SIXTH FRAMEWORK PROGRAMME

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EUROMBRA

Membrane bioreactor technology (MBR) with an EU perspective for advanced municipal wastewater treatment strategies for the 21st century.

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Introduction

The status of MBR technology worldwide has been the subject of a recent report (Hanft, 2006), and has also featured in a number of text books (Judd, 2006; WEF 2006; Pinnekamp and Friedrich, 2006). As part of the EUROMBRA programme one of the initial tasks is to collect data from existing plant and pilot plants and compile an overview of the operating data as per date. A review of the current status of the technology is presented so as to ascertain:

- the market value of the technology, and
- the technologies currently available.

Market value and drivers

Market analyst reports indicate that the MBR market is currently experiencing accelerated growth, and that this growth is expected to be sustained over the next decade. The global market doubled over a 5-year period from 2000 to reach a market value of $217 million in 2005, this from a value of around $10 million in 1995 (Fig. 1). It is expected to reach $360 million in 2010 (Hanft, 2006). As such, this segment is growing faster than the larger market for advanced wastewater treatment equipment and more rapidly than the markets for other types of membrane systems. In Europe, the total MBR market for industrial and municipal users was estimated to have been worth €25.3 million in 1999 and €32.8 million in 2002 (Frost and Sullivan, 2003). In 2004, the European MBR market was valued at $57 million (Frost and Sullivan, 2005). Market projections for the future indicate that the 2004 figure is expected to rise annually by 6.7%; the European MBR market is set to more than double its size over the next 7 years (Frost and Sullivan, 2005).

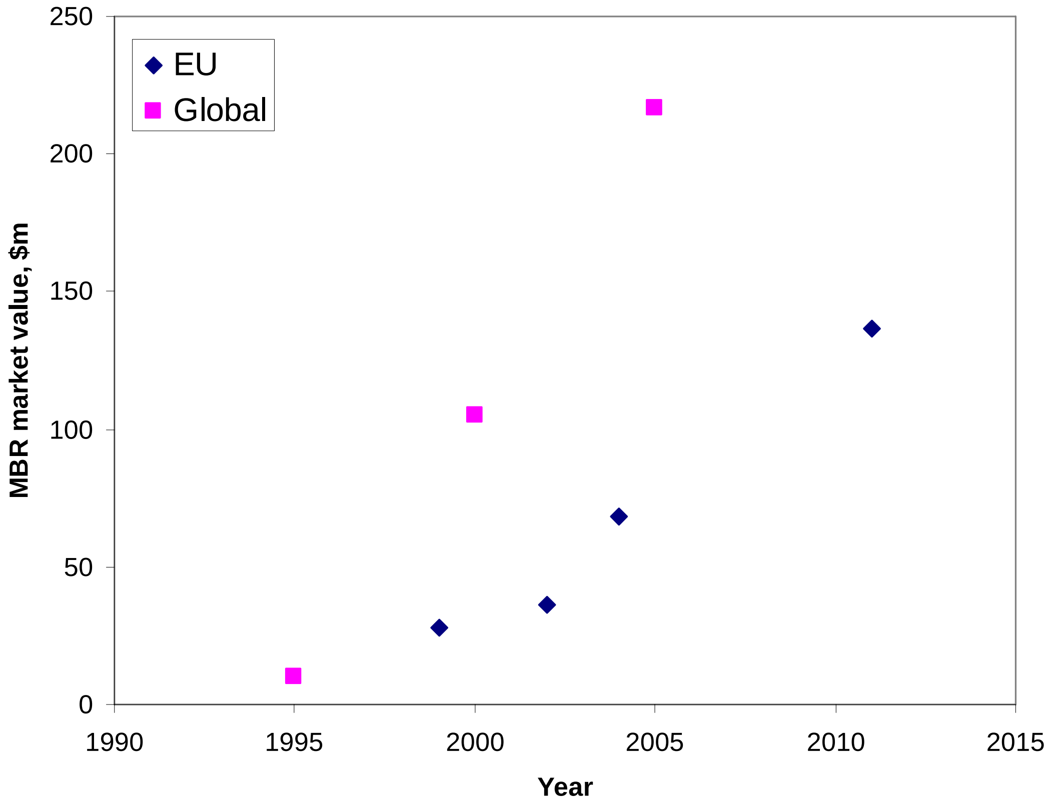

Fig. 1 Estimations of market value (Hanft, 2006; Frost and Sullivan, 2005)

The US and Canadian MBR market is also expected to experience sustained growth over the next decade, with revenue from membrane-based water purification, desalination and waste treatment totalling over $750 million in 2003, and projected to reach $1.3 billion in 2010 (Frost and Sullivan, 2004a, b, c). According to some analysts, the MBR market in the USA (for the years 2004–2006) is growing at a significantly faster rate than other sectors of the US water industry, such that within some sub-sectors, such as the filtration market, technologies like membrane filters or ultraviolet radiation are growing at rates in excess of 15% (Maxwell, 2005). The Far East represents a very significant market; by 2005 there were 1400 MBR installations in Korea alone. The future for the MBR market is thus generally perceived to be optimistic with, it is argued, substantial potential for growth. This level of optimism is reinforced by an understanding of the key influences driving the MBR market today and those which are expected to exert an even greater influence in the future. These key market drivers include greater legislative requirements regarding water quality, increased funding and incentives allied with decreasing costs and a growing confidence in the performance of the technology.

Available technologies

Currently available technologies have been reviewed by Judd (2006). There are essentially three different membrane process operational modes (diffusion, extraction and rejection, Fig. 2) of which only the latter – the classical biomass rejection mode of operation – has been commercialised. Extractive and diffusive systems are still at the developmental stage and appear to be limited to niche applications. Process configurations include immersed (iMBR) and sidestream (sMBR), of which the former has achieved more extensive market penetration since its commercialisation in the early 1990’s due to its lower operating cost than the sidestream mode. Membrane configurations comprise hollow fibre (HF), flat sheet (FS) and multi-tube (MT). The latter are employed exclusively for sMBRs and FS and HFs predominantly for iMBRs.

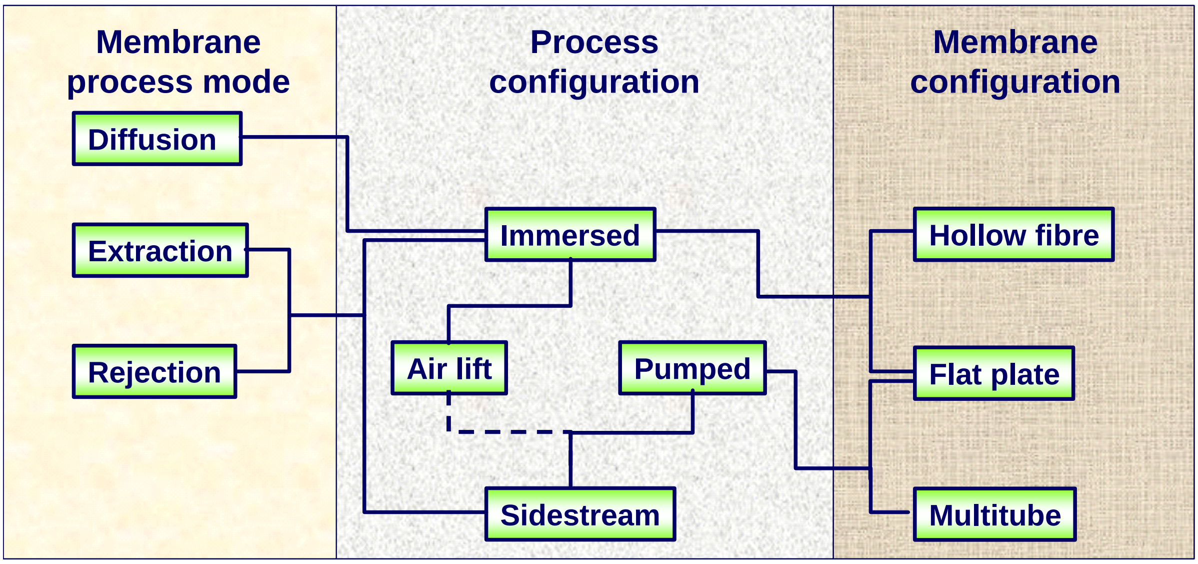

Fig. 2 Membrane and process configurations

Commercial technologies identified by Judd (2006) are listed in Table 1. Whilst this listing is unlikely to be comprehensive, it provides an indication of the dominance of the FS and HF iMBR technologies in the marketplace, accounting for the two leading technology suppliers: GE-Zenon (HF) and Kubota (FS). It should be noted that whilst some membrane suppliers offer a process, typically GE-Zenon, Koch Membrane Systems–Puron and Siemens Water Technologies–Memcor, some suppliers provide only the membrane (e.g. Kubota, Norit-Xflow and Toray). Some companies, such as Wehrle in Germany and Dynatech in the US, provide patented processes based on generic MT membranes for sMBRs. Since around the turn of the Millennium there has been significant market activity, with key acquisitions by some significant multinational companies (Table 2). A number of products (e.g. the *Membright* MBR by Brightwater, Toray's flat sheet membrane, Mitsubishi Rayon's vertical PVDF *SADF* membrane, Huber's *Vacuum Rotating Membrane* and Memcor's *Memjet* system) date back no more than 5-6 years and some products are undoubtedly under development currently and due for launching within the next few years.

Whilst the number of products and suppliers appears to be expanding rapidly, Kubota and GE-Zenon still account for the majority of the MBR installations worldwide. Around half of all MBR global installations (2500-3000) are Kubota, whilst GE-Zenon account for a significant proportion of the installed capacity; the total installed capacity for Zenon is over 1.5 gigalitres a day and they account for 9 of the 210 largest MBR plant worldwide. Having said this, the consolidation in the marketplace indicated by Table 1 suggests that other major players are likely to materialize.

Table 1 Commercial technologies

FS	*HF*	*MT*
Kubota	Asahi Kasei	Berghof
Huber	Siemens Water Technologies-Memcor	Norit X-Flow
Toray	Kolon*	Novasep Orelis (Kerasep)
Novasep Orelis (Pleiade®)	Mitsubishi Rayon	Millenniumpore*
Colloide*	Motimo*	
Brightwater	Polymem*	
ITRI non-woven*	Koch Membrane Systems-Puron	
Microdyn-Nadir*	GE-Zenon	
Han-S*	Ultraflo	
A3*		

**Small companies and/or incipient stages of development*

Table 2 Key membrane company acquisitions since 2000

Membrane company	*Buyer*	*Year*
Zenon	GE	2006
Puron	Koch Membrane Systems	2005
Memcor	Siemens	??
PCI Membranes	ITT	2002

Features of commercial technologies

A summary of some of the technologies is provided in Table 3. As expected, the specific surface area (the membrane area per unit module volume) tends to increase from the FS to the HF configuration, with little change for the FS products and the SSA tending to increase with decreasing filament diameter for the HF products. Across the range of products summarised in the table, a number of generalisations can be made:

All but one **sMBR** technology is based on **pumped MT modules**, the exceptions being:

- the Orelis *Pleaide* FS membrane module,
- the Polymem (and possibly Ultraflo) HF, and
- the Norit/Wehrle air-lift sidestream system.

Almost all **iMBRs** are either:

- **vertically oriented PVDF HF** modules of **outside diameter predominantly between 2 and 2.8 mm**, or
- **FS rectangular membranes 1-1.2m in depth** with a **membrane separation between 6 and 10 mm**,

the exceptions being:

- the Huber VRM rotating membrane module,
- the Mitsubishi Rayon horizontal *Sterapore* membrane, which is a horizontally oriented PE, and
- the Koch-Puron membrane (PES), the Polymem (PS) and the Ultraflo (PAN).

The principal differences between the most common products therefore arises from:

- the membrane and panel substrate materials, in the case of the FS iMBRs,
- the use of reinforcement (for the HF modules), and
- the air-sludge contacting

There are none-the-less some recognisably original features, some of the more striking being:

- the use of a rotating membrane to ensure the whole membrane surface is effectively air scoured (Huber VRM);
- the use of individually sealed hollow fibres to allow debris to be readily flushed from the top of the membrane (Koch-Puron);
- the use of a pressure-sealed system to form a single stack with integral permeate collection channels along the length of the panels (Kubota EM).

Table 3 ***Membrane specifications***

Supplier	*Membrane (Config., material)*	*Pore size, µm*	*Channel width or fibre diameter (spacing), mm*	*Specific surface area,* m^{-1}	*Proprietary name, membrane or module*
Brightwater	FS, PES	0.08	9	110	MEMBRIGHT®
Kubota	FS, PE	0.4	8	115	Kubota
Colloide	FS, PES	0.04	10	133	Sub Snake
Toray	FS, PVDF	0.08	7	135	Toray
Huber	FS, PES	0.038	6	160	VRM
Berghof	MT, PES or PVDF	0.08 0.12	9	110	Hy*Perm-AE* Hyper*Flux*
Millenniumpore	MT, PES	0.1	5.3	180	Millenniumpore
Norit-Stork	MT, PVDF	0.038	5.2 8	320 290	F4385 F5385
Koch-Puron	HF, PES	0.05	2.5 (3.5)	260	Puron
Zenon	HF, PVDF	0.04	1.9 (3.0)	300	Zeeweed 500c,d
Mitsubishi	HF, PE	0.4	0.54 (1.7)	425	SUR Sterapore
Rayon	HF, PVDF	0.4	2.8 (2.9)	333	SADF
USF-Memcor	HF, PVDF	0.04	1.3 (1.4)	600-700	Memjet B10R, B30R
Asahi Kasei	HF, PVDF	0.1	1.3 (1.3)	710	Microza
Polymem	HF, PS	0.08	0.7 (1.1)-1.4	800	Immem
Motimo	HF, PVDF	0.1-0.2	1.0 (0.9)	1100	Flat Plat

Summary

The available commercial MBR technologies largely comprise immersed membrane products of either flat sheet (FS) or follow fibre (HF) configurations. With only a few exceptions, the products do not ostensibly differ greatly in design, although the small differences are sufficient to differentiate one product from another. The main barriers to implementation remain insufficiently well understood phenomena such as fouling, clogging and foaming, and the possibly related impacts of dynamic effects. The latter include changes in MLSS concentration through dilution, hydraulic and organic loading changes, shock loading of onerous reagents (e.g. chlorine, salt) and interruptions in air and power supply. Further incremental improvements can be expected as more is understood about the interrelationship between operation, biomass characteristics and permanent fouling and cleaning, and as membrane costs continue to be driven downwards. More significant “quantum leap” improvements are less easily envisaged, however, and it remains to be seen whether any profoundly original MBR products will arise from current research and development activity.

Rationale

Recent years have seen a significant increase in the number of pilot plant studies based on real sewage feedwaters. A vast number studies, mainly at bench scale, have also been conducted in which hydraulic performance (*i.e.* permeability and/or its rate of decline) has been correlated with specific operating parameters and other system characteristics such as aeration rate or hydrodynamic parameters derived from aeration, biomass concentration or biomass-derived candidate foulant concentration and membrane characteristics. However, it is well-recognised that hydraulic performance elucidated at bench-scale cannot be reliably applied to higher scales. Against this, correlations produced from data derived from different pilot and/or full-scale studies have been rare and, in particular, the bases for cost evaluation, in those instances where such data is produced, are not always clear and rarely the same between different studies.

In this WP the cost issue is addressed through identifying and calculating key unifying normalised parameters across a number of studies within a single simple cost model. The work reported in this progress report focuses on data collated from both pilot trials, including those conducted by two of the partners alongside other published data, and full-scale operating plant. The use of normalised parameters allows data from such a large number of disparate sources to be compared on what is ostensibly a common basis. It is intended that this will provide valuable benchmark information for the EUROMBRA and AMEDEUS programmes as a whole.

As a first step towards producing a practical model based on analytical expressions derived from empirical and heuristic information, the latter must be acquired and collated. The results of this exercise, with information taken from both pilot and full-scale plant, are presented in this report.

Data acquisition

An opportunity was taken to conduct the review of both literature pilot plant comparative data and full-scale operating plant for the forthcoming reference book (Judd, 2006) to substantially supplement data from the pilot plant studies conducted by two of the partners (Annexes 1-2). Data from long-term pilot trials has been provided by two of the collaborators, and data from two of the case studies were provided by two other collaborators. Data has been acquired from a number of sources, including five published pilot-scale studies (Table 4) and 16 full-scale operating plants.

Table 4 Comparative pilot plant trials

Technology tested	Reference				
	Adham et al (2005)	*van der Roest et al (2002)*	*Tao et al (2005)*	*Trento Annex 2*	*Eawag Annex 2*
Zenon	X	X	X	X	X
Kubota	X	X	X	X	X
Mitsubishi Rayon	X	X	X		X
Norit X-Flow	-	X	-		
Memcor	X			X	

Data summary, MBR plant

Data from the pilot trials (Table 5) and case studies (Table 6) have been processed to produce the key operating and primary normalised parameters for each plant. It should be noted that the data provided refer to the *mean* values provided by the plant operator, and they are therefore subject to significant temporal, diurnal and seasonal variation.

Table 5 Summary of pilot plant SAD data, four common MBR technologies

Technology	*J, LMH*	*K, LMH/bar*	R_M, $Nm^3m^{-2}hr^{-1}$	R_V	*Source*
Kubota	8.3-12.5	500-500	0.75	60-90	van der Roest et al, 2002
	32.5-42[1]	350[1]	0.75[1]	60-90[1]	van der Roest et al, 2002[1]
	25	250	0.6	24	Adham et al, 2005
	26	650[2]	0.67-1.2	28-50	Tao et al, 2005
	18-25	200-500	0.67-1.2	28-50	Tao et al, 2005
	15-16	261-320	0.7-0.98	19-79	Trento[3]
	9.5	200	1.5	88	Eawag
M. Rayon	5-8	200	0.28-0.38	48-56	van der Roest et al, 2002
	20[1]	140-150[1]	0.28-0.38[1]	12-14[1]	van der Roest et al, 2002[1]
	20-25	140	0.9-1.14	45	Adham et al, 2005
	16-24	66[2]	0.38-0.58	16-24	Tao et al, 2005
	4.8	90	0.37	38	Eawag
Zenon	20	200-250	0.54	27	van der Roest et al, 2002
	35[1]	200-250[1]	0.54[1]	15[1]	van der Roest et al, 2002[1]
	37.2	270	0.52	14	Adham et al, 2005
	6.2-29.6	124[2]	0.25-0.37	20-30	Tao et al, 2005
	16-31	61-120	0.33-0.38	12-27	Trento[3]
	10	200	0.54	28	Eawag
Memcor	20-40	150	0.39	10-20	Adham et al, 2005
	21-22	182-270	0.2	17-22	Trento[3]

[1]peak loading conditions; [2]initial permeability; [3]range refers to mean-optimum

The key normalised parameters to which the data refer are:

$$K = \frac{J_{net}}{\Delta P} \tag{1}$$

$$R_M = \frac{Q_{A,m}}{A_m} \tag{2}$$

$$R_V = \frac{Q_{A,m}}{JA_m} \tag{3}$$

where K is the permeability (l m^{-2} hr^{-1} bar^{-1}), J_{net} is the net flux (l m^{-2} hr^{-1}), ΔP the transmembrane pressure (bar), $Q_{A,m}$ the aeration rate per membrane module or element, and A_m the membrane module or element area. R_M (Nm^3 m^{-2} hr^{-1}) and R_V (Nm^3 m^{-3}, or unitless) then both represent the **aeration demand**: the air flow rate normalised against membrane area and permeate flow rate respectively.

Table 6 Summary of full-scale plant specific aeration demand data

Technology	Capacity MLD	Flux LMH	K LMH bar^{-1}	R_M^2, Nm^3 $m^{-2}hr^{-1}$	R_V^2 -	MLSS g/L
FS (Flat Sheet)						
Kubota	1.9	20	350	0.75	32	12-18
	13	33	330	1.06	32	8-12
	4.3,s	25	680	0.56	23	na
Brightwater	1.2	27	150	1.28	47	12-15
Toray	0.53	25	208	0.54	22	6-18
	1.1,i	21.6	1500	0.4	19	22
Huber	0.11	24	250	0.35	22	ns
Colloide	0.29	25	62.5	0.5	20	ns
HF (Hollow Fibre)						
Zenon	2	18	95	1	56	15
	48*	18	144	0.29	16	8-10
	0.15*,i	12	71	0.65	54	10-15
	3.2	26	300	0.44	17	14
	48*	24	200	0.40	17	12
M. Rayon	0.38	10	30	0.65	65	12
USF Memcor	0.61	16	150	0.18	11	12
Asahi-kasei	0.9, i	16	80	0.24	15	8
KMS Puron	0.63*	25	160	0.25	10	ns
Polymem	-	10-20	ns	0.15-0.25	13-25	ns

*intermittent/cyclic aeration, i – industrial effluent feedwater, ns – not specified, s - stacked

Summary and future work

The data provided and summarised in this report is be used for the model defining operating costs in an MBR. The model will combine empirical expressions relating flux or permeability with aeration demand, using the values for SAD garnered from pilot plant and full-scale data. Thus far summary data from 16 full-scale case studies and five comparative pilot trials have been surveyed for use to provide the relationship between feedwater quality and cost for specific membrane configurations.

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Annex 1 Pilot plant report: Pietramurata, University of Trento

In the trials conducted by the University of Trento at Pietramurata wastewater treatment plant in Italy the plants tested were originally Zenon and Kubota. More recently a Memcor plant has also been studied. The first plant installed in June 2001 consisted of two separate MBRs whose biotreatment tanks were provided by dividing a single rectangular stainless steel tank into two separated treatment lines for a Zenon and Kubota MBR, both configured with pre-denitrification. All experimental activities on site have been performed between March and December; the whole system is outdoors and the ambient temperature is too low to operate during the winter months.

The biological volume was calculated according to a rather conservative flux value of 15 LMH resulting in volumes of 5.14 and 4.23 m^3 for the aerobic tanks, and 2.76 and 2.27 m^3 for the anoxic tanks for the respective Zenon and Kubota processes. The permeate is removed by suction, originally using progressing cavity (*Mono*) pumps but a self-priming pump was installed in 2003. A PC pump is also used for recirculation from the aerobic to the anoxic tank at recycle ratios between 3 and 5. Aeration for the biological process is supplied to both aerobic tanks from the main aeration pipe of the full scale plant and is measured by specific air flow meters. The Zenon/Memcor and Kubota systems were operated under different SRTs, imposed by daily sludge wasting. All the usual operating parameters have been monitored (TMP, DO, etc.) and, since this effluent is re-used for agriculture, from 2004 onwards the effluent nitrate concentration from the Zenon plant has been measured.

Membrane modules originally installed comprised a Zenon 500c (66.6 m^2 membrane surface area) and a Kubota E50 (40 m^2 of membrane surface area). In November 2003 a new hollow fibre module (US-Filter Memcor) was installed as a side-stream to the Zenon MBR tank. The module, 40 m^2, was immersed in a tank (0.3 m^3) and fed with sludge from the aerobic tank and fed back to it under gravity. Due to this special combination, the permeate flow suctioned from both HF lines was often reduced to avoid excessive organic loading of the biological system. Simultaneous short and long term flux-step tests on both systems were likewise also avoided. Due to some technical and budgeting problems, operation of some modules was stopped for long periods; the Zenon module was not used during 2003 and the Kubota module was not used during 2005. In 2005 the Memcor module was operated for a few weeks on biomass previously acclimatised by the Zenon module. The aerator depth was 1.9-2.0m for the Zenon and Memcor modules and 2.4m for the Kubota stack.

During 2002 the Zenon module was cleaned monthly using 300 mg/L NaOCl as Cl_2. From 2004 onwards the concentration for the monthly clean was reduced to 200 mg/L. From 2002 to 2003 the Kubota module was cleaned twice yearly with 3000 mg/L (i.e. 0.3 wt%) NaOCl as Cl_2 and once a year with a 10,000 mg/L (1 wt%) solution of oxalic acid. From 2004 the module was cleaned monthly with a 200 mg/L NaOCl solution with no additional acid cleaning. The Memcor module was cleaned monthly using 300 mg/L NaOCl. For all three modules the membranes were additionally cleaned using 100 mg/L NaOCl immediately before each flux step test.

The mean feed COD and $N\text{-}NH_4^+$ levels were 575-988 and 23-33 mg/L respectively, with the BOD/COD ratio generally being <0.5. The corresponding outlet concentrations were <22 and <5 respectively, with the TON being below 11 mg/L at all times. Summary data are provided below.

Table 7 O&M data: data summary

Parameter	*No.*[1]	*Zenon*		*Kubota*		*Memcor*	
Membrane aeration rate, Nm^3/h	1-2	16.7	25.0	38	46	8	
	3	25.0	25.0	38	46	8	
	4	-	-	38	46	-	-
	5	-	-	28		-	-
Cycle, mins	1-2	9 on / 1 off		9 on / 1 off		9 on / 1 off	
	3	9 on / 1 off		8 on / 3 off		-	-
	4	-	-	9 on / 1 off		-	
	5	-	-	continuous		-	-
Net flux, LMH[2]	1	7.2	28.8	6.3	28.4	9	31.5
	2	9	30.6	7.6	11.9	21.6	
	3	8.6	14	6.9	16.7	-	-
	4	-	-	8.6	9.5	-	-
	5	-	-	16	37.5	-	-
HRT, h	1	4.1	16.5	10.7	42.9	4.5	14
	2	4.5	14	18.1	18.1	11	
	3	10	13.4	10	22	-	-
	4	-	-	18		-	-
	5	-	-	5.5	8	-	-
SRT, d	1	35		40		8	20
	2	8	20	8		15	
	3	15		20		-	-
	4	-	-	12		-	-
	5	-	-	9	12	-	-
DERIVED DATA							
Permeability LMH/bar	1	144	144	630	81	250	58
	2	138	61	167	264	300	200
	3	123	108	276	239	-	-
	4	-	-	264	271	-	-
	5	-	-	320	100	-	-
SAD$_m$, Nm^3/(h.m^2)	1	0.25	0.375	0.95	1.2	0.2	
	2	0.25	0.375	0.95	1.2	0.2	
	3	0.375	0.375	0.95	1.2	-	-
	4	-	-	0.95	1.2	-	-
	5	-	-	0.7		-	-
SAD$_p$, m^3 air/m^3 permeate	1	35	13	37	136	5.7	20.0
	2	28	12	87	113	8.3	
	3	44	27	50	100	-	-
	4	-	-	110	100	-	-
	5	-	-	19	44	-	-

[1] Trial number; trials range between 2 and 9 months in duration

[2] Temperature-corrected to 20ºC

Table 8 O&M data: most optimum and mean

Parameter	*Zenon*		*Kubota*		*Memcor*	
	Opt[1]	***Ave***	*Opt*[1]	***Ave***	*Opt*[1]	***Ave***
HRT, h	14	**10**	6	**17**	11	**10**
SRT, d	20	**21**	9	**17**	15	**14**
Membrane aeration rate, Nm^3/h	25	**22**	28	**39**	8	**8**
Cycle, mins	**9 on / 1 off**		**-**[2]		**9 on / 1 off**	
Flux, LMH	31	**16**	16	**15**	22	**21**
Permeability, LMH/bar	61	**120**	320	**261**	270	**182**
SAD_m, $Nm^3/(h.m^2)$	0.38	**0.33**	0.70	**0.98**	0.20	**0.20**
SAD_p, m^3 air/m^3 permeate	12	**27**	19	**79**	22	**17**

[1] conditions employed under which the highest fluxes and lowest aeration rates were sustained

[2] 9 on / 1 off routinely, continuous operation for final trial

Annex 2 Pilot plant report: Eawag pilot plant MBR, Kloten/Opfikon

Eawag (The Swiss Federal Institute of Aquatic Science and Technology) is a Swiss national research organisation committed to ecological, economical and socially responsible management of water. A pilot scale MBR was set up and operated continuously for 4 years by the engineering department of Eawag to gain hands-on experience of running such plants. The test protocol incorporated the study of the impact of membrane maintenance protocols, SRT and chemical flocculants on performance with reference to three different MBR technologies. The pilot plant was also used for studying the fate of micropollutants in an MBR compared with conventional technologies.

The pilot plant is located on the municipal sewage treatment plant of Kloten/Opfikon, a conventional activated sludge plant with an average dry weather flow of 17±4.3 MLD (55,000 p.e; maximum flow 645 l/s). This plant receives sewage from Zürich airport (~50% of the influent flow) and from the nearby towns of Kloten and Opfikon. The pilot plant is fed with primary effluent (Table 6) from the full scale plant following primary treatment, comprising screening at 10mm, a sand/oil trap and primary clarification at 2h HRT). The flow rate was proportional (~0.2%) to the full scale facility. The volume of wastewater treated was 30±12 m^3/d, with a maximum daily flux of 74 m^3/d.

Table 9 ***Feedwater quality*** (value ± standard deviation)

Parameter, mg/l	*MBR feed (after primary clarification)*
Ammonia-N	21±5 mgNH_4^+-N L^{-1}
BOD_5	not available
COD	282±91 mgCOD L^{-1}
TOC	not available
TKN	38±9 mgN L^{-1}
Ortho-Phosphate-P	2.1±0.7 mgP L^{-1}
P total	4.2±1.3 mgP L^{-1}

The pilot comprises a cascade of 2 to 6 tanks (Fig. 4), each of 2 m^3 volume, providing anaerobic and anoxic treatment at recycle rates of 80±30 and 50±23 m^3/d respectively and at mean sludge concentrations of around 4.8 g/l. Aerobic treatment at mean MLSS concentrations of between 7 and 8.3 g/l was coupled with membrane separation in discrete compartments, operated in parallel and providing a membrane area of between 40 and 80 m^2 (Table 8), all modules being single-deck. 4 phases of work can be identified:

- 1st year (day 1 to 385): 17±2 d sludge age, 8 m^3 anaerobic volume
- 2nd year (day 410 to 745): 32±3 d sludge age, 6 m^3 anaerobic volume
- 3rd year (day 770 to 1090): 58±10 d sludge age, 6 m^3 anaerobic volume
- 4th year (day 1090 to 1510): 56±11 d sludge age, no anaerobic volume, Fe^{3+} addition

Table 10 **Design information** (value ± standard deviation)

	Kubota	*Zenon*	*Mitsubishi Rayon*
Tank size, m^3	2.6	1.6	1.9
Sludge recycle ratio	1.3±0.5	1.2±0.5	1.3±0.5
Sludge content, gSS/L	8.3±3.4	8.2±3.5	7.0±2.9
MEMBRANE			
Type	0.8 m^2 panels	ZW500a	Sterapore SUR
Configuration	50 panels	1 module	80 x $1m^2$
Total membrane area, m^2	40	46	80
Net permeate prod., m^3/d	9.1±3.9	11±4.5	9.4±3.8
Max. permeate prod., m^3/d	25.4	28.7	24.2

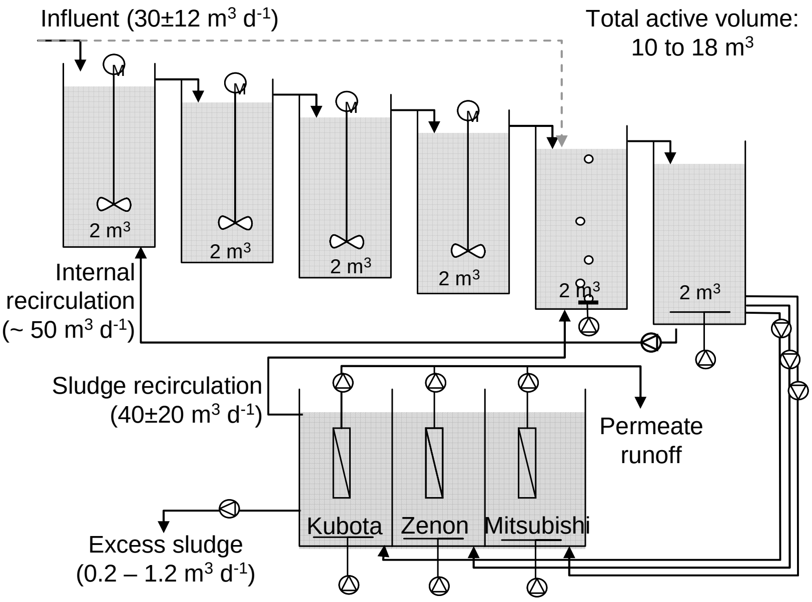

Figure 1 ***Pilot plant operated at Eawag***

Data for the three technologies (Table 9) indicate considerable changes in permeability (Fig. 5), particularly for the Kubota module. Permeability fluctuations for this membrane did not appear to correlate with operational changes such as cleaning protocols. For the Zenon module permeability correlated roughly with MLSS concentration in the membrane compartment from the start of operation until January 2004. The permeability increase from January 2004 onwards correlated with the introduction of regular maintenance CIPs (Table 10) every 14 days with 150 ppm NaOCl followed by a citric acid clean pH 2.5.

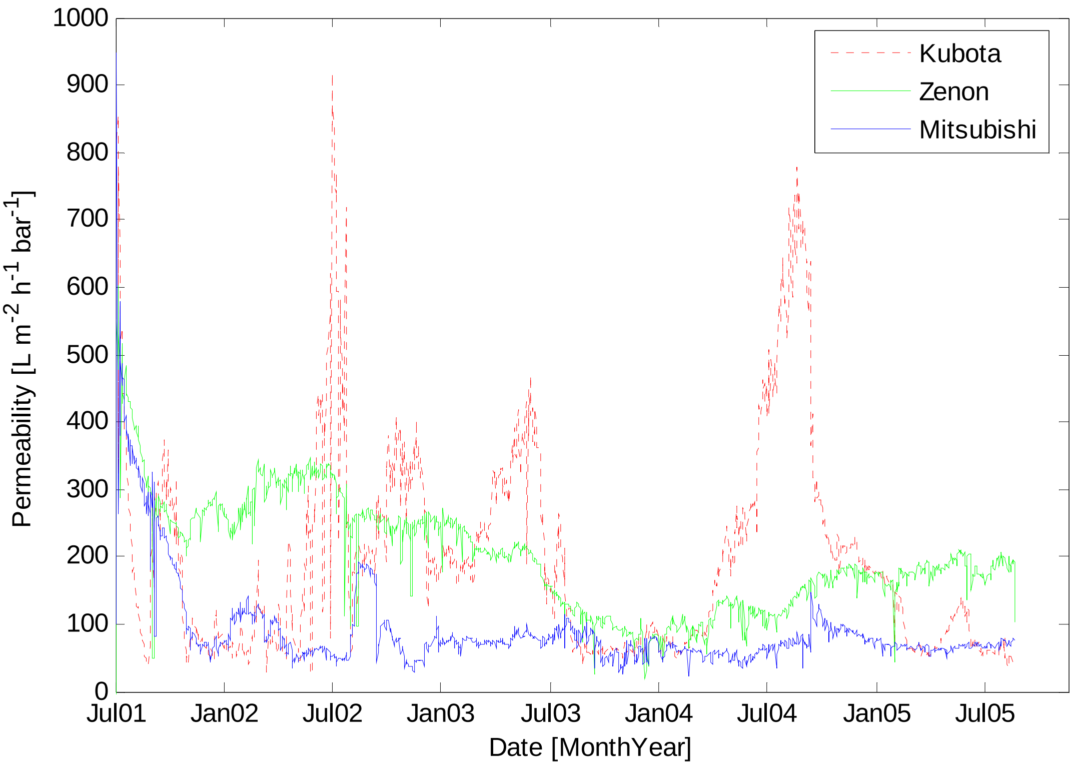

Figure 2 Permeability of the modules as observed during the total operation time of the MBR pilot. Data corrected to 20°C according to viscosity correction.

Table 11 O&M data

	Kubota	*Zenon*	*Mitsubishi Rayon*
Membrane aeration rate, Nm^3/h	60±4	50±5, air cycling on/off 10s/ 10s	29±4
Cycle, min	8 on / 2 relax	5 on / 0.5 bflsh.	8 on / 0.5 bflsh. +1.5 relax
Ave. net flux, LMH	9.5±4	10±4	4.8±2
Gross flux, LMH	17±4	19.5±3	10±2
Fine bubble aeration rate, Nm^3/h	0 - 10	0 - 10	0 - 10
HRT, h**	3±1.3	1.9±0.8	1.9±1.1
SRT, d	15 - 67	15 - 67	15 - 67
MLSS, g/L	8.3±3.4	8.2±3.5	7±2.9
DERIVED DATA			
SAD$_m$, Nm^3/(h.m^2)	1.5	0.54	0.37
SAD$_p$, m^3 air/m^3 permeate	88	28	38
TSAD$_p$, m^3 tot. air/m^3 perm.	88-90	28-38	38-48
Mean permeability, LMH/bar	200±160	200±83	90±70
Cleaning cycle time^2, d	variable	variable, 14d	variable

**HRT in the membrane compartment only

The Mitsubishi Rayon unit provided a low permeability throughout the study due to clogging of the hollow fibres by dehydrated sludge. Several measures taken to ameliorate this problem, such as overnight relaxation and intensive or regular chemical cleaning, were unsuccessful. Regular backflushing for 30s during each permeate production cycle, as applied to the Zenon module, provided a stable low permeability. No difference in efficacy of maintenance cleaning at low hypochlorite concentrations "in air" rather than in place was noted.

Table 12 Cleaning protocols for the four MBR technologies

	Kubota	*Mitsubishi Rayon*	*Zenon*
Reagents used	NaOCl, 150 – 2000 mg/L Citric acid pH 2.5	NaOCl, 150 – 1000 mg/L Citric acid pH 2.5	NaOCl, 150 – 1000 mg/L Citric acid pH 2.5
Established protocol	-*	-*	Maintenance clean, 150 mg/L NaOCl and citric acid clean every 14 days.

*no protocol tested yielded satisfactorily reproducible results.

Maintenance cleaning in place was conducted through backflushing for 20-30 minutes using 150 mg/L NaOCl followed by an acid clean at pH 2.5±0.5. For hollow fibre membranes the backflush (1.5 times the maximum operating flux) was applied intermittently with 20-30 second pulses at applied at 5 minute intervals. FS membranes where backflushed continuously under gravity at a maximum hydrostatic head of 0.1 bar (the limit recommended by the supplier is 0.2 bar). Chemical usage per backflush was between 2 L/m^2 for the HF membranes to 5 L/m^2 for the FS ones. Intensive (recovery) cleaning was through soaking the membranes for 3-6 hours in a high-strength (0.1-0.5 wt%) NaOCl solution with pulsed aeration combined with suction for 5-10 seconds every 20 minutes. For hypochlorite significant foam formation took place due to the organic matter present. The amount of chemical solution required depended on the packing density of the membrane, but appeared to be in the range of 200-100 L/m^2. Care was taken to drain the membrane of hypochlorite before applying the acid wash of 0.5 mM sulphuric acid together with a 5 mM citric acid buffer, the mineral acid being used to counter the alkalinity and the citric acid to stabilise the pH at 2.5.