPS is composed of a matrix of polysaccharides and proteins[ref. 2,3]. In this matrix other compounds such as heavy metals and salts can be captured [ref. 4]. Bacteria produce EPS matrixes with a wide range of compositions. The protein content can vary between 10 to 80% of the total dry-weight, and the length and branching of the polysaccharide molecules can vary strongly. All these EPS types have different characteristics and can be used by bacteria for different purposes. Due to the latter diversification and numerous causes it is difficult to find a common factor responsible for stimulating the production of EPS.
Production of excessive amounts of EPS is commonly found under conditions of: overloading, overaeration, toxicity, nutrient-limitation and grazing of protozoa [ref. 5,6,7].
When the EPS content of a floc increases, the specific volume of a sludge floc will be larger, thereby increasing the viscosity of the sludge. Since EPS can contain water up to 1000 times its weight, it is clear that excessive formation of EPS by bacteria can increase the specific sludge volume dramatically, thus negatively effecting the α-factor.

Flocs with filamentous bacteria
Filamentous bacteria are frequently present in activated sludge. These bacteria will put their filaments into the water-phase, or will bridge the separate flocs with their filaments. In this way the sludge viscosity will increase.

At least 40 types of filamentous bacteria are known. Every filamentous bacterium has it's own specific growth conditions. A common cause for filamentous growth is therefore difficult to point out and each type of filamentous bacterium should be fought separately. For instance hydrophobic filamentous bacteria can accumulate in the scum layer on top of the reactor. Removal of the scum layer is the most effective way to fight these bacteria.

Microbial products excreted in the water phase:

All the compounds produced by bacteria and excreted into the water are called soluble microbial products (SMP) [ref. 8]. These compounds will be washed out in the settling tank of conventional systems. In a MBR however, the membrane will retain the larger compounds in the activated sludge in the water phase. These compounds are then able to influence the aeration characteristics or foul the membranes.

Some filamentous bacteria are hydrophobic and can cause scum-layers on the top of an aeration tank. It is known that these bacteria excrete hydrophobic compounds to change the water characteristics to their own benefit. Hydrophobic compounds however, lower the α-factor.

Also EPS can have display hydrophobic characteristics. This depends on the protein content of EPS. When sludge is exposed to high mechanical stress, the EPS, which is loosely associated to the floc, will dissolve into the water-phase [ref. 9]. Dependent on the type of EPS, the α-factor can be influenced. Sludge mineralisation also produces SMP. These products are compounds originating from the cell membrane of bacteria.

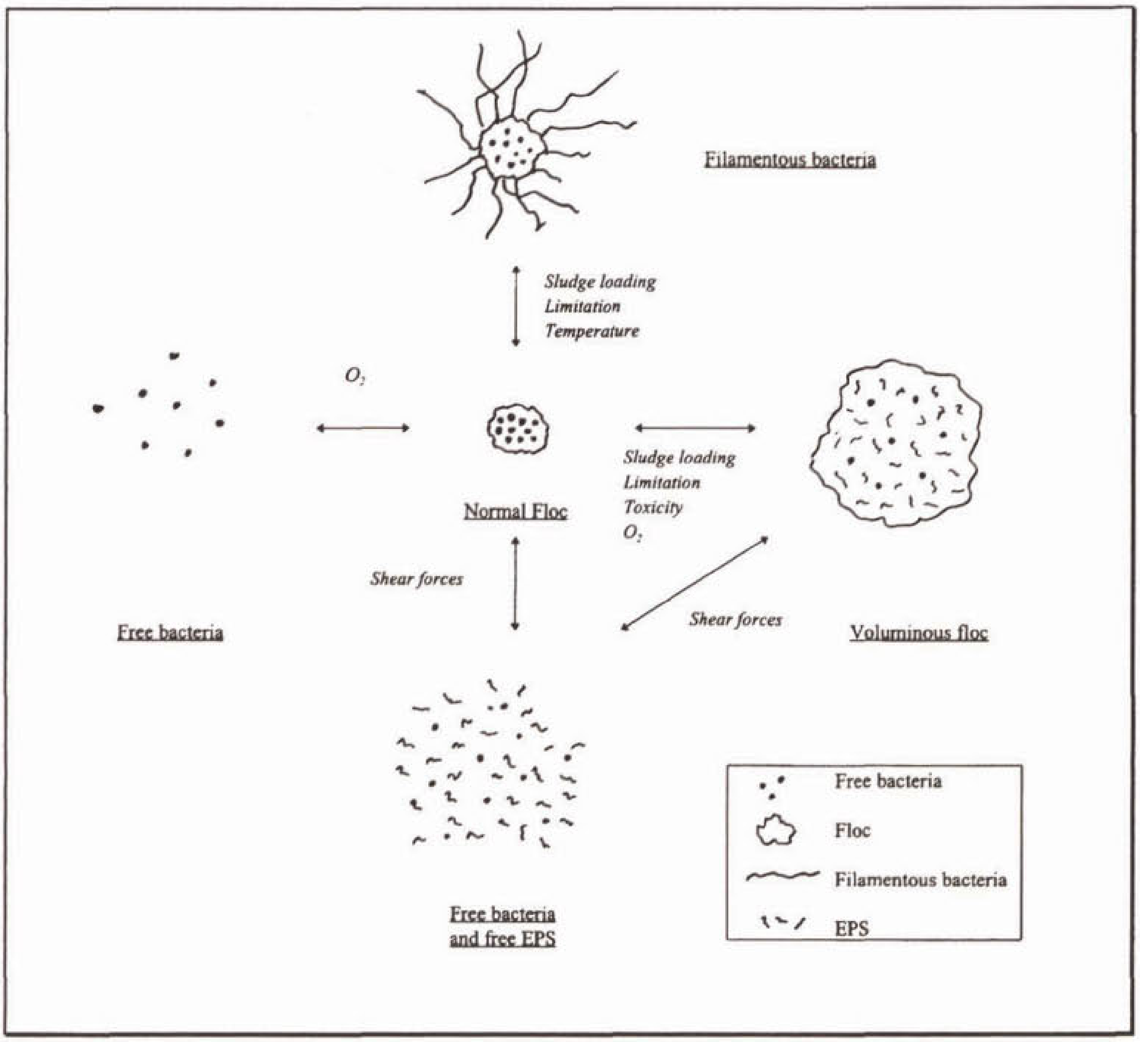

Figure 3 - Different growth forms of bacteria in activated sludge and factors influencing the growth

4 RESULTS

4.1 Introduction

After the theoretical phase of this side study was completed, experiments were carried out to investigate the cause of lower α-factors in the pilot MBR's. The results of these experiments are presented in the next section.

4.2 α-factor measurements in water-phase

The first experiment was to determine if lower α-factors, measured in the activated sludge sample, were caused by a substance in the water-phase or by the characteristics of the sludge. α-factors were determined in a mixed sludge sample, the water-phase above the settled sludge and the permeate obtained from the reactor at the same time as the sludge sample was taken. The results of this experiment are shown in table 1.

Table 1 - Values α-factor measurements in permeate and water phase and sludge

System	Date	Sludge	Permeate / effluent	Water phase
Zenon	06-02-01	0,4	1,0	0,8
	21-02-01	0,2	1,0	0,8
	01-03-01	0,6	1,1	0,9
X-Flow	08-02-01	0,8	1,0	-
	28-02-01	0,9	1,0	1,0
	06-03-01	0,8	-	1,0
Mitsubishi	01-02-01	0,4	1,0	-
	14-02-01	0,7	1,0	1,0
	05-03-01	0,5	-	0,9
Kubota	05-02-01	0,5	0,9	-
	14-02-01	0,3	1,0	1,0
	20-02-01	0,4	1,0	0,9
Aeration tank 1	07-02-01	0,8	0,9	1,0
Beverwijk wwtp	20-02-01	0,8	1,0	1,1
	06-03-01	0,9	-	1,0

The difference between permeate and water-phase values gives an indication of a soluble component in the water-phase of the sludge, retained by the system by a membrane barrier, or through characteristics of the sludge. In general the results in table 1 show there to be no significant difference between the α-factors of permeate and water-phase.

Only the water-phase of the sludge sample from the Zenon pilot yielded a lower α-factor. The sludge from this installation contained high amounts of filamentous bacteria. Mainly types which are known for their hydrophobic character. This suggested that a specific bacteria (filamentous) excreted soluble compounds into the water phase able to negatively effect the sludge overall α-factor. Other MBR sludge that also contained filamentous bacteria was also tested under the above conditions but never yielded a difference as displayed by the Zenon MBR. The above effect was compared to the varying pore sizes of the various membranes but no correlation could be ascertained.

4.3 α-factor and sludge concentration

To determine the influence of sludge concentration on the α-factor, a sludge sample of the MBR-pilot installation of Kubota was diluted several times with permeate of the same installation. The experiment was carried out with Kubota sludge as this pilot installation was operated under very stable conditions (other pilots were undergoing different R&D programs).

The results of the experiment are shown in figure 4 (◆, linear trend line). Since sludge samples with a higher sludge content were difficult to obtain it was not clear how the α-factor behaved at sludge-concentrations above 15 g/l. The line drawn is the best fitting linear line. In this figure also separate measurements on sludge from the Kubota pilot plant over a period of 3 months are displayed.

The calculated trend-line does not fit that as described by Günder. The individual measurements are also way outside the range suggested by Günder.

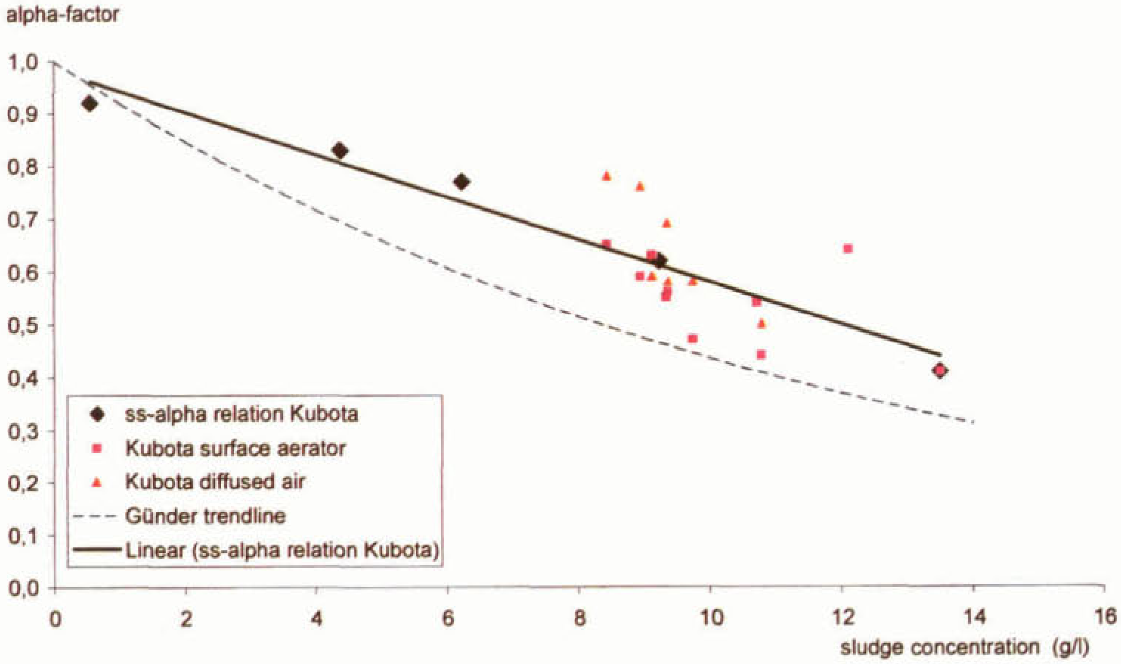

Figure 4 - α-factor-sludge concentration trend-line according to Günder and determined by experiments with Kubota sludge

All the α-factor measurements in the Kubota pilot, carried out in the period from February to April 2001, are also presented in figure 4. Most of the points were in the range of the plotted line. However some points deviated strongly. Since this difference was not within the range of the error margin (± 0,05), the difference in α-factor must have been caused by a change in sludge property or operating conditions of the pilot.

4.4 Viscosity and sludge concentration

As mentioned in chapter 3 the α-factor will decrease with increasing viscosity. Simultaneous with the α-measurements viscosity measurements were executed. In figure 5 the viscosity is plotted against the α-factor. This data was obtained from the Kubota Pilot plant over a period of 3 months.

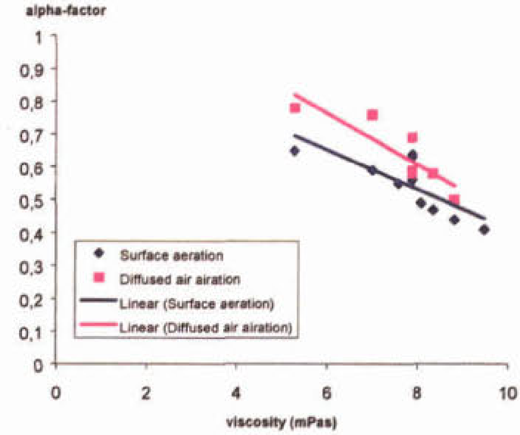

Figure 5 - Relationship between α-factor and viscosity (Kubota period of 3 months).

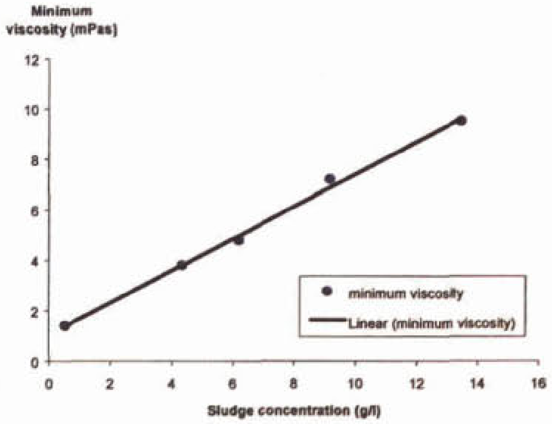

Figure 6 - Relationship between viscosity and sludge concentration. (Kubota 12-03-2001)

Figure 5 suggests that the α-factor decreases with increasing viscosity. Figure 6 shows that this is due to the change in sludge concentration. In both figures the minimum viscosity is used as measured in the viscosity assay (See also figure 7).

The viscosity of a fluid depends on the input of mixing energy into the system. Figure 7 shows a typical viscosity plot where the viscosity is measured at a wide range of mixing energy (shear rate).

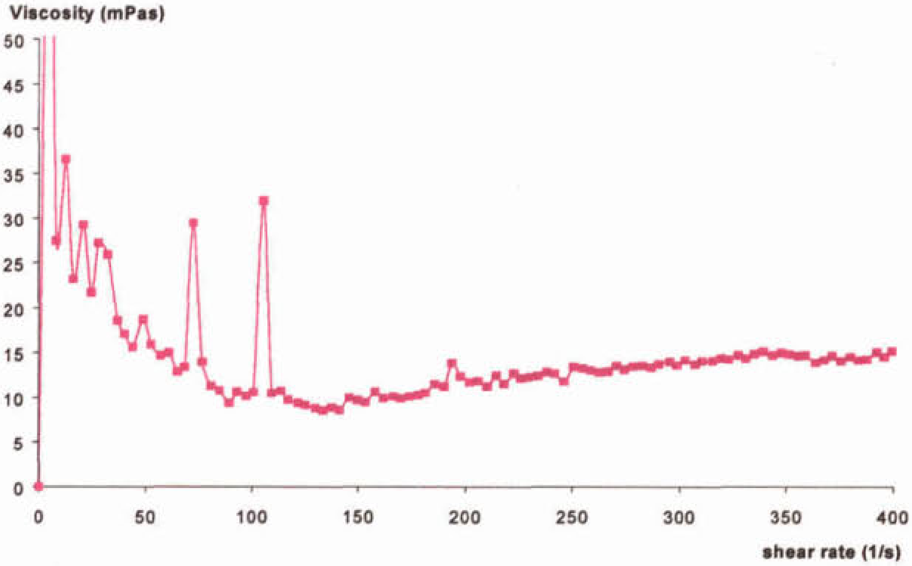

Figure 7 - Viscosity measurements at different shear rates (Mitsubishi sludge 23-4-2001)

4.5 Microscopic characterization of activated sludge

In the period from February to April 2001 every two weeks a sludge sample was examined microscopically. The presence of filamentous bacteria in the sludge, the floc size and the EPS content of activated sludge was determined.
The composition of sludge differed between the four pilot-installations, but did not change significantly in this period. The differences in sludge composition are mainly caused by differences in pilot configuration, equipment characteristics and biological loading.

Table 2 - Average sludge characteristics of the full-scale installation and the four pilot-installations in the months February to April 2001

	Full-scale	Zenon	X-Flow	Kubota	Mitsubishi
Percentage flocs < 30 µm (%)	26	83	90	40	80
Average floc size (µm)	129	33	25	141	29
Slime content biomass (% total biomass)	30	64	72	43	69
Loosely attached slime (0-6)	2	1	3	2	4
Fixed slime (0-6)	3	4	2	2	1
Percentage filamentous bacteria (%)	23	29	8	11	8
Gram+ filamentous bacteria (0-6)	3	4	2	2	1
Gram- filamentous bacteria (0-6)	1	1	1	1	1
Higher organisms (0-6)	2	2	2	3	2
Free bacteria in water-phase (0-6)	1	3	2	2	2
Inorganic particles (0-6)	2	2	1	2	2

- At the (0-6)-scale means: 0 = not present; 1= slightly present; 2= a few present; 3= commonly present; 4= very commonly present; 5= dominantly present; 6= extremely present.

The sludge of the full-scale installation contained a high percentage of Gram+ filamentous bacteria and also some clearly detectable slime (EPS). This was not commonly seen in activated sludge from municipal wastewater treatment plants. Compared to the MBR pilot plants the slime-content was low.

The sludge characteristics of the four pilot plants varied from each other.
Zenon pilot plant: This sludge contained a high percentage of Gram+ filamentous bacteria. The amount of filamentous bacteria varied between 15 and 50% of the total biomass. The sludge contained a high content of slime. The slime was mainly in a fixed form. See figure 8.
X-Flow pilot plant: This sludge contained a low percentage of filamentous bacteria and very small (< 30 µm) flocs. The sludge contained a high content of slime. The slime was mainly in a loosely attached form. See figure 9.
Kubota pilot plant: This sludge contained the largest flocs and a low percentage of flocs smaller than 30 µm. The average floc size decreased after the the pilot was rebuild to a biological phosphor removal cofiguration and the ferric dosing was stopped. The percentage of filamentous bacteria was low. See figure 10.
Mitsubishi pilot plant: This sludge contained the highest content of loosely attached slime. The floc size didn't increase after a pump with low shear forces replaced the turbulent recycle pump. See figure 11.

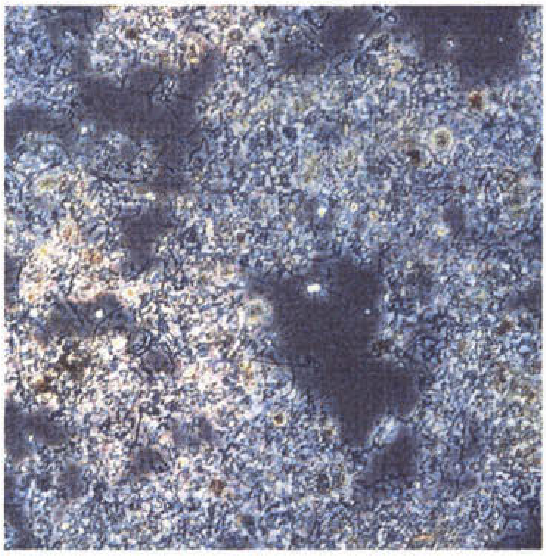

Figure 8 - Microscopic picture of sludge sample from the Zenon pilot plant taken at 1-2-2001

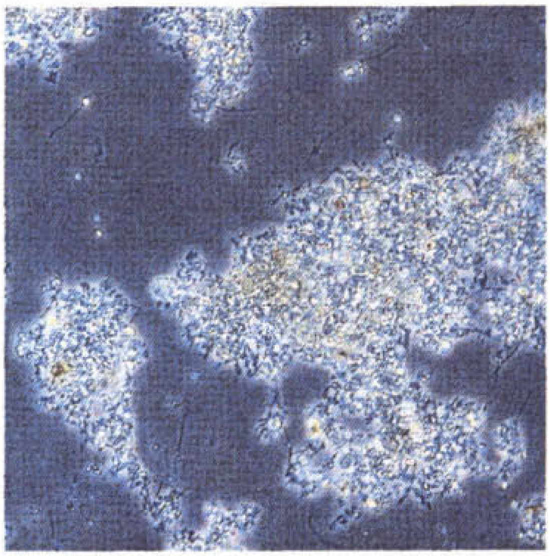

Figure 9 - Microscopic picture of sludge sample from the X-Flow pilot plant taken at 9-2-2001

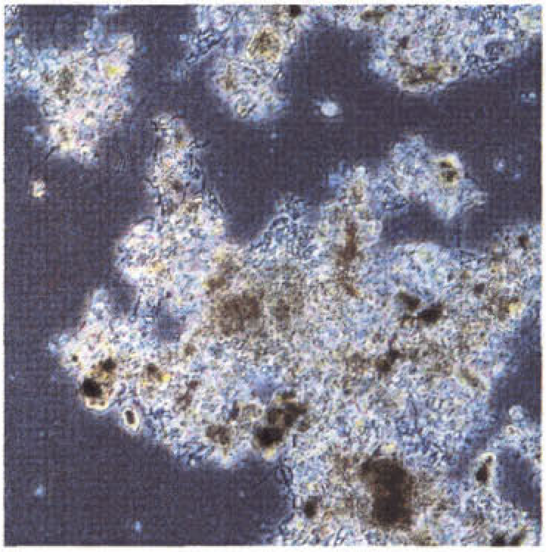

Figure 10 - Microscopic picture of sludge sample from the Kubota pilot plant taken at 1-2-2001

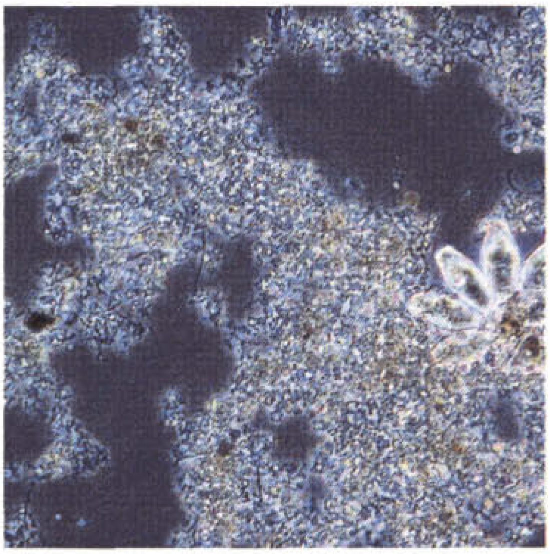

Figure 11 - Microscopic picture of sludge sample from the Mitsubishi pilot plant taken at 1-2-2001

4.6 α-factors in the separate pilot plants

To compare the aeration characteristics of the sludge from the four pilot installations, α-factors were measured over a period of 3 months. Since the α-factor was correlated to sludge concentrations, the values can only be compared when plotted against the sludge concentration. The results are shown in figure 12.

Figure 12 suggests that all the sludges are within the range of the SS-α-factor trend line as acquired in the experiment with Kubota sludge (par 4.3). No significant difference in aeration characteristics was present between the four different types of activated sludges. A difference can be seen when diffused air aeration and surface aeration are compared. The α-factors measured with diffused air aeration are moderately higher than the α-factor measured with surface aeration, except for the Mitsubishi sludge.

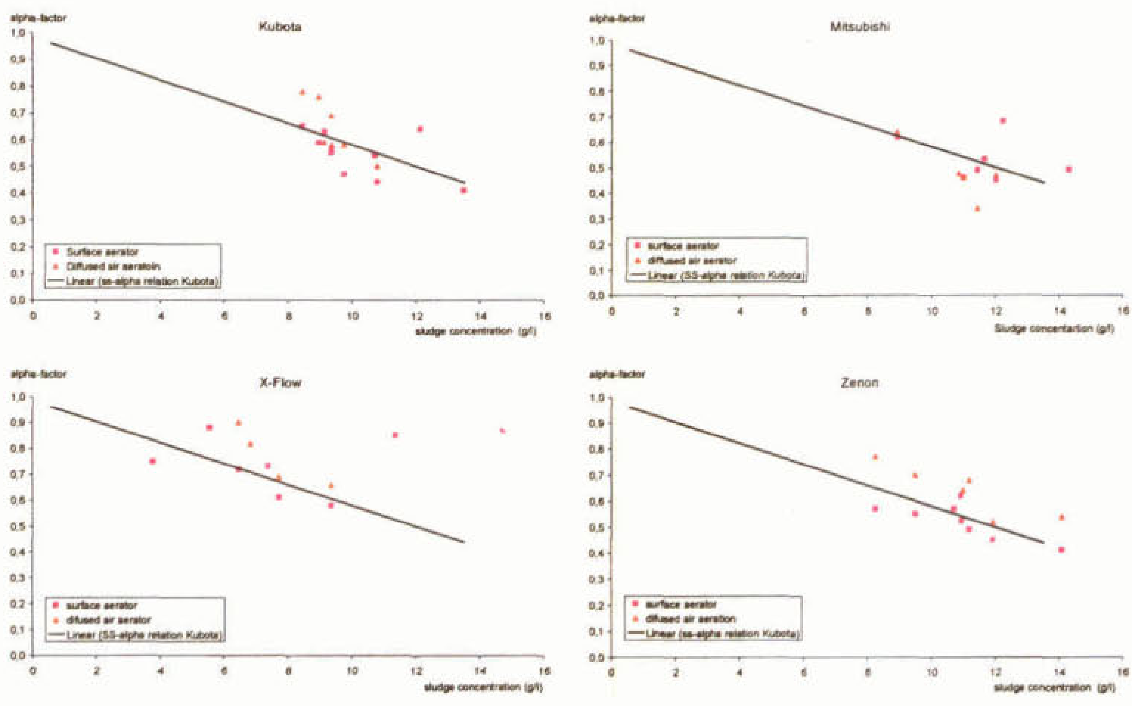

Figure 12 - Results of α-factor measurements plotted against the sludge concentration

4.7 α-factors compared to sludge characteristics

The difference between the single measured values and the SS-α-factor trend line in figure 12 are larger than the measurement error determined for the α-factor assay. This suggests that changes in sludge characteristics are responsible for a difference in α-factor. A relationship with other sludge characteristics was investigated for the Kubota sludge by plotting the α-factor against several sludge parameters measured. The results of this test are presented in table 3.

Table 3 - Correlation between α-factor and other sludge parameters of sludge from the Kubota pilot plant

Parameter	Correlation with α-factor		Increasing value parameter makes α-factor ……
Aeration device	surface	diffused air	
CST	-	±	Higher
DSVI	-	-	
Gravity thickening	-	+	Lower
Settling velocity	±	-	Higher
Mechanical thickening	-	-	
Y-flow	+	-	Higher
Inorganic content sludge	+	-	Higher

+ = linear relation (95% certainty of relationship between α-factor and parameter)

± = possible linear relation (90 - 95% certainty of relationship between α-factor and parameter)

- = no linear relation

A clear relationship between α-factor and gravity thickening, Y-flow and inorganic content of sludge was found depending on the aeration system chosen, but significant differences were seen between surface aeration and diffused air dependencies.

5 EVALUATION

The results of the literature study, brainstorm session and internal discussions suggested that the actual α-factor in a MBR would be determined by:

1. Reactor configuration and mixing/aeration device;
2. Soluble compounds in the water phase.
3. Sludge characteristics and sludge concentration;

Reactor configuration and mixing/aeration device

The relationship between viscosity and α-factor which is shown in figure 5, meant that α-factor can be increased by decreasing the viscosity of the activated sludge mixture in the reactor of the MBR. Since viscosity can be influenced by changing the mixing energy-input or shear forces inside the sludge (figure 7), the aeration and/or mixing device and the applied shear forces in a MBR with high sludge concentrations will be a very important aspect in the engineering of a MBR concerning the energy aspects of a MBR.

The higher α-factors found for diffused air aeration compared to surface aeration can not be translated to the full-scale installation, since shear-forces in the test-unit were unknown.

Soluble compounds in the water phase

The literature study showed that bacteria are able to produce soluble microbial product (SMP) responsible for lowering the α-factor. These compounds can be excreted actively in the water-phase to create optimal growth conditions for the specific bacteria (hydrophobic filamentous bacteria). They can also be released into the water-phase as a result of high shear forces applied on the sludge or as a result of sludge starvation at low sludge loading. Since a MBR can retain larger molecules inside the reactor by its membrane barrier, accumulation of these compounds can be expected resulting in a lowering of the α-factor.

The experimental results show however, that for most of the pilot plants the α-factor in the water-phase was equal to the α-factor in the permeate. No components that could lower the α-factor were accumulating in MBRs. The only exception to the latter was the Zenon sludge, where a lower α-factor was measured. Since the pore size of X-Flow membranes were in the same range as the pore size of Zenon and no lower α-factor was measured in the X-Flow water phase, pore size alone could not explain the lower α-factor. The lower α-factor can be explained by the presence of a high percentage of hydrophobic filamentous bacteria in the sludge. These bacteria produce hydrophobic compounds. Growth of these filamentous bacteria should be avoided.

Since the water-phase of most of the tested pilot plants did not contain an α-factor lowering compound, the characteristics of the sludge itself are responsible for lowering the α-factor.

Sludge characteristics and sludge concentration

A clear relationship between α-factor and sludge-concentration was found in the experiment with different dilutions of Kubota sludge. This suggested that a lower α-factor at higher sludge concentrations is inevitable.

The viscosity of the sludge as shown in figure 5 influences the α-factor. This suggested that sludge characteristics can influence the α-factor positively or negatively. When the results of the MBRs at Beverwijk wwtp were compared with the Günder trend line, two differences were observed:

1. All measured α-factors were higher than expected with the Günder trend line.
2. The relation between the sludge concentration and the α-factor show a different trend.

These results inferred that the aeration characteristics of the sludges from the four pilot-installations was much improved as compared to that examined by Günder.

Microscopic observations showed a structural difference between the sludge composition of the four pilot-systems. This difference did not lead to a difference in the average aeration characteristics. This lead to the conclusion, that the sludge compositions observed were within the operational scope of a MBR in relation to the aeration characteristics.
Within this scope a slight improvement of the α-factor was found with a decrease of sludge volume (Gravity thickening and Y-flow), and increase of inorganic content. Sludge settling characteristics (DSVI) could not be correlated to the α-factor. Since no extreme EPS-production and excessive growth of filamentous bacteria were observed during the test period, no hard conclusions could be drawn regarding the relationship between sludge characteristics and α-factor.

α-factors of 0,5 can be maintained at sludge concentrations of 12 g/l when the sludge is composed of flocs with an average size of 30 to 200 μm and SVI lower than 150 ml/g. A certain amount of EPS (60% microscopically observed) is allowed as long as the mechanical stress is not strong enough to loosen the EPS from the flocs into the water-phase.

6 CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

from literature study and brainstorm

The level of the α-factor at a certain sludge concentration can be influenced by:

1. Microbial products excreted in the water phase;
2. Sludge characteristics like EPS-content and amount of filamentous bacteria;
3. Type of aeration/mixing device used and reactor configuration.

from experiments

Soluble microbial product responsible for lowering the α-factor were not accumulated in a MBR with normal sludge characteristics. The presence of hydrophobic filamentous bacteria can decrease the α-factor in the water phase. Growth of filamentous bacteria should be avoided.

The α-factor of a sludge/water mixture was strongly influenced by the sludge concentration. This relationship was caused by the viscosity.

Although the sludge characteristics noticed under the microscope were different, no difference could be seen between the mean α-factor of the separate pilot plants.

The measured α-factors were higher than expected using the Gunder trend line. The experiments yielded another trend line.

The sludge characteristics of the 4 pilot plants were within the operating window of the MBR concerning the α-factor for full scale development.

6.2 Operating window concerning the α-factor

The sludge should be composed of flocs with an average size of 30 to 200 µm and SVI lower than 150 ml/g. Growth of hydrophobic filamentous bacteria should be avoided. A certain amount of EPS (60% microscopically observed) is allowed as long as the mechanical stress is not strong enough to loosen the EPS from the flocs into the water-phase.

With the tested MBR sludge, α-factors higher than 0,5 can be maintained at sludge concentrations up to 12 g/l.

These sludge characteristics can be obtained by applying the operating conditions used for the pilot installations during the test period. Sludge loading, oxygen concentration and mechanical stress are the most important parameters.

During the engineering of a MBR, aeration/mixing device and reactor configuration should be adapted to the viscosity characteristics of a sludge/water mixture at higher sludge concentrations.

6.3 Recommendations

Since the values of the α-factor measurements were difficult to translate to the α-factor in a full-scale installation it is important to measure the standardized oxygen-transfer rate in all the pilot-installations. By comparing this value with the calculated oxygen transfer rate during operation conditions the actual α-factor can be calculated. The full-scale α-factor for each pilot-installation can be used for evaluation of the aeration/ mixing device and reactor configuration of the different pilot-installations.

The higher α-factors found for diffused air aeration compared to surface aeration can not be translated to the full-scale installation, since shear-forces in the test-unit were unknown.
Measurements of shear rate can help to translate α-factor measurements to full-scale reactor, aerator and mixer design.

Since no extreme sludge characteristics were observed during the test period it would be of interest to measure α-factors of activated sludge with excessive growth of filamentous bacteria or EPS production. Understanding of the relationship between sludge concentration and α-factor would be advised to determine each type of sludge associated α-factor/sludge concentration trend line. Supporting viscosity measurements would be advisable.

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stowa

Stichting Toegepast Onderzoek Waterbeheer

Development MBR technology for large wwtp's

Pilot-research wwtp Beverwijk

Side study 4: Effluent quality

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APPENDICES

1 INTRODUCTION

1.1 The project

Since April 2000 four MBR pilot systems have been in operation at the Beverwijk WWTP. The goal of the research was to investigate the technical feasibility of the MBR system and to compare the four systems.

In the main STOWA report the experiences with the MBR pilot systems are described. Especially the biological performances and the membrane performances are mentioned for each system. Alongside the main report five more fundamental side studies were carried out.

The five side studies are described and summarised in the main report. The subjects of these side studies were:

1. Pre-treatment
2. Fouling and cleaning
3. α - factor
4. Effluent quality
5. Sludge treatment

This report describes the investigation of the effluent quality of MBR systems (side study 4).

1.2 Side study: effluent quality

One of the main advantages of the MBR system is the "superior" effluent quality which can be achieved. The goal of side study 4 was to verify this statement and to verify this quantitatively. The results of this side study will be part of a future STOWA study on the possibilities of reaching MTR quality (minimum quality [ref. 8]) on a MBR system.

[redacted]

Figure 1 - WWTP effluent and MBR permeate

In this report the permeate data are coupled with the MBR system. It should be pointed out that there is no direct relation between the membrane type and the permeate quality. The results are indicative and cannot be statistically compared.

To illustrate: in Figure 1 the effluent of the Beverwijk wwtp secondary clarifier (left) and the permeate of the MBR pilot plants (right) are shown.

1.3 Reader

The set up of the study is described in chapter 2. In chapter 3 the results of a literature review are presented. In chapter 4 the results of the measurement programme are summarised and the evaluation of the results is described. The detailed results are presented in the appendices. The theoretical evaluation and the conclusions are presented in chapter 5.

2 SET UP

2.1 Introduction

On the Beverwijk wwtp 4 membrane bioreactors (MBR) are tested. During the testing period the influent and sludge composition has changed due to different types of primary treatment and phosphorus removal. The 4 phases of the research program are:

1. 03/2000 - 08/2000 : influent after primary sedimentation and preprecipitation;
2. 09/2000 - 12/2000 : influent after primary sedimentation and simultaneous precipitation;
3. 01/2001 - 05/2001 : raw waste water and simultaneous precipitation;
4. 06/2001 - 12/2001 : raw waste water and biological phosphorus removal.

During the different phases of the research programme additional measurements on effluent quality have taken place. The organisational and technical set up is described in this chapter. Besides the measurements a literature review has been performed by DHV.

2.2 Organisational set up

The measurement programme was defined in association with the USHN project group and the STOWA steering committee. The sampling and analyses have been executed by different laboratories, as shown in Table 1.

Table 1 - Analyses programme

parameters	phase 1	phase 2	phase 3	phase 4
microbial parameters	PWN	PWN	PWN	-
heavy metals	USHN	Analytico	USHN [1]	USHN [1]
polycyclic aromatic hydrocarbons (PAH's)	USHN	Analytico	USHN [1]	USHN [1]
extractable organic halogens (EOX's)	USHN	USHN	USHN	-
phthalates	-	Analytico	KIWA [1]	-

1: only measured for influent, effluent WWTP and Zenon and Kubota MBR permeate

Pesticides have not been measured as the measurement period was mainly in winter time, a period in which pesticides are not expected to be traceable in wastewater.

2.3 Technical set up

In general proportional samples were taken, except for the microbial quality measurements. The proportional samples were collected by USHN and DHV. The grab samples for bacteriological quality measurements were taken by PWN. Before the samples were taken, permeate side of the membranes were disinfected, except for the Kubota pilot in which this procedure is not possible.

The sampling points are schematically presented in Figure 2.

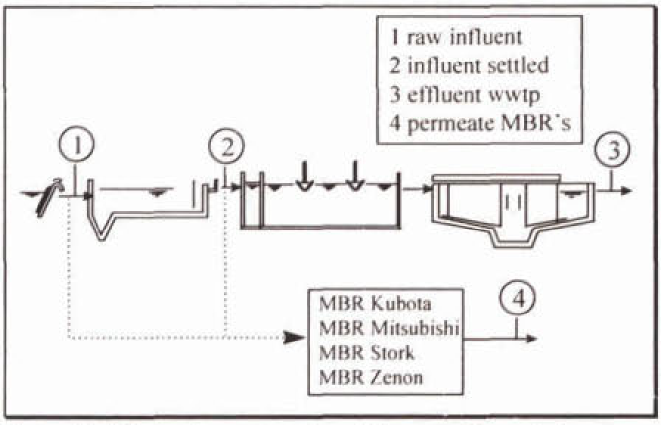

Figure 2 - Schematic presentation of the sampling points

3 LITERATURE REVIEW

3.1 Introduction

In general only COD, BOD, SS and nutrient removal in MBR systems are described in literature. The results on nutrient removal were often very good due to the very low loading of the systems. The SS permeate concentration was usually below detection level.

For a number of installations the microbial parameters were measured and published. The main results are presented in paragraph 3.2. In paragraph 3.3 results on other parameters are described.

3.2 Microbial parameters

Typical Zenon process effluent quality parameters are: BOD < 2 mg/l, SS < 1 mg/l, NH_4-N < 0.1 mg/l, TN (cold climates) < 10 mg/l, TN (warm climates) < 3 mg/l, TP (chemical treatment) < 0.1 mg/l, turbidity < 0.1 NTU, total coliforms < 100 cfu/100 ml, fecal coliforms < 20 cfu/100 ml, SDI < 3 [ref. 1].

Porlock and Kingston Seymour - Kubota

Extensive measurements have been carried out at the Porlock WWTP and at the Kingston Seymour pilot plant, both installations using Kubota plate membranes [ref. 2,3]. The Porlock WWTP is a full scale plant (capacity 80 m^3/h) which is in operation since 1998. The Kingston Seymour pilot plant was operated for 2.5 years by Wessex Water. The main results on both installations are presented in Table 2.

Table 2 - Effluent quality at the Porlock wwtp and the Kinston Seymour pilot plant

parameter	unit	E.G.[1]	Porlock WWTP			Kingston Seymour		
			influent	*effluent*	*removal*	*influent*	*effluent*	*removal*
suspended solids	mg/l	-	230	< 1	>99.5%	293	< 1.5	>99.5%
BOD	mg/l	-	224	< 4	>97%	216	< 4	>98%
COD	mg/l	-	-	-	-	604	< 23	>96%
Total coliforms	in 100 ml	500/10,000	-	-	-	$60 \cdot 10^6$	< 40	>log 6
Faecal coliforms	in 100 ml	100/2,000	$1.0 \cdot 10^7$	< 20	>log 6	$16 \cdot 10^6$	< 20	>log 6
Faecal streptococcus	in 100 ml	100/-	$1.3 \cdot 10^6$	< 11	>log 5	$1.4 \cdot 10^6$	< 13	>log 5
Coliphage virus	PFU/ml	2/10	811	< 19	>log 1.6	1,540	< 0.4	>log 3
Primate enterovirus	PFU/10 l	-/0	-	-	-	128	< 2	>log 1.8

1: European swimming water guideline from 8/12/1975 (ambition value for 80% of samples / limit value for 95% of samples)

At the Kingston Seymour pilot plant, a number of samples was analysed for virus removal monitoring both coliphage indicator virus and primate enterovirus. Removal efficiencies of 4 log are indicated. No enteroviruses have been detected in 20 samples of the final effluent (pfu/10 l) indicating > 3 log removal. It is concluded that, since the minimum dimension of the viruses monitored is of the order of 0.025 μm, their removal is likely to be via a combination of the dynamic ultrafiltration membrane layer formed on the base microfiltration membrane in operation, and adsorption of virus to larger particles.

California - Mitsubishi and Zenon

In the Aqua 2000 research Center in Califonia a pilot plant research has been executed, using a Mitsubishi and a Zenon pilot system [ref. 4]. Both systems showed good removal on total coliphorms and feacal coliphorms removal, as shown in Table 3. Permeate turbidity of both systems was < 0.1 NTU.

Table 3 - Effluent quality at the pilot plants in California [ref. 4]

parameter	**unit**	**influent**		**Mitsubishi**		**Zenon**	
		phase 1	**phase 2**	**phase 1**	**phase 2**	**phase 1**	**phase 2**
total coliphorms	MPN/100 ml	1.7×10^7	9.5×10^6	< 2	< 2	40	< 2
faecal coliphorms	MPN/100 ml	5.0×10^6	2.3×10^6	< 2	< 2	< 2	< 2
total coliphages	PFU/100 ml	1.4×10^4	4.5×10^3	< 1	< 1	< 1	< 1

The decrease in total coliphorms in phase 2 of the Zenon pilot is probably due to irreversible pore blocking of the membranes, which results in decreased particle breakthrough.
The coliphage removal was better than expected as the size is much smaller than the membrane pores. This reduction is probably due to virus particles absorbing to larger particles that are rejected by the membranes.

Immenstaad wwtp - Kubota and Zenon

On the Immenstaad wwtp in Germany a pilot plant research programm was executed [ref. 5]. Two pilot installations were tested; one with Zenon membranes and one with Kubota membranes. From the Immenstaad research it was concluded that in a technical good performing MBR installation, the microbial effluent quality requirements for swimming water can be obtained. An advantage of this membrane disinfection method is that the micro-organisms are totally removed and not just inactivated with a risk of re-activation.

Swanage wwtp - Kubota

According to Kubota, typical sewage concentrations are:

- faecal coliforms: 3×10^7 counts / 100 ml
- F+ bacteriophages: 2×10^3 counts / 100 ml

The Swanage wastewater treatment plant design criteria for bacteriological parameters are:

- faecal coliforms: < 100 counts/100 ml for 80% of minimum 20 samples in any year
  < 2,000 counts/100 ml for 95% of minimum 20 samples in any year
- F+ bacteriophages: < 2 PFU/ml for 80% of minimum 20 samples in any year
  < 10 PFU/ml for 95% of minimum 20 samples in any year

No data on the Swanage permeate quality are available at this moment.

3.3 Other parameters

Only one publication was found in which attention was paid to the removal of micro-pollutants [ref. 5]. Heavy metals, PCB's and AOX's were measured in the sludge of both MBR pilot installations and the Immenstaad WWTP. Except for Ni and Hg, the metal content of the MBR sludge was higher than for the WWTP sludge. In combination with a complete SS removal this will lead to a lower effluent concentration on these parameters. For PCB's the difference was negligible. The AOX content of the MBR sludge was higher due to the use of NaOCl for membrane cleaning.

AOX's, medical substances, pesticides and endocrine substances (phthalates) were measured in both the MBR's permeate and the Immenstaad WWTP effluent. The AOX level in the MBR permeates was equal to the conventional effluent. For all the other substances significant lower concentrations were measured in the MBR permeate. For instance, the di-n-butylphatalate concentration was reduced from 1,000 ng/l (WWTP) to 100-150 ng/l (MBR's).

Phthalates are xeno-oestrogenic compounds with can cause hormone disorder. Recently, a lot of attention is paid on this kind of compounds. From a research report from the ministry of "Verkeer en Waterstaat" [ref. 6] it is shown that the expected range of the total-phthalates is 1-70 μg/l for the raw influent and 0.5-7 μg/l for the effluent of a conventional wwtp. The total phthalates content of the sludge is 2.3-250 μg/g TSS.

4 RESULTS

4.1 Introduction

In this chapter the results of the measurements are presented and a comparison is made between the MBR permeate and the WWTP effluent quality. For phase 3 and 4 it should be noted that the feed to both systems differed; raw wastewater for the MBR's, influent after primary clarification for the WWTP.

4.2 Microbial quality

The microbial parameters which were determined at the Beverwijk pilots were:

- colony number at 22° as an indicator for the bacteria population at operating conditions;
- thermo-tolerant coli-bacteria (at 44°C) as an indicator for faecal contamination;
- bacteriophages as an indicator for entero-viruses.

The measurements were carried out twice in each research phase for the permeates of the MBR pilot systems as well as for the influent and effluent of the Beverwijk WWTP. The results are summarised in Table 4. For the comparison between the conventional treatment and the MBR system, the results of the 4 pilot plants are presented together. The detailed results, including the colony number measurements, are presented in appendix 1.

Table 4 - Microbial measurements (2 measurements for each phase)

parameter	phase	raw influent	settled influent	effluent WWTP	permeate MBR's
thermotolerant coli-bacteria [in 100 ml]	1	-	$3 \cdot 10^5 / 3 \cdot 10^6$	$4 \cdot 10^4 / 2 \cdot 10^5$	0
	2	-	$3 \cdot 10^5 / 8 \cdot 10^5$	$2 \cdot 10^4 / 2 \cdot 10^5$	0
	3	$1 \cdot 10^3 / 2 \cdot 10^5$	-	$4 \cdot 10^4 / 7 \cdot 10^4$	0
bacteriophages [pfu/ml]	1	-	17 / 16	1,000 / 100	0.1 - 10 [1]
	2	-	7 / 853	12 / 75	0.01 - 0.3 [1]
	3	$1 \cdot 10^4 / 1 \cdot 10^4$	-	610 / 770	1 - 100 [1]

1: a range is presented as the separate values show major variations

From the measurements it can be concluded that the thermotolerant coli-bacteria are removed completely. The MTR value amounts 20 MPN/ml for 80% of the samples.
The results on bacteriophages showed relatively major variations. In general it can be concluded that the bacteriophage concentration in a MBR permeate was 100 to 1,000 times lower than in the WWTP effluent. The MTR value for viruses and bacteriophages amounts 0 per 10 l.

4.3 Heavy metals

The heavy metals have been measured extensively in phase 1, 3 and 4. In phase 2 only two measurements have taken place. The detection limit in phase 1 and 2 was relatively high compared to phase 3 and 4. As a consequence the phase 3 and 4 results give the best impression on the heavy metal removal.

In Table 5 the average results of the phase 3 measurements are presented. The detailed results of phase 2, 3 and 4 are presented in appendix 2.

Table 5 - Heavy metal measurements in phase 3 (in µg/l, averages of 6 DWF measurements)

process flow	As	Cd	Cr	Cu	Hg	Pb	Ni	Zn
raw influent	< 11	< 2.5	13.2	89	0.26	49	< 12	332
WWTP effluent	0.98	0.038	0.96	1.9	0.04	1.1	4.2	32.4
Zenon permeate	0.84	0.006	0.79	**0.51**	**0.01**	0.57	4.5	27.3
Kubota permeate	1.07	0.003	0.93	0.80	**0.03**	0.63	3.5	**19.4**
improvement by MBR[1] [in %]	*2*	*87*	*11*	*66*	*51*	*45*	*4*	*28*

[1] based on a comparison between the average MBR permeate concentration (both Zenon and Kubota) and the average WWTP effluent concentration

Because individual results can vary, a statistical evaluation has been performed. Statistically (using a students T-test) only the bold values in Table 5 show a significant improvement compared to the WWTP effluent concentration. Based on the average values the Cd, Cu, Hg, Pb and Zn concentration tended to decrease in a MBR system. The same trends were measured in phase 1.

The phase 4 measurements show a different picture. The absolute differences between the MBR permeates and the WWTP effluent were smaller. For some metals (As, Hg, Ni, Zn) the WWTP effluent showed a better quality. For Cd and Cr one respectively two peak values (>10 times higher than the other average values) were measured in the MBR permeates, which influenced the average values enormously. If those 3 peak values are not taken into account, the same improvement as measured in phase 3 was found.

The differences between the effluent and the permeate, and the differences between the phase 3 and phase 4 measurements, can be related to the following operational differences:

- primary clarification on Beverwijk WWTP, raw wastewater on the MBR's in phase 3 and 4;
- simultaneous chemical dosing on Beverwijk WWTP and the MBR's in phase 3, no dosing in phase 4.

From the results shown in this paragraph one can conclude that the number of measurement is too small for a statistical evaluation of the results and additional measurements under well-defined equal circumstances are required. This will be done in the STOWA project on the Maasbommel WWTP.

4.4 PAH's

The results the Polycyclic Aromatic Hydrocarbons measurements in phase 3 are summarised in Table 6. The measurement results from phase 1 are not presented in the table as the results showed merely non-detectable levels for the effluent and the permeates. The phase 2 measurements were only 2 days. The detailed results of phase 2, 3 and 4 are presented in appendix 3.

Table 6 - Total PAH's (EPA 16, µg/l) in phase 3

date	raw influent	effluent WWTP	permeate Kutoba	permeate Zenon
07-03-01	12.3	0.144	0.006	0.017
08-03-01	4.6	0.126	0	0
09-03-01	5.8	0.120	0	0.061
13-03-01	7.7	0.081	0	0
15-03-01	6.3	0.047	0.012	0.069
16-03-01	5.3	0.091	0.006	0.005

From the phase 3 results a clear difference between the conventional WWTP and the 2 MBR systems is shown. During phase 3 the effluent quality improved significantly from (on average) 0.10 μg/l for the conventional system to around 0.005-0.025 μg/l for the Kubota and Zenon MBR system respectively. This corresponded with an effluent quality improvement of 96 and 75% respectively.

According to the Dutch average values [ref. 6] the average total PAH's content of the sludge amounted to 10 μg/g TSS. Assuming an average SS effluent concentration of 10 mg/l, the additional PAH's removal with a MBR system would amount to 0.1 μg/l, which corresponds with the above presented measured values.

From the phase 4 results the difference between the conventional WWTP and the 2 MBR systems is less clear. The effluent quality improved from (on average) 0.07 μg/l for the conventional system to around 0.05 μg/l for both the Kubota and the Zenon MBR system. This corresponded with an effluent quality improvement of around 30%, which is less than expected according to the above presented calculation. This may be related to the factors discussed in the previous paragraph.

From the phase 3 measurements and the above presented calculation, it can be concluded that the PAH's are mostly attached to sludge. By decreasing the effluent sludge concentration, the PAH's level can be reduced to nearly complete removal.

4.5 EOX's

EOX is a sum parameter for halogenated organic compounds, expressed as chloride. As NaOCl is used for membrane cleaning, chlorine compounds are introduced in the MBR system on a regular basis. In the analyses programme the cleaning procedures were not taken into consideration. As a consequence, high peak EOX concentrations were measured at some of the pilot plants. The occurrence and height of those peak values is coincidental and can not be related to the membrane system.

The average EOX concentrations under normal conditions (excluding the peak measurements during or after a chemical cleaning), are presented in Table 7. To illustrate the peak values measured for each installation are added to the last row of the table. The detailed results for all phases are presented in appendix 4.

Table 7 - Average EOX concentration (in μg/l)

Phase	Influent settled	Beverwijk effluent	Kubota permeate	Mitsubishi permeate	X-Flow permeate	Zenon permeate
1	5.0	1.1	0.5	0.8	2.0	1.0
2	4.0	1.8	0.3	0.7	2.4	0.4
3	5.2	1.6	1.0	2.4	1.8	1.9
peak values	*14*	*7.4*	*19 / 54*	*270*	*7.5*	*8.8*

Based on the average values, statistically only the Kubota MBR yielded a significant better performance than the Beverwijk WWTP effluent. In general, it can be concluded that due to regular chemical cleaning the effluent EOX discharge will increase. Based on the measurements this was hard to quantify.

In a full scale design attention should be paid to the cleaning procedures, to limit the EOX increase in the permeate. This item is being investigated in the pilot plant research program at Beverwijk. Both the cleaning procedures and the dosing concentrations are being optimised.

4.6 Phthalates

The phthalates have been analysed in phase 2 and 3. The results are summarised in Table 8. The detailed results are presented in appendix 5.

Table 8 - Phthalates total in phase 2 and 3 (in μg/l)

flow	phase 2		phase 3	
	01-03-01	*01-04-01*	*03-06-01*	*03-07-01*
influent raw	5.8	36.6	21.3	19.4
influent settled	11.9	11.9	-	-
effluent wwtp	< 1	< 1	3.9	4.2
Kubota	< 1	< 1	5.9	5.5
Mitsubishi	1.2	< 1	-	-
X-Flow	3.3	1.3	-	-
Zenon	< 1	< 1	3.2	3.7

In phase 2 the analyses were executed by Analytico. The detection level of these analyses amounted 1 μg/l for each phthalate component. As shown in Table 8 the detection level was limiting for most of the permeate flows. Therefore the analyses were executed by KIWA in phase 3. The detection limit of their analyses amounted 0.1 μg/l for each phthalate component.
From the measurements no conclusions on the difference between MBR and WWTP can be drawn. This is partly due to the small amount of measurements executed.

5 EVALUATION AND CONCLUSIONS

5.1 Theoretical evaluation

Due to the limited number of analyses performed in this study it is difficult to quantify the removal efficiency of the MBR systems in comparison to the conventional WWTP. As a consequence it is difficult to draw conclusions on the benefits of the MBR system. Therefore in this paragraph, the results on the heavy metal measurements are theoretically evaluated, based on mass balances.

The theoretical effluent quality improvement has been estimated, using literature values for heavy metal content of the sludge. The results of this evaluation are presented in Table 9 and compared to the maximum acceptable risk (MTR) quality.

Table 9 - Theoretical evaluation of heavy metal removal

parameter		unit	As	Cd	Cr	Cu	Hg	Pb	Ni	Zn
content sludge	CBS [1]	[mg/kg TS]	7,5	1,8	50	390	1,4	140	33	865
effluent quality	CBS [1]	[µg/l]	1,5	0,18	3,6	12,5	0,06	6,0	10,1	55,5
	MBR [2]	[µg/l]	1,4	0,16	3,1	8,6	0,05	4,6	9,8	46,9
	MTR	[µg/l]	25	0,40	8,7	1,5	0,02	5,1	11,0	9,4
improvement	calculated [3]	[%]	5	10	14	31	23	23	3	16
	measured [4]	[%]	2	87	11	66	51	45	4	28

[1] based on the Dutch average measured values for public wwtp's in 1997 [ref. 7]

[2] calculated, based on the CBS values and an average effluent quality of 10 mg SS/l for conventional wwtp's

[3] calculated based on the above mentioned starting points

[4] measured in phase 3 of the Beverwijk pilot research, as presented in Table 5

In general, the theoretical evaluation shows a similar tendency for the effluent quality improvement compared to the Beverwijk pilot measurements. Except for cadmium which is available at Beverwijk at much lower concentrations than average and consequently gives a much better relative improvement.

5.2 Conclusions

From the Beverwijk research and experiences on other MBR's it is concluded that in a technical good performing MBR installation, the microbial effluent quality requirements for swimming water can be obtained. In the literature on MBR's little attention is paid to the micro-pollutants in the effluent.

From the Beverwijk measurement results presented it can be concluded that by using a MBR system the effluent quality improves significantly for microbial parameters, heavy metals (especially Cu, Hg, Pb and Zn) and PAH's. The EOX discharge will probably increase due to the NaOCl use for chemical cleaning, attention has to be paid to this in a full scale design. For the phthalates no difference has been observed between the MBR permeate and the WWTP effluent.

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Appendix 1 Microbial parameters

Table 10 - Microbial quality in phase 1

	date [-]	colony number at 22°C [kvd/ml]	thermotolerante bacteria [/100 ml]	bacteriophages [pfu/ml]
effluent requirement		-	20,000	0.10
influent settled	8-aug-00	70,000 - 380,000	260,000 - 280,000	14 - 21
	17-aug-00	1,000,000-2,500,000	2,970,000-3,190,000	15 - 17
effluent wwtp	8-aug-00	25,000 - 360,000	150,000 - 200,000	960 - 1,480
	17-aug-00	4,100 - 21,000	25,000 - 57,000	81 - 208
permeate Zenon	8-aug-00	290	0	0.40
	17-aug-00	980	0	0.00
permeate Kubota	8-aug-00	340	0	3.5
	17-aug-00	1,700	0	12.8
permeate X-Flow	8-aug-00	130	350	9.4
	17-aug-00	4,700	0	0.06
permeate Mitsubishi	8-aug-00	540	2	1.9
	17-aug-00	36,000	1	0.10

Table 11 - Microbial quality in phase 2

	date [-]	colony number at 22°C [kvd/ml]	thermotolerante bacteria [/100 ml]	bacteriophages [pfu/ml]
influent settled	3-jan-01	410,000	275,000	7
	4-jan-01	460,000	825,000	853
effluent wwtp	3-jan-01	9,600	20,000	12
	4-jan-01	36,000	165,000	75
permeate Zenon	3-jan-01	1,800	0	0.07
	4-jan-01	3,900	0	0.03
permeate Kubota	3-jan-01	0	0	0
	4-jan-01	3,100	0	0.02
permeate X-Flow	3-jan-01	5	0	0.30
	4-jan-01	80	0	0.20
permeate Mitsubishi	3-jan-01	21,000	0	0.07
	4-jan-01	25	0	0.03

Table 12 - Microbial quality in phase 3

	date [-]	colony number at 22°C [kvd/ml]	thermotolerante bacteria [/100 ml]	bacteriophages [pfu/ml]
influent settled	27-feb-01	510,000	99,000	10,000
	28-feb-01	60,000	240,000	10,000
effluent wwtp	27-feb-01	35,000	37,000	610
	28-feb-01	26,000	69,000	770
permeate Zenon	27-feb-01	22	0	3.3
	28-feb-01	16	0	54
permeate Kubota	27-feb-01	26	0	8.6
	28-feb-01	42	0	40
permeate X-Flow	27-feb-01	90	0	2.4
	28-feb-01	290	0	1.6
permeate Mitsubishi	27-feb-01	590	56	54
	28-feb-01	1,900	40	109

Appendix 2 Heavy metals

Table 13 - Heavy metals in phase 2 (in μg/l)

date	sample	as	cd	cr	cu	hg	pb	ni	zn
detection limit		5	5	5	5	0.1	5	5	10
3-1-01	raw influent			6.1	19		41		250
	settled influent			9.1	24		16		130
	effluent			6.5					23
	Zenon permeate								9.1
	Kubota permeate			6.1					26
	X-Flow permeate			6.5					38
	Mitsubishi permeate			6.7				6.2	24
4-1-01	raw influent				16		6.7		67
	settled influent	5.4		7.0	27		18		150
	effluent			6.6					38
	Zenon permeate			7.3					23
	Kubota permeate			15				8.7	60
	X-Flow permeate			6.8					54
	Mitsubishi permeate			13	5.6				22

Table 14 - Heavy metals in phase 3 (in μg/l)

date	sample	as	cd	cr	cu	hg	pb	ni	zn
7-3-01	raw influent	<11	<2.5	13	82	0.385	40	<12	270
	Zenon permeate	0	0	1.1	0.98	0.006	1.07	4.66	21.5
	Kubota permeate	0.34	0	1.18	0.68	0.003	1.07	4.21	22.6
	effluent	0	0	1.06	1.97	0.001	1.13	5.28	23.3
8-3-01	raw influent	<11	<2.5	14	98	0.05	60	<12	400
	Zenon permeate	1.84	0.014	1.02	0.81	0.004	0.35	3.79	20.6
	Kubota permeate	1.21	0	0.81	0.59	0.114	0.36	3.94	18.3
	effluent	1.25	0.071	1.1	2.91	0.004	0.72	5.2	58.5
9-3-01	raw influent	<11	<2.5	13	77	0.155	44	<12	320
	Zenon permeate	1.28	0	0.86	0.48	0.002	0.4	3.78	14.9
	Kubota permeate	1.41	0	1.25	2.59	0.006	0.37	5.49	19.7
	effluent	1.61	0.139	1.14	0.51	0.001	0.98	3.97	24.3
13-3-01	raw influent	<11	<2.5	10	82	0.59	53	<12	340
	Zenon permeate	0.99	0.003	0.51	0.8	0.008	0.52	2.64	23.5
	Kubota permeate	1.22	0.003	0.58	0.93	0.008	0.57	2.31	23.1
	effluent	0.97	0.014	0.68	3.03	0.014	1.28	3.4	36.1
15-3-01	raw influent	<11	<2.5	15	100	0.166	44	<12	350
	Zenon permeate	0.7	0.021	0.55	0	0.012	0.6	4.3	35.5
	Kubota permeate	1.69	0	0.88	0	0.008	0.75	2.37	18.8
	effluent	1.18	0.005	0.91	2.1	0.013	1.44	3.29	28.2
16-3-01	raw influent	<11	<2.5	14	96	0.197	51	<12	310
	Zenon permeate	0.23	0	0.71	0	0.011	0.46	7.86	47.6
	Kubota permeate	0.55	0.017	0.87	0	0.037	0.65	2.71	13.6
	effluent	0.84	0.001	0.88	0.94	0.19	0.99	3.86	23.9

Table 15 - Heavy metals in phase 4 (in µg/l)

date	sample	as	cd	cr	cu	hg	pb	ni	zn
26-6-01	raw influent	<11	<2,5	8	23	0,044	6	<12	130
	Zenon permeate	2,17	**0,172**	**6,3**	1,76	0	1,58	5,51	37
	Kubota permeate	1,22	0	0,62	0,81	0	1,25	5,25	19
	effluent	0,6	0	1,13	1,52	0	1,43	3,58	15
29-6-01	raw influent	<11	<2,5	<5	<90	0,098	29	<12	310
	Zenon permeate	1,5	0,001	0,71	1,84	0	1,33	5,21	38
	Kubota permeate	1,18	0	0,61	1,22	0	1,29	5,37	33
	effluent	0,59	0	0,6	0,88	0	1,42	3,4	23
3-7-01	raw influent	<11	<2,5	5	100	0,022	30	12	230
	Zenon permeate	0,98	0,007	0,75	1,41	0,014	1,56	5,06	41
	Kubota permeate	0,4	**0,121**	0,53	0,51	0,037	1,47	4,7	18
	effluent	1,27	0,063	0,61	1,61	0,047	1,39	3,94	24
4-7-01	raw influent	<11	<2,5	<5	110	0,018	39	<12	230
	Zenon permeate	0,92	0	0,67	0,47	0,008	1,43	4,44	89
	Kubota permeate	0,94	0	0,65	0,88	0,008	1,12	4,67	20
	effluent	0,71	0,002	0,95	1,85	0,01	1,51	3,61	26
6-7-01	raw influent	<11	<2,5	7	120	0,013	26	<12	230
	Zenon permeate	0,83	0,01	0,73	0,7	0,035	1,52	5,29	17
	Kubota permeate	1,14	0	0,8	1,76	0,031	1,44	5,67	25
	effluent	1,13	0,001	0,89	2,85	0,004	1,89	3,81	35

Appendix 3 PAH´s

Table 16 - PAH's in phase 2 (VROM 10) (white = lower than detection level)

	Datum [-]	Naft [ug/l]	Ant [ug/l]	Fen [ug/l]	Fluor [ug/l]	B(a)a [ug/l]	Chry [ug/l]	B(k) [ug/l]	B(a)p [ug/l]	B(g) [ug/l]	Inden [ug/l]
MTR		1.2	0.08	0.3	0.5	0.03	0.9	0.2	0.2	0.5	0.4
Detectiegrens		0.010	0.005	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010
Ruw influent	3-jan-01	1.2	0.082	0.46	0.38	0.072	0.09	0.03	0.07	0.044	0.05
	4-jan-01	0.38	0.012	0.16	0.11	0.018	0.029		0.016	0.015	0.016
VBT influent	3-jan-01	0.29	0.015	0.14	0.13	0.026	0.038	0.012	0.024	0.02	0.025
	4-jan-01	0.32	0.022	0.19	0.19	0.038	0.04	0.016	0.033	0.036	0.036
NBT effluent	3-jan-01			0.025	0.013						
	4-jan-01					0.012	0.024		0.011		
Zenon	3-jan-01			0.029							
	4-jan-01			0.015							
Kubota	3-jan-01			0.038							
	4-jan-01	0.22		0.099	0.21		0.011			0.013	0.018
X-Flow	3-jan-01			0.026							
	4-jan-01										
Mitsubishi	3-jan-01			0.022							
	4-jan-01			0.024							

Naft = Naftaleen. Ant = Anthraceen. Fen = Fenanthreen. Fluor = Fluorantheen. B(a)a = Benzo(a)anthraceen. Chry = Chryseen. B(k) = Benzo(k)fluorantheen. B(a)p = Benzo(a)pyreen. B(g) = Benzo(ghi)peryleen. Inden = Indeno(123-cd)pyreen

Table 17 - PAH's in phase 3, in μg/l (EPA 16)

		acenafteen	acenaftyleen	anthraceen	benzo(a)anthrace	benzo(a)pyreen	benzo(b)fluoranth	benz(ghi)peryleen	benzo(k)fluorathe	chryseen	dibenz(ah)anthrac	fenantreen	fluoreen	fluorantheen	indeno(123cdpyre	naftaleen	pyreen	PAH's total
7-3-01	settled infleunt	0,31	0,389	0,267	1,119	0,975	0,977	0,571	0,473	0,997	0,204	1,554	0,248	1,893	0,691	0,258	1,404	12,33
	Zenon, permeate	0	0	0	0	0	0	0	0	0	0	0,005	0	0	0,012	0	0	0,017
	Kubota, permeate	0	0	0	0	0	0	0	0	0	0	0,006	0	0	0	0	0	0,006
	wwtp, effluent	0	0,068	0	0,009	0,008	0,012	0	0,005	0	0,006	0,015	0	0	0,009	0	0,012	0,144
8-3-01	settled infleunt	0,129	0,347	0,1	0,37	0,311	0,339	0,194	0,163	0,344	0,062	0,523	0,105	0,671	0,21	0,132	0,566	4,566
	Zenon, permeate	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0,000
	Kubota, permeate	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0,000
	wwtp, effluent	0	0,057	0,002	0,008	0,009	0,011	0,006	0,004	0,007	0	0	0	0	0,009	0	0,013	0,126
9-3-01	settled infleunt	0,222	0,501	0,134	0,419	0,353	0,405	0,228	0,188	0,396	0,07	0,669	0,149	0,911	0,258	0,231	0,675	5,809
	Zenon, permeate	0	0,058	0,003	0	0	0	0	0	0	0	0	0	0	0	0	0	0,061
	Kubota, permeate	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0,000
	wwtp, effluent	0	0,073	0,002	0,007	0,006	0,008	0,004	0	0	0	0	0	0	0,009	0	0,011	0,120
13-3-01	settled infleunt	0,243	0,19	0,147	0,65	0,609	0,6	0,382	0,315	0,597	0,124	0,763	0,148	1,281	0,415	0,233	0,996	7,693
	Zenon, permeate	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0,000
	Kubota, permeate	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0,000
	wwtp, effluent	0	0,018	0	0,008	0,009	0,012	0,006	0,004	0	0	0	0	0	0,011	0	0,013	0,081
15-3-01	settled infleunt	0,253	0,362	0,094	0,477	0,444	0,482	0,294	0,236	0,452	0,091	0,833	0,174	0,871	0,339	0,236	0,705	6,343
	Zenon, permeate	0	0,038	0	0	0,006	0,008	0,005	0	0	0	0,006	0	0	0,006	0	0	0,069
	Kubota, permeate	0	0	0	0	0	0	0	0	0	0	0,009	0	0	0,003	0	0	0,012
	wwtp, effluent	0	0	0	0,007	0,006	0,008	0	0	0	0	0,01	0	0	0,007	0	0,009	0,047
16-3-01	settled infleunt	0,243	0,344	0,074	0,384	0,344	0,371	0,223	0,182	0,371	0,072	0,703	0,152	0,74	0,256	0,192	0,667	5,318
	Zenon, permeate	0	0	0	0	0	0	0	0	0	0	0,005	0	0	0	0	0	0,005
	Kubota, permeate	0	0	0	0	0	0	0	0	0	0	0,006	0	0	0	0	0	0,006
	wwtp, effluent	0	0,049	0	0,005	0,006	0,009	0	0	0	0	0,012	0	0	0	0	0,01	0,091

Table 18 - PAH's in phase 4, in µg/l (EPA 16)

	acenaftaleen	acenaftyleen	anthraceen	benzo(a)anthracee	benzo(a)pyreen	benzo(b)fluoranthe	benzo(ghi)peryleen	benzo(k)fluoranthe	chryseen	dibenz(ah)anthrace	fenantreen	fluoreen	fluorantheen
26-6-01 B'wijk. verdeelwerk	0.119	1.735	0.078	0.102	0.08	0.099	0.054	0.046	0.104	0.016	0.367	0.085	0.306
26-6-01 B'wijk.pilot Zenon.permeaat	0	0	0	0	0	0	0	0	0	0	0.01	0	0.04
26-6-01 B'wijk.pilot Kubota.permeaat	0	0.07	0	0	0	0	0	0	0	0	0	0	0
26-6-01 B'wijk. effluent	0	0.38	0	0	0	0	0	0	0	0	0	0	0
29-6-01 B'wijk. verdeelwerk	0.159	1.096	0.081	0.168	0.141	0.168	0.098	0.081	0.173	0.029	0.513	0.111	0.42
29-6-01 B'wijk.pilot Zenon.permeaat	0	0.041	0.005	0	0	0.005	0	0	0	0	0.01	0	0
29-6-01 B'wijk.pilot Kubota.permeaat	0	0	0.003	0.003	0	0.005	0.002	0	0	0	0.008	0	0.021
29-6-01 B'wijk. effluent	0	0.046	0.003	0.003	0.002	0.006	0	0	0.005	0.003	0.012	0	0
3-7-01 B'wijk. verdeelwerk	0.082	0.212	0.047	0.066	0.059	0.072	0.042	0.035	0.073	0.013	0.227	0.053	0.218
3-7-01 B'wijk.pilot Zenon.permeaat	0	0	0.002	0	0	0.007	0.003	0	0	0	0	0	0
3-7-01 B'wijk.pilot Kubota.permeaat	0	0.032	0.004	0	0	0	0	0	0	0	0.012	0	0
3-7-01 B'wijk. effluent	0	0.051	0.004	0.003	0	0.006	0.003	0	0	0	0.01	0	0
4-7-01 B'wijk. verdeelwerk	0.133	0.564	0.076	0.13	0.104	0.131	0.072	0.063	0.13	0.021	0.409	0.081	0.408
4-7-01 B'wijk.pilot Zenon.permeaat	0	0.059	0	0	0	0.008	0.002	0	0	0.002	0.009	0	0
4-7-01 B'wijk.pilot Kubota.permeaat	0	0	0.007	0	0	0.008	0	0	0	0	0.021	0	0
4-7-01 B'wijk. effluent	0	0	0.004	0	0	0.008	0.004	0	0	0.002	0.01	0	0
6-7-01 B'wijk. verdeelwerk	0.13	0	0.053	0.07	0.054	0.067	0.038	0.032	0.072	0.01	0.34	0.081	0.234
6-7-01 B'wijk.pilot Zenon.permeaat	0	0	0	0.002	0	0	0	0	0	0	0.01	0	0
6-7-01 B'wijk.pilot Kubota.permeaat	0	0	0.006	0	0	0.006	0	0	0	0	0.009	0	0
6-7-01 B'wijk. effluent	0	0	0.004	0	0	0.007	0.002	0	0.006	0	0.011	0	0

Appendix 4 EOX´s

Table 19 - EOX's in phase 1, 2 and 3 (in µg/l)

Date	Influent settled	wwtp effluent	Kubota permeate	Mitsubishi permeate	X-Flow permeate	Zenon permeate
7-4-00	10					4.9
20-4-00	4.7					1.7
27-4-00	5.6					0.9
4-5-00	11		3.2	2.3	2.1	1
19-5-00	4.2		0.8	2	1.6	1.3
26-5-00	3.9			0.7	1.6	<0.5
31-5-00	8		<0.5	0.9	1	1.1
9-6-00	6.9		1	1.4	5.6	1
16-6-00	3.2		0.6	0.8	5.9	0.6
23-6-00	4.6		<0.5	1	7.5	2.2
30-6-00	6.5		<0.5	0.5	4.2	0.9
7-7-00	4.9		0.6	<0.5	2.6	1
14-7-00	2.5		1.1	0.7	1.6	0.8
21-7-00	4.3		0.9	0.6	1.8	1
28-7-00	4.3		<0.5	<0.5	<0.5	<0.5
3-8-00	14	1.5	0.6	0.7	0.7	0.6
4-8-00	7.6	<0.5	<0.5	<0.5	0.6	0.6
11-8-00	7	<0.5	0.7	0.8	3.8	1.5
14-8-00	6.6	1	0.6	0	0	0
16-8-00	5.4	3.5	19	2.8	0	0
18-8-00	3.8	<0.5	<0.5	2.2	0.7	1.4
21-8-00	5.3	1.6	<0.5	<0.5	0	0
25-8-00	4.5	0	<0.5	<0.5	<0.5	0.5
1-9-00	5.8	0	<0.5	<0.5	<0.5	<0.5
8-9-00	4.3	2.3	<0.5	<0.5	<0.5	0.6
15-9-00	<0.5	0	0.7	<0.5	0.6	<0.5
22-9-00	4.2	<0.5	<0.5	<0.5	0.5	0.7
29-9-00	5.3	0.9	1.3	0.9	1	1
6-10-00	3.6	<0.5	<0.5	<0.5	0	<0.5
20-10-00	4.3	0	0.6	1.6	0	0.5
27-10-00	5.8	0	1.3	1.7	1.4	<0.5
3-11-00	3.5	0.9	<0.5	0	2.4	<0.5
10-11-00	1.8	0.5	<0.5	0	<0.5	<0.5
17-11-00	2.9	0.8	<0.5	0.7	4.2	0.7
24-11-00	0	<0.5	<0.5	<0.5	4.9	<0.5
1-12-00	4.7	7.4	<0.5	1.2	3.3	1.1
8-12-00	3.3	0	<0.5	<0.5	0	<0.5
15-12-00	2.3	0	0	<0.5	0	<0.5
22-12-00	4.1	3.3	0	270	1.5	0.9
5-1-01	7.9	1.2	0.8	0.9	1.6	1.6
12-1-01	6.9	<0.5	2.3	0.9	5.6	1
19-1-01	1.2	0.5	0	1	0.9	1.1
26-1-01	6	6.3	1	9.9	1.4	8.8
2-2-01	6.6	0.8	0.9	1	1.6	1.2
9-2-01	2	3.8	54	1.9	1.7	<0.5
16-2-01	4.5	<0.5	0.6	0.9	<0.5	0.9
23-2-01	9.2	<0.5	<0.5	0.9	1.1	0.6

Appendix 5 Phthalates

Table 20 - Phthalates in phase 3 (in µg/l)

date	phthalate	influent raw	effluent wwtp	Kubota	Zenon
6-3-01	dimethylphthalate	1,4	0,15	0,21	0,18
	diethylphthalate	10	0,12	0,21	0,14
	diisobutylphatalate	2,1	0,84	1,2	1,1
	di-n-butylphthalate	0,98	0,66	1,1	0,22
	diisoctylphthalate	6,5	1,9	3,0	1,3
	di-n-octylphthalate	0,33	0,24	0,21	0,24
	TOTAL	*21,3*	*3,9*	*5,9*	*3,2*
7-3-01	dimethylphthalate	1,2	0,16	0,08	0,17
	diethylphthalate	10	1,09	0,18	0,35
	diisobutylphatalate	2,4	0,67	0,83	0,69
	di-n-butylphthalate	1,0	0,27	0,34	0,21
	diisoctylphthalate	4,5	1,8	3,9	2,0
	di-n-octylphthalate	0,25	0,24	0,19	0,26
	TOTAL	*19,4*	*4,2*	*5,5*	*3,7*

stowa

Stichting Toegepast Onderzoek Waterbeheer

Development MBR technology for large WWTP's

Pilot-research WWTP Beverwijk

Side study 5: Sludge treatment

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1 INTRODUCTION

1.1 The project

Since April 2000 four MBR pilot systems have been in operation at the Beverwijk WWTP. The goal of the research was to investigate the technical feasibility of the MBR system and to compare the four systems.

In the main STOWA report the experiences with the MBR pilot systems are described. Especially biological performances and membrane performances are mentioned for each system. Alongside the main report five more fundamental side studies were carried out.

The five side studies are described and summarised in the main report. The subjects of these side studies were:

1. Pre-treatment
2. Fouling and cleaning
3. α - factor
4. Effluent quality
5. Sludge treatment

This report describes the investigation of sludge digestion and sludge de-watering of MBR systems (side study 5).

1.2 Side study: Sludge digestion and de-watering

MBR technology has several advantages compared to traditional activated sludge processes, e.g. high effluent quality, limited space requirements and modular set up. However, the structure and composition of the MBR sludge can be considerably different from sludge seen in conventional WWTP's. Considering that half the exploitation costs from a conventional WWTP are related to sludge treatment, a good overview of the handling of MBR sludge was necessary. A better effluent quality produced by an MBR-system could be offset against an unworkable sludge quality, thus reducing the applicability of MBR for the municipal market.
Side study 5 was directed towards additional sludge characterisation tests to determine the workability of MBR-sludge.

The goal of this side study was to:

1. investigate the gas production in relation to the degradability of MBR sludge in comparison with activated sludge from a conventional WWTP;
2. investigate the digestion of MBR sludge in relation to the dewaterability ;
3. investigate the thickening of MBR sludge in comparison with activated sludge from a conventional WWTP;
4. investigate the de-watering of MBR sludge in comparison with activated sludge from a conventional WWTP;
5. define further investigation into treating MBR sludge.

1.3 Reader

In chapter 2 the set up and organisation of the side study is defined.
In chapter 3 the set up of the digestion experiment is given and the results of the practical tests are presented. In chapter 4 the set up and results of the thickening experiments are given, followed by the set up and results of the de-watering in chapter 5.
In chapter 6 conclusions are drawn and recommendations are given. Also topics for further investigation are discussed.

2 SET UP OF SIDE STUDY

2.1 Organisation of side study

After analysis of documented sludge treatments in MBR systems, it was realised that the available knowledge was severely limited, particularly with respect to municipally generated MBR sludge. Most installations were very low loaded biologically and thus produced small sludge volumes. The sludge that was produced was often transported to centralised sludge treatment works where the volume was effectively lost in the overall process. There was some reference to thickening using filter presses but always on a small scale - no serious work had been directed to larger installations addressing the dilemma of quantity and quality of the sludge produced. The following three items were highlighted as key study points requiring attention: digestion, thickening and de-watering.

Each of these items was investigated separately. The digestion test, thickening tests and part of the de-watering tests were carried out at DHV's Water Research Laboratory (DHV-WRL). The de-watering tests with the centrifuges were executed at Beverwijk WWTP.

2.2 Test conditions

The degradability, thickening and de-watering tests have been carried out with the four different MBR sludges in comparison with the activated sludge from the Beverwijk WWTP (AT-sludge).

Digestion

The digestion of the sludge was tested using two basic methods. The first method was a batch test where the digested sludge from a working digester was fed with the different sludge types from the MBR systems, as well as activated sludge from Beverwijk WWTP. The second method was a semi-continuous laboratory digestion test using sludge from the Zenon MBR in comparison to a mixture of primary and secondary sludge from a conventional WWTP.

Thickening and de-watering

The thickening and de-watering tests were executed using various types of equipment. These methods are described in separate chapters in this report.

Phasing of the research

During the testing period three phases could be distinguished, and the sludge characterisation and sludge testing bridged these phases. These phases are distinguished in the main report and were based on the different types of influent fed to the MBR's. The phases are summarised in Table 1.

Table 1 - phases of the MBR research

phase 1	influent after primary sedimentation and pre-precipitation
phase 2	influent after primary sedimentation and simultaneous precipitation
phase 3	raw screened influent and simultaneous precipitation and bio-P removal

Choice of Poly-electrolyte

Prior to the thickening and de-watering tests, a suitable poly-electrolyte (PE) was selected from a range of standard poly-electrolytes, with varying molecular weight, cationic charge and gradient of branching. The most applicable PE resulted in the use of Zetag 78FS40 from Ciba.

3 SLUDGE DIGESTION

3.1 Material and methods

Batch digestion tests

The batch tests were performed in a mixed 1 litre bottle placed in a water tank at 33 ± 2 °C. The bottles were filled with 100 ml of digested sludge from a suitable digestion reactor and 200 ml of the MBR sludge sample. The bottles were flushed with nitrogen gas for about 5 minutes and kept under a slight overpressure of 50 mbar. During the digestion period of 62 days the gas production was measured several times with a gas collection syringe. The sludge concentration and the organic content were measured before and after the test.

Before the tests at DHV's WRL a similar test was carried out at the University of Aachen for a period of 28 days. The test conditions differed slightly from those used by DHV. At Aachen 50 ml digested sludge and 250 ml sludge sample was used.

Semi continuous anaerobic digestion

The anaerobic digestion tests were performed on a laboratory scale using two identical digesters with a volume of 9 litre each. One reactor was filled with digested sludge from the reference laboratory scale digester and fed with a mixture of primary and secondary sludge from Amersfoort WWTP (the reference sludge). The other reactor was filled with digested sludge from the reference laboratory scale digester and fed with sludge from the Zenon pilot plant. The reactors were continuously stirred and operated at a temperature of 33 ± 2 °C. The reactors were connected to separate gas collection devices (gas bags), and two hose pumps for feeding and extracting sludge. Figure 1 shows a schematic overview of the installation and a photographic representation.

The reactors were fed once a day 6 times per week with 450 ml sludge, resulting in a sludge residence time (SRT) of 23 days. Before the feeding 450 ml of sludge was extracted near the bottom of the reactor by means of a hose pump.

The start up of the test was in January 2001 with Zenon sludge from phase 2 at a concentration of 12.1 g/l, and the sludge characteristics were the same as in the batch test. Due to the long residence time in the digester a considerable time was needed before the test ran steadily on the new feed sludge, with each conditional change this adaptation period had to be kept in mind. A weekly collected sample was analysed on dry solids and organic content. The dewaterability of the sludge was also determined with a laboratory filter-press, which is described in the dewatering chapter.

Table 2 shows the different feeding conditions during the test period from January till June 2001.

Table 2 - Feeding conditions

date	feeding conditions
10 January - 20 February	Zenon sludge from phase 2 with a concentration of 12.1 g/l
28 February - 17 April	Thickened Zenon sludge from phase 2 with a concentration of 19.0 g/l
17 April - 23 April	Zenon sludge from phase 3 with a concentration of 14.8 g/l
23 April - 31 May	Thickened Zenon sludge from phase 3 with a concentration of 24.8 g/l

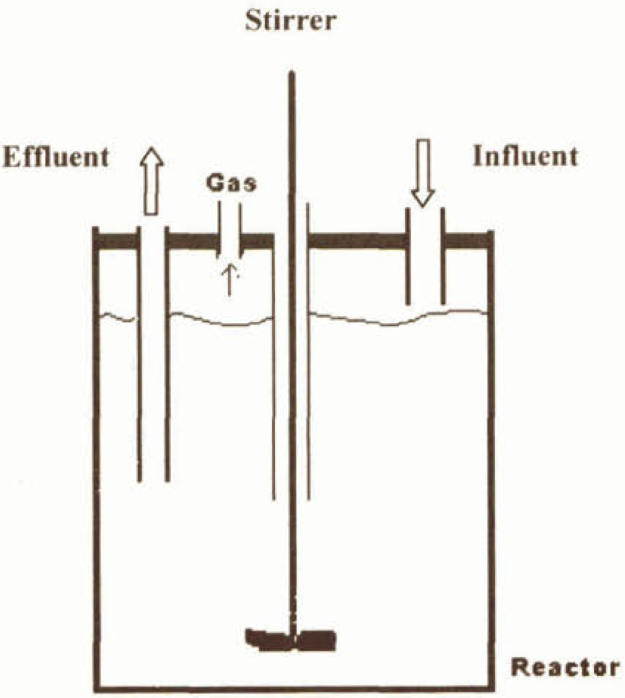

Figure 1 - Scheme of the laboratory digester

3.2 Results

Batch digestion tests

The results of the batch test are presented in Table 3, including the characteristics of the used sludge. The sludge load is expressed as gram organic (MBR or activated) sludge per gram of digested sludge. The net gas production is expressed as the gas production in ml per gram of organic material added from the used sludge (the gas production of the digested 'seed' sludge is subtracted from the total production).

Table 3 - Sludge characteristics (test DHV)

Sludge type (phase 2)	Sludge load g/g	MLSS concentration g/l	organic fraction % of MLSS	net gas production ml/g organic matter added
digested sludge lab reactor	-	16.7	64.1	-
AT-1 sludge Beverwijk	1.05	8.8	69.2	471
MBR -sludge (average)	1.09	9.1	63.4	300 - 425

The sludge used in the tests at the University of Aachen had different characteristics and a different sludge load. The sludge used was from phase 1 (with pre-precipitation) and at the different organic loading the results were not comparable with the DHV test. The sludge load, the characteristics and the net gas production for Aachen are presented in Table 4.

Table 4 - Sludge characteristics and results from the test at the Aachen University

Sludge type	Sludge load g/g	MLSS concentration g/l	organic fraction % of MLSS	net gas production ml/g organic matter added
digested sludge lab reactor	-	21.9	44.9	-
AT sludge Beverwijk	0.92	4.0	63.4	125
MBR -sludge (average)	1.8 - 2.7	9.3 - 11.7	61.6 - 64.3	104 - 175

Semi continuous anaerobic digestion

As seen in the batch tests, it was possible to digest MBR sludge. Due to the long adaptation period and the short test period the results gave a rough indication of what was possible in practice.

The semi continuous digester was originally started up with the untreated (non thickened) sludge from the Zenon MBR. The latter proved problematic due to the relatively low sludge concentration, this was latter changed to a PE- thickened sludge at 19 g/l to induce stability into the system.

In Table 5 the organic load of the reactor is presented together with the removal of organic material, both have the units of g/d. During the test a period of two months was observed to wash out the old sludge, followed by a more stable period of 5 weeks. The new feed sludge from the Zenon installation was from phase 3 (raw influent and simultaneous P removal) and was at a relatively low concentration of (14.8 g/l), this required thickening to 24.8 g/l to aid the stability of the digestion test. The onset of new sludge quality caused non-steady state conditions in the digester, followed by a recovering to the values of the earlier stable period.

The specific gas production of the digester, fed with MBR sludge was lower than the reference digester and also lower than in the batch test, but higher than the results from Aachen In the beginning a drop in initial gas production was measured, followed by a period of increased stability.

Table 5 - Test conditions and results from the semi continuous anaerobic digestion

Parameter	unit	value
sludge load	g/d	3,7 - 7,4
removed organic matter	g/d	1,6 - 6,0
gas production	ml/g organic matter added	60 - 263

3.3 Discussion

Based on the various digester tests it was clear that MBR sludge could be digested. It required a relative long adaptation period before the gas production became stable, thereafter, a stable gas production of 240 ml/g organic matter added was possible. In comparison to the batch test the latter was 65 % of the maximum amount of gas production. In comparison to a mixed sludge feed of primary and secondary sludge with a HRT = 20-25 days, the MBR sludge gas production was at 60 %.

In an earlier study (1987) with two 270 litre reactors, the gas production was calculated for the break down of a pure secondary sludge. In this study a gas production was found between 320 and 400 ml gas per g organic matter added. Here the system was fully acclimatised to the feed sludge and the system was stable. The gas production using an MBR sludge was lower than that achieved using secondary sludge from a conventional WWTP and could be explained by the long adaptation period normally required to promote additional enzyme production to break down the complex organic structures. This hydrolysis step is normally the kinetically limited process step. In this case the break down of the exo-polymers of the bacteria are probably responsible for the reduced hydrolysis, certainly in the beginning of the test and to a limited degree later in the test.

4 SLUDGE THICKENING

4.1 Material and methods

Thickening of sludge was executed using two methods, a thickening belt (belt-filter) and with a centrifuge.

Due to the small amount of available MBR surplus sludge and the large scale of a commercial belt-filter (minimum 5 m^3/h) no possibility was available to thicken the sludge on a commercial sized device. A simulation of a belt-filter was used.

After preparation and dosing of PE to 500 ml sludge the sludge was poured over a filter belt test plate and turned over with a spatula. This experiment was carried out twice: once with sludge from phase 2 and once with sludge from phase 3. Each test was duplicated and the average value presented.

Mechanical thickening tests were also performed with a small decanter from Alfa Laval (P600), see Figure 2. On location, at Beverwijk WWTP, a stream of AT sludge and access MBR sludge from the Kubota MBR pilot were thickened without the dosing of PE.

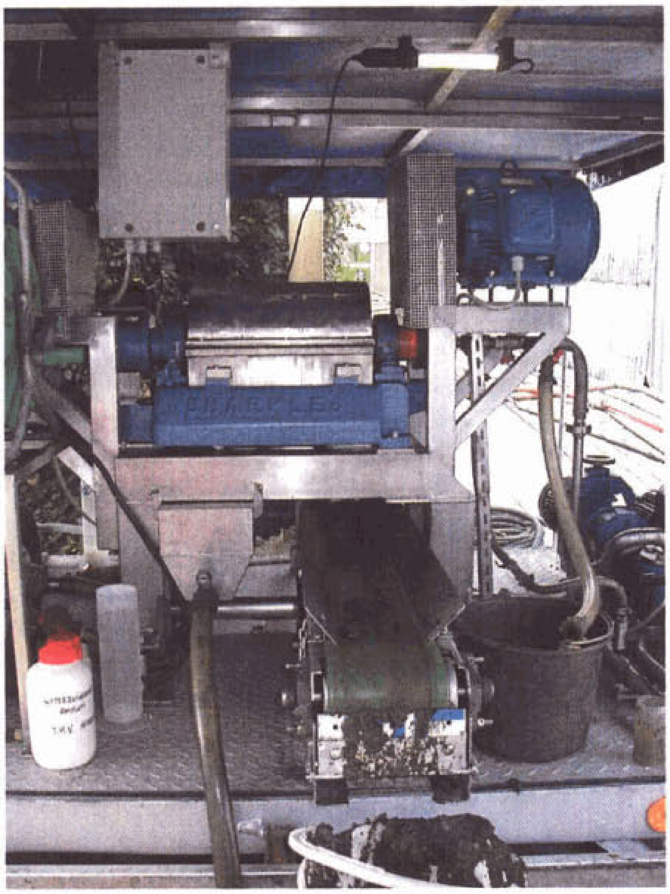

Figure 2 - P600 centrifuge from Alfa Laval

4.2 Results

The results of the different thickening tests are presented in Table 6. There were no recovery results mentioned from the belt-filter experiments, due to belt cleaning problems on such a small scale. The recovery from a belt-filter is normally 96% and this would be expected for the MBR sludge. Thickening of MBR sludge with a centrifuge was not possible without PE.

Table 6 - sludge thickening results

parameter	unit	AT-sludge	Kubota	Mitsubishi	X-Flow	Zenon
phase 2 - Primary settled waste water and simultaneous precipitation						
Thickening with a belt-filter						
MLSS concentration	%	0.32	0.88	0.91	0.96	1.17
organic fraction	% of MLSS	59.2	66.5	62.5	56.2	68.3
dry solid content after thickening	%	5.1	5.6	5.3	5.4	5.8 -6.2
PE-dosing of active product	g PE/kg MLSS	8.0 - 15.8	10.6	15.0	6.5	12.2 -17.6
Thickening with a centrifuge			not possible	not measured	not measured	not measured
MLSS concentration	%	0.32				
organic fraction	% of MLSS	59.2				
dry solid content after thickening	%	7.1				
PE-dosing of active product	g PE/kg MLSS	0				
recovery	%	91				
phase 3 - Raw influent and simultaneous precipitation						
Thickening with a belt filter						
MLSS concentration	%	0.48	1.08	1.27	1.26	1.15
organic fraction	% of MLSS	54.3	64.3	62.8	58.0	63.0
dry solid content after thickening	%	4.9	5.7	5.3	5.1	5.1
PE-dosing of active product	g PE/kg MLSS	5.2	6.5	6.7	8.0	8.2

4.3 Discussion

As shown in Table 6 the mechanical thickening of MBR sludge was possible. However, the feed conditions and the thickening equipment used caused differences in results. Only with large amounts of PE (8 - 15 g/kg MLSS) could the sludge from phase 2 be thickened to 5 - 6 %. In practise this was not economical. Considering the fine MBR sludge flocs and the necessity to form aggregates and free removable water, it was logical that the MBR sludge would require more poly-electrolyte. The actual difference between the various MBR systems was small.

In phase 3 the same dry solid contents could be achieved as for the AT sludge and the required PE was comparable, with the exception of the X-Flow sludge. This effect was explained by the large quantity of small particles (feed debris/material) in the sludge, the latter being caused by the pre-treatment devices of the influent. In phase 2 the influent was settled in a primary sedimentation tank while in phase 3 the influent of each MBR installation was directly treated by fine screen filtration (see side study 1: pre-treatment). The pre-treatment methods were not as efficient as primary sedimentation and gave rise to more particles in the influent and thus in the activated sludge (except for the X-Flow sludge which had the finest pre-filter which was as efficient as the pre-sedimentation tank).

Thickening of sludge without PE, on sludge from the full scale AT at Beverwijk with a centrifuge yielded good results. Thickening of the MBR sludge with a centrifuge without PE did not work, here the recovery was less than 80 %.

5 SLUDGE DE-WATERING

5.1 Material and methods

A laboratory scale filter press (Mareco, as shown in Figure 3) was used to de-water the sludge. To reach a suitable dewaterability, the sludge sample was flocculated with PE (Zetag 78FS40) before pressing. The tests were performed at 6.5 ± 0.5 bar for a duration of 6 minutes. This test was carried out with the untreated sludge from the AT of Beverwijk and the four MBR's. This test was also carried out weekly with the digested Zenon sludge from the laboratory digester.

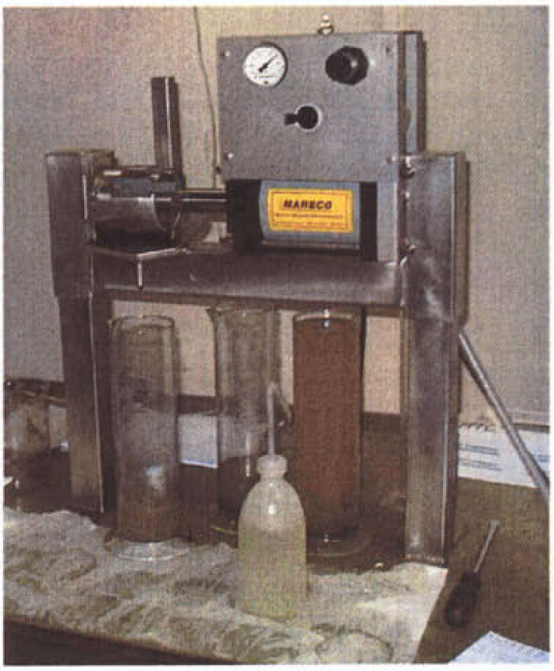

Figure 3 - The small filter press

Mechanical de-watering tests were also performed with centrifuges. Most of this work was carried out on a small decanter from Alfa Laval (P-600), with an internal diameter of 152 mm. In some cases the tests were carried out with the small centrifuge with a special inlet cone for sludge (BD3 cone, this was the same as in full scale Alfa Laval centrifuges).

Alongside the tests with the small centrifuge it was planned to test with a full scale centrifuge. This full scale test was carried out on activated sludge from the Beverwijk WWTP in December 2000. MBR surplus sludge was treated with the selected PE at several PE-loads (g active PE/kg DS) and settings to obtain an optimum setting.

5.2 Results

Results from the laboratory filter press

The untreated (non digested) activated sludge from the Beverwijk AT and the four MBR's were tested with a laboratory filter press for direct de-watering. It was not possible to de-water the sludge with the small filter press. The flocs were not stable enough to keep them on the filter press for 6 minutes at 6,5 bar.

The digested Zenon sludge was difficult to de-water, but after two months the results improved until the maximum dewaterability was reached. The results of the de-watering test with the digested Zenon sludge, including the PE dosing, are presented in Figure 4.

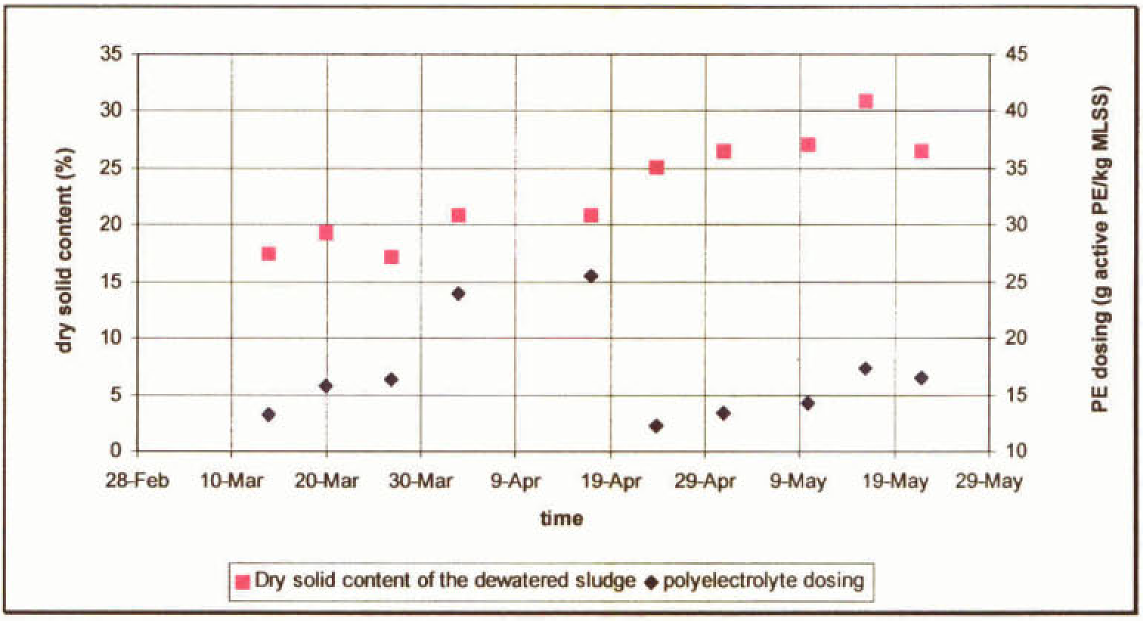

Figure 4 - De-watering results from the digested sludge

Results from the pilot and full-scale tests with a centrifuge

The results from the various centrifuge tests are presented in Table 7. However, the results of the P-600 centrifuge were not the maximum expected values due to unforeseen problems with the frequency converter of the centrifuge.

The dry solids recovery with the P-600 centrifuge was better than 98 %. The range shown in the table was caused by centrifuge optimisation during the test work. During phase 1 more PE was used than in phase 2. This was for the same reason as for the thickening tests.

Results from other installations

In Germany two full scale MBRs are running with a sludge de-watering installation. Rodingen is a 135 m^3/h MBR and sludge from this reactor is dewatered with a centrifuge to 29 % dry solids. Markränstadt (Leipzig) has a capacity of 180 m^3/h and the sludge is dewatered with a belt-filter press (Bellmer WPN 0,8) to 25 % dry solids with 3 - 6 g active PE/kg dry solids. The average MLSS concentration of the sludge is 20 - 25 g/l with an organic fraction on 35 %. The recovery on the belt-filter press is 99 % at 3 m^3/h and 94 % at 10 m^3/h.

Tests with a Westfalia centrifuge (CA458) showed comparable results. Running at 10-20 m^3/h and a PE-dosing of 5 g/kg MLSS the dry solids content was 24,5 % and a recovery of 98 %).

5.3 Discussion

De-watering of the undigested MBR sludge with a filter press was not possible. Due to the small flocs it was difficult to form good aggregates, which remained stable under high shear forces or high pressures in a filter press.

Table 7 - De-watering results

parameter	unit	AT-sludge	Kubota	Mitsubishi	X-Flow	Zenon
phase 1 - Primary settled waste water and pre-precipitation						
P600 centrifuge (Aug 2000)						
flow	l/h	580	180	180	180	180
MLSS concentration	%	0.55	1.03	1.05	1.14	1.08
dry solid content after de-watering	%	8.2 - 10.8	10.7 -11.5	10.2 - 12.1	11.6 - 12.7	9.4 -12.6
PE-dosing of active product	g PE/kg MLSS	4.3 - 13.8	5.5 - 11.6	9.2	10	6.5 -18.1
recovery	%	98.8 - 99.6	99.9	99.6 - 99.8	99.6 - 99.8	99.1 -99.9
phase 2 - Primary settled waste water and simultaneous precipitation						
P600 centrifuge (Dec 2000)			not measured	not measured	not measured	
flow	l/h	500				190
MLSS concentration	%	0.38				1.41
dry solid content after de-watering	%	8.8 - 12.1				9.7 - 11.0
PE-dosing of active product	g PE/kg MLSS	6.1 - 9.0				4.4 - 8.0
recovery	%	95.5 - 98.1				98.9
P600 BD3centrifuge (Dec 2000)					not measured	not measured
flow	l/h	500	200	200		
MLSS concentration	%	0.43	1.4	1.4		
dry solid content after de-watering	%	8.8 - 12.3	12.1 - 12.7	11.3 - 12.6		
PE-dosing of active product	g PE/kg MLSS	4.7 - 9.4	3.3	4.4		
recovery	%	97.5 - 98.9	98.8	99.6		
NX 4850 BD3 centr. (Dec 2000)			not measured	not measured	not measured	not measured
flow	m3/h	34.8 / 50.6				
MLSS concentration	%	0.41 -0.46				
dry solid content after de-watering	%	15.0 - 19.8				
PE-dosing of active product	g PE/kg MLSS	11.2 - 20.5				
recovery	%	92.2 - 97.8				

Probably as a consequence of the higher specific gravity of the MBR sludge the dewaterability of the MBR sludge in a centrifuge showed a better result than with activated sludge. No full scale test with a centrifuge on MBR sludge was carried out and is therefore difficult to predict the feasible dry solid content of MBR centrifuged sludge.

The results in Germany however, showed that dewaterability of MBR sludge could yield good results. It must be mentioned that historically the sludge in Germany is better to de-water than the sludge produced in the Netherlands.

The dewaterability tests with the digested Zenon sludge and a laboratory filter press suggested that digestion improves the dewaterability. After adaptation to the MBR sludge the digesters produced a good dewaterable sludge.

6 CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

In the previous chapters the degradability, thickening and de-watering of MBR sludge was given in comparison with activated sludge from a conventional WWTP (Beverwijk). The following conclusions can be drawn:

Digestion

- Batch tests yielded a gas production from MBR sludge in the range of 65 percent of the gas production from activated sludge from a conventional WWTP;
- A laboratory digestion reactor with a hydraulic residence time of 20-25 days, which was fed with thickened MBR sludge, improved the sludge dewaterability;
- The gas production from a digester fed with thickened MBR sludge was about 60 % of a reactor fed with a mixture of primary and secondary sludge.

Thickening

- In comparison to activated sludge from a conventional WWTP it was possible to thicken the MBR sludge from phase 2 to a slightly higher dry solid content.
- Mechanical thickening of MBR sludge without PE was not possible.

De-watering

- The tests suggested that the undigested MBR sludge was dewaterable with a small decanter centrifuge, but not with a laboratory scale filter press.
- MBR sludge appeared to be better to de-water than AT-sludge in a small centrifuge, but it was difficult to predict the dry solids content of the dewatered sludge with a full scale centrifuge.
- The small scale tests at Beverwijk were confirmed by full scale tests with centrifuges and belt-filter presses in Germany where they reached DS contents of 29 and 25 % respectively.

6.2 Recommendations

The following recommendations resulted from this side study:

- To improve the thickening and de-watering it is recommended to look into more detail to the optimal type of poly-electrolyte;
- It is recommended to do full scale de-watering tests with MBR sludge at the end of the research in Beverwijk. Only if the tests with the full scale de-watering are done it is possible to predict the dry solid content of MBR sludge on the bases of a pilot scale centrifuge.