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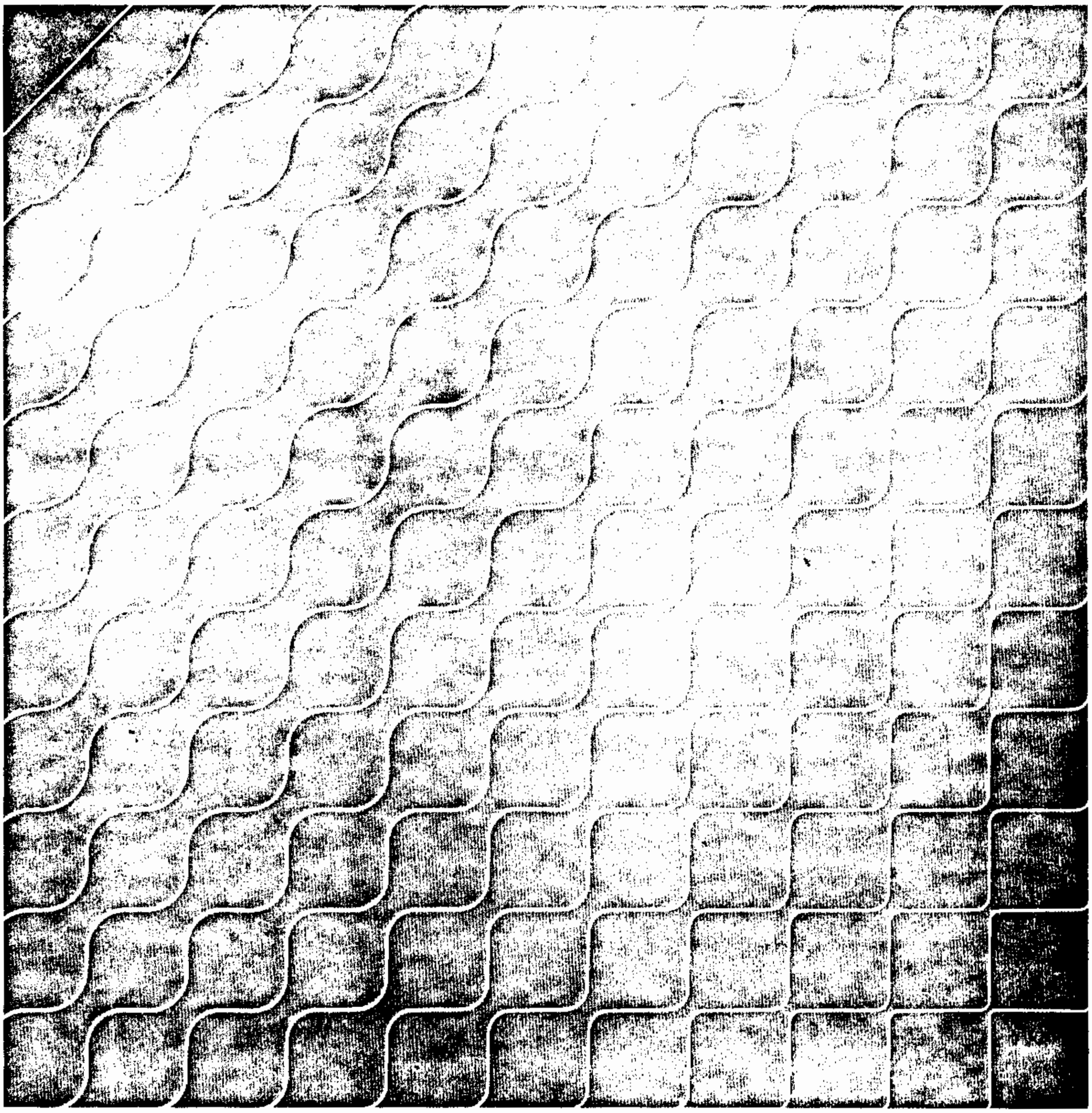
PERSPECTIVES FOR THE UTILIZATION OF MEMBRANE-ASSISTED SLUDGE RETENTION IN MUNICIPAL WASTE WATER TREATMENT PLANTS

a feasibility study



RIZA

rijkswaterstaat
rijksinstituut voor integraal zoetwaterbeheer
en afvalwaterbehandeling

postbus 17, 8200 AA lelystad 03200-70411

stora

stichting toegepast onderzoek
reiniging afvalwater

postbus 80200, 2508 GE den haag 070-3512710

neratie rioolwaterzuiveringsinrichtingen RWZI 2000
projectleiding en secretariaat: postbus 17, 8200 AA Lelystad 03200 - 70467

PERSPECTIVES FOR THE UTILIZATION OF MEMBRANE-ASSISTED SLUDGE RETENTION IN MUNICIPAL WASTE WATER TREATMENT PLANTS

A feasibility study aimed at the development of high-performance bioreactor systems for application in the treatment of municipal waste water

STOWA
Stichting Toegepast Onderzoek Waterbeheer
Postbus 8090
3503 RB Utrecht
tel. 030-321199
fax 030-321766

Publikaties en het publikatieoverzicht
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author(s):
Groningen Biotechnology Center
University of Groningen :

dr. ir. J.Dolfing
prof. dr. B.Witholt

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APPENDICES

PREFACE

Under the researchprogramme RWZI 2000 fundamental research is stimulated to reduce sludge production at the biological treatment of municipal wastewater.
In this report the results of a feasibility study are given, in which the possibilities are evaluated to develop high-performance bioreactor systems for utilization in the aerobic treatment of municipal waste water. These systems originate from biochemistry and should enhance the volumetric activity and oxidation of substrates rather than conversion of substrates into biomass. Therefore a high biomass concentration is essential. In existing municipal wastewater treatment plants the biomass concentration is created by settling of the sludge in the secondary sedimentation tanks. By application of membrane filters for biomass retention, it is possible to work at higher biomass content and at high sludge ages, which should result in lower sludge production. The little available literature and data suggest that cross-flow filtration units may be applicable in sludge retention for municipal waste water treatment if the energy demand for cross-flow filtration and the investment in filtration systems can be brought down. With respect to the energy demand, it must be brought down to about 1 kWh/m3 of effluent, compared to the 3-6 kWh per m^3 of filtrate required in the operation of present cross-flow filtration systems. With respect to filter cost and performance, flux rates of 1 m^3 of filtrate/m^2 of filter/h instead of 0.04 $m^3/m^2.h$ will need to be obtained, at costs of about Dfl. 300/m^2 (at the moment Dfl. 950/m^2) of filter if filtration systems are to be cost-efficient. If membrane-assisted sludge retention will be cost-effective by a break-through in the development of membrane technology in future, there is sufficient ground for further development of high-performance bioreactor systems for the treatment of municipal waste water. Apart from a lower sludge production and the elimination of the large secondary sedimentation tanks, other benefits will be the possibility to obtain complete nitrification and possibly even simultaneous denitrification in highly-loaded systems, and a theoretical chance that in such systems organisms can be retained that specifically degrade hitherto recalcitrant compounds.

The feasibility study has been done by Groninger Biotechnology Center of the University of Groningen, accompanied by a committee of ir. C. Kerstens (chairman), ir. C. van Beersum, drs. N. Boots, ir. A.J.M.L. Borghans, ir. E. Eggers, ir. D. Eikelboom, ir. B.A. Heide, prof. dr.ir.J.J.Heynen, prof.dr.ir. S.A.L.M. Kooijman, dr. R. Mulder, ing. G.B.J. Rijs, ir. P.C. Stamperius, ir. W. van Starkenburg and prof. dr. A.H. Stouthamer.

Lelystad, June 1991

On behalf of the Steering
committee RWZI 2000

dr. J. de Jong
(chairman)

SUMMARY

The feasibility of the use of membrane assisted sludge retention in municipal waste water treatment plants has been evaluated. This technology is an alternative for the current methodology to retain biomass with the use of separate settling tanks. The major drawbacks of the latter approach are that the efficiency of the settlers poses a limit to the sludge concentration that can be maintained in the bioreactor, and that settling tanks are not able to adequately separate filamentous or bulking sludges from the effluent. In contrast, cross flow filtration along microporous or ultraporous membranes offers the potential of complete biomass retention irrespective of the concentration or the morphology of the biomass to be retained.

Experience with the application of crossflow filtration for biomass retention in waste water treatment is virtually non-existent. Only a few papers on this subject have been published in the open literature, and in these laboratory scale experiments, mainly performed with anaerobic treatment systems, transmembrane fluxes were in the range of 10 to 50 $l/m^2/h$.

From those experiments, as well as from experience gained in the application of crossflow filtration in biotechnological processes, a variety of factors has been identified that influence the transmembrane flux. Of these the most important are the biomass concentration, the composition of the waste water and the crossflow velocity. Many technological aspects remain to be defined, including important parameters such as the long term flux stability and the optimal composition and pore-size of the membrane.

Several important questions concerning the microbiological characteristics of filtered sludge also remain open. Theoretically the biological formation of surplus sludge can be avoided by complete biomass retention, but it is not clear how such a strategy will influence the specific activity of the biomass. Gaudy and coworkers have claimed the feasibility of total oxidation processes, but this claim was based on studies with model waste waters, while biomass retention was achieved via centrifugation of the effluent. The results of these studies support the validity of the complete oxidation concept for mixed culture systems under a regime of complete biomass retention in a continuously fed system, but further research with real waste water and the certainty that complete biomass retention is indeed achieved are needed to prove the applicability of this concept to municipal waste water treatment.

With respect to the volumetric loading rate achievable under those conditions, it was estimated that a reactor completely filled with biomass should be able to handle substantially higher volumetric loading rates than the current aeration tank-type activated sludge systems, even when operated as a no-growth system. It is expected that in practice the objectives of a high volumetric loading rate and a zero-surplus sludge production will be incompatible, and economic considerations will determine where the optimum is. Imposing a permanent nutrient limitation may be a

useful tool to achieve partial decoupling between activity and growth, and may be helpful in reconciling the two objectives.

The characteristsics which have emerged from the available literature and data on present waste water purification processes suggest that cross-flow filtration units may be appplicable in sludge retention for municipal waste water treatment if the energy demand for cross-flow filtration and the investment in filtration systems can be brought down. With respect to the energy demand, it must be brought down to about 1 kWh/m^3 of effluent, compared to the 3-6 kWh per m^3 of filtrate required in the operation of present cross-flow filtration systems. With respect to filter cost and performance, flux rates of 1 m^3 of filtrate/m^2 of filter/h will need to be obtained, at costs of about Dfl. 300/m^2 of filter if filtration systems are to be cost-efficient. At present fluxes of about 0.04 m^3/m^2/h can be attained at membrane-costs of ~ Dfl. 900/m^2.

The present study has reviewed information which touches on the feasibility of the above goals, and has identified some of the interesting features membrane assisted sludge retention has to offer. Apart from elimination of the large and inefficient settling compartments, these features include the possibility to obtain complete nitrification and possibly even simultaneous denitrification in highly-loaded systems, and a theoretical chance that in such systems organisms can be retained that specifically degrade hitherto recalcitrant compounds.

The study concludes that in spite of these prospects membrane assisted sludge retention is presently not an economical process. It is however advisable to further develop this technology as soon as a breakthrough in membrane technology results in a significant reduction in membrane prices or a drastic increase in membrane fluxes.

1 GENERAL INTRODUCTION

Enactment in the Netherlands of a law against pollution of surface waters in 1970 has resulted in a sharp increase in the quantity of municipal waste water that is biologically treated before being discharged. Nowadays more than 90 % of the dutch households is connected to the sewer system, and on its way to the receiving surface waters essentially all this sewage passes through some kind of sewage treatment plant. A wide variety of designs is currently in operation, but the common denominator is that most sewage treatment plants are of the activated sludge type (Table 1.1). Numerically the oxidation ditch is the most important system but based on the capacity installed the aeration tank is the main system. The design characteristics of the typical dutch municipal waste water treatment plant are given in appendix 1 .

Table 1.1 Municipal waste water treatment plants in operation on 31 december 1987 (Centraal Bureau voor de Statistiek 1989).

Treatment type	Number	Capacity (1000 p.e.)*
Mechanical	28	1743
Trickling filter	56	1867
Aeration tank	67	8900
Oxidation tank	53	1112
Oxidation ditch	119	916
Carrousel	82	4421
Two-stage system	37	4112
Other	48	661
Total	490	23732

*: p.e. = population equivalent

The classical objective of treating waste water in sewage treatment plants is to prevent oxygen depletion in the receiving water by removing potentially oxygen demanding compounds from the waste stream. In this respect the municipal waste water treatment systems function well: more than 90 % of the BOD is indeed removed. Unfortunately the efficiency for the removal of nitrogen and phosporus is substantially lower (Table 1.2), and this is more and more perceived as a problem.

Table 1.2 **Treatment efficiency of municipal waste water treatment systems in the Netherlands in 1987.**

	concentration (mg/l)		% removal
	influent	effluent	
BOD	211	20	90
COD	563	98	83
N-kjeldahl	49	17	66
P-total	14	8	40

Another weak point of the current generation of sewage treatment plants is related to the costs. In 1986, the last year for which such data are available, the total costs for sewage treatment were Dfl. 839 million of which Dfl. 657 million were actual treatment costs. For this money the waste of 13.1 mln people was treated in municipal sewage treatment plants, plus an industrial waste stream equivalent to the waste of 5.4 mln people, for a total of 18.5 mln population equivalents (p.e.). As a consequence of the costs of effluent purification in communal waste water treatment plants, many industries have reduced their discharges to the sewer system, with the result that some treatment plants are overdimensioned. The total treatment capacity installed in 1986, 23.1 mln p.e, received only 18.5 mln population equivalents. The composition of the treatment costs in 1987 is given in Table 1.3.

Table 1.3 **The composition of the municipal waste water treatment costs in the Netherlands in 1987 per population equivalent removed per year (Centraal Bureau voor de Statistiek 1989).**

	Costs (Dfl)	Costs (%)
Capital	25.37	59
Personnel	5.20	12
Sludge disposal	4.30	10
Energy	3.44	8
Maintenance	3.01	7
Chemicals	0.86	2
Total	43.00	100

Two dutch public bodies with expertise on waste water treatment, DBW/RIZA and STORA, have recently investigated the weak points of the current generation of municipal sewage treatment plants, and have examined the possibilities to remedy these problems.

The following problem areas were originally identified in 1982 (Anonymous 1987):

-The large surface area occupied by the installations
-The nuisance for the surroundings
-The high energy consumption
-The high proportion of the capital costs in the total costs.

Against this background the following design criteria for the next generation of sewage treatment plants have been formulated:

-smaller reactors
-better solids/liquid separation, resulting in smaller settlers
-less sludge production

Comparison of these two short-lists shows that the ideas about waste water treatment are still evolving. Sludge disposal was not mentioned in the 1982 list of areas for special attention, but the increasing concern about soil pollution has led to an aversion against the use of sewage sludge as fertilizer, and it is therefor expected that this low-cost sludge disposal method will be abandoned in the near future, and that the costs of sludge disposal will rise sharply.

Similarly, it is striking that a better removal of nitrogen, phosphor, and recalcitrant compounds are not explicitly mentioned as design criteria for the next generation of sewage treatment plants, despite the fact that with present technologies it will be hard to reach the goals that follow from international treaties specifying substantially better nitrogen and phosphorus removal than currently achieved. What was specified in the design criteria, however, was that the next generation of sewage treatment plants should do better than the present one, which implied: the same for less money, or better for less or the same amount of money.

The most important conclusion from these surveys was the realisation that these goals will not be met unless significant attention is given to fundamental studies aimed at the development of better treatment technologies. In order to promote such studies a special budget was set apart with the objective to promote long term research aimed at pushing forward the frontiers of waste water treatment technology. This program, RWZI-2000, presently stimulates research in the following areas:
Sludge dewatering and sludge disposal
Development of novel treatment technologies.
In both areas opportunities are created for long-term research that would otherwise not be carried out (Anonymous 1988b, 1989).

The present study has been undertaken within the scope of the RWZI-2000 program, and originated from the idea to evaluate the feasibility of introducing proven advanced industrial bioprocessing technologies to municipal waste water treatment systems, with special emphasis on the possibilities to develop high-performance bioreactors for waste water treatment.

1.1 Objectives and focus of the present study

The objective of the present study is to evaluate the posssibilities to develop high-performance bioreactor systems for utilization in the aerobic treatment of municipal waste water. These reactors should combine the following characteristics:

- enhanced volumetric activities
- enhanced oxidation of substrates rather than conversion of substrates into biomass
- widened substrate range in order to also degrade recalcitrant compounds

In bioreactors the biocatalyst is the cornerstone of the system. The concentration and potential activities of the biomass determine the volumetric loading rates and the substrate range that can be treated in the system. Thus development of high-performance bioreactor systems hinges on two factors: a high concentration of biocatalyst, and an optimal activity of this biocatalyst (activated sludge).

In principle two complementary approaches for the development of such systems can be envisaged: an (eco)physiological approach and a technological approach. In the present study the emphasis is on the technological approach, but whenever necessary the physiological aspects will be included in the discussion/evaluation.

In most conventional waste water treatment systems the "high" concentration of biocatalyst is obtained by selection for well settling sludge flocs which are separated from the effluent of the reactor in a settling tank. A small fraction of the settled sludge is discharged into the anaerobic sludge digestor, while most of the sludge is recycled to the reactor where it is used again to oxidize the biodegradable material present in the waste water. This sludge recycling via settling tanks is one of the weak points of the current aerobic treatment technology. Settling tanks are not able to efficiently handle sludge concentrations of more than 10 kg/m3 and they need a lot of space. Furthermore they occasionally fail when the sludge develops its notorious bulking characteristics.

Thus the above objectives can be narrowed down to finding an economical alternative for the settling tank. Membrane-assisted sludge retention is a possible alternative, and therefor the objective of the present study is to evaluate the feasibility of membrane-assisted sludge retention in the development of high-performance bioreactor systems for the treatment of municipal waste water.

In principle the application of membrane filters for biomass retention in waste water treatment systems offers the opportunity to work at high biomass concentrations. Efficient biomass retention also offers the opportunity to work at high sludge ages, a practice which according to the present theories should result in lower sludge production. Other microbiological (physiological) aspects of efficient biomass retention are the possibility to obtain full nitrification (and even denitrification) at high volumetric loading rates, and the possibility to select for (or add and retain) organisms that are able to degrade recalcitrant compounds (Table 1.4)

Table 1.4 Membrane-assisted biomass retention in municipal waste water treatment plants: possible benefits and problems.

Possible benefits:

-Efficient biomass retention. This allows high biomass concentrations and may therefor permit high loading rates
-High sludge ages. This is associated with low surplus sludge production
-Simultaneous nitrification and denitrification in highly-loaded systems
-Degradation of recalcitrant compounds

Potential problems:

-Problems in maintaining long term flux stability
-High energy consumption

In addition to an evaluation of these microbiological aspects this study focusses on the technological aspects of membrane-assisted sludge retention. In product oriented biotechnological processes, biomass is sometimes retained by a process called cross or tangential flow filtration. In this process the contents of the bioreactor are forced rapidly along a membrane. Deposition of particles and plugging of the membrane is minimized by the shear forces thus applied, and a part of the reactor contents is pushed through the membrane by the application of a pressure difference over the membrane. This technology generally works well and has the major advantage over classical dead-end filtration that there is little membrane clogging. Nevertheless some degree of fouling will gradually occur, and the present study will review the state of the art in this area. The two main topics to be covered are the degree of membrane fouling that is to be expected, and the energy consumption of cross flow filtration processes.

The technical feasibility study will be followed by an economical analysis in order to evaluate the overall technical and economic feasibility of membrane enhanced sludge retention in municipal waste water treatment systems.

2 MICROBIOLOGICAL ASPECTS OF BIOMASS RETENTION IN MUNICIPAL WASTE WATER TREATMENT SYSTEMS

2.1 Introduction

In this chapter those aspects of biomass retention that are relevant for the specific activity of activated sludge will be discussed against the background of the possibilities offered by membrane enhanced biomass retention. As stated previously, two objectives will be evaluated in this study, viz. the feasibility of a high volumetric activity, and the feasibility of a low sludge production. In the present chapter both aspects will be discussed, and it will be evaluated whether both objectives can be met simultaneously, or whether a choice must be made between the two. Furthermore it will be evaluated what possibilities complete biomass retention has for the elimination of nitrogen and recalcitrant compounds.

2.2 Biomass concentration and specific activity of sludge

Intuitively, complete biomass retention should, at a constant loading rate, result in a steady state biomass concentration that is related to this loading rate. The concept behind this hypothesis is that microorganisms harness the energy obtained during the degradation of organic material and use this energy for cell maintenance and growth. The energy used for maintenance is thought to be constant or at least have some minimal value, and since due to cell growth the amount of energy available per cell gradually drops if the loading rate is kept constant in a system with complete biomass retention, the system will reach a state where the amount of energy available to the cells is just enough to cover their expenses for maintenance and not for growth.

This line of reasoning suggests that the limit to the concentration of sludge that can be obtained in a bioreactor is determined by the packing density of the biomass, as long as the rate of substrate and oxygen transport from the water phase to the cells, as well as the rate of product and CO_2 transport from the cells to the water phase are not limiting. Since the density of biomass in biolayers is about 100-150 kg/m^3 (Heijnen 1983, 1984) it seems reasonable to assume this to be the upper limit. The loading rate that can be achieved in such a reactor completely filled with biomass is then determined by the maintenance energy requirements of the cells. This parameter is expected to depend on a variety of both microbial and environmental factors and may therefor vary widely in a practical waste water treatment plant. The loading rate of the current generation of municipal waste water treatment systems is about 0.5 $kgBOD/m^3/day$ at a sludge concentration of 3.5 kg/m^3. This implies an oxygen consumption rate of about 11 μmoles/l/min, a value which is 200 times lower than the oxygen transfer rates in large industrial fermentors. Thus it seems unlikely that the transport rate of oxygen will become rate limiting even if biomass concentrations of 40 times the current value can be achieved. Therefor in the present study no further attention will be given to the possibility that transport of substrates or products may become rate limiting at high biomass densities, but it should be kept in mind that transport processes may become rate limiting if the specific activity of the sludge can be improved significantly over the current levels.

2.2.1 Estimates of the maintenance energy requirements of sludge

The literature values for maintenance energy show much variation (Roels 1983; Stouthamer et al. 1987). The interpretation of the values presented for actual waste water treatment systems is tricky because these data are frequently expressed in different units, and have been obtained with different waste waters and at different temperatures. Another problem is that the maintenance coefficient is obtained from plots of the specific activity of the sludge versus the growth rate of the biomass; the maintenance coefficient is then estimated from an extrapolation to zero growth, i.e. to an infinite sludge age. Obviously such an extrapolation is already highly controversial in pure culture systems, and even more so in mixed culture systems as changes in the growth rate imposed on the system can be expected to result in population shifts in a mixed culture system. With these reservations in mind the data presented by Rensink and coworkers (de Vries et al. 1985) suggest that the specific activity of activated sludge in a dutch municipal waste water treatment system under no-growth conditions will be about 90 gCOD/kg sludge/day (appendix 2). The upper limit to the volumetric loading rate in a system with complete sludge retention is then in the order of 9 to 14 kg COD/m^3/day. This value is a factor 10 to 20 higher than the volumetric loading rates of the current one reactor-systems, and equal to or two times lower than the target value for the fluidized bed system currently under development in Delft (Kampf et al. 1987).

To further illustrate the pitfalls of estimating the maintenance coefficient from published data Figure 2.1 is included. It is clear that no correlation can be detected between sludge age and sludge yield (surplus sludge production). Apparently the primary sludge produced in the presettling tank masks any correlation between sludge age and overall sludge yield. This is an important point to keep in mind if a choice has to be made between the possibility to achieve higher volumetric activities in a membrane enhanced system and the possibility to lower the surplus sludge production in such a system.

2.2.2 Variations in the maintenance energy requirements of sludge

An interesting phenomenon in this context is the observation of Neijssel and Tempest (1976) that the "maintenance requirements" of *Klebsiella aerogenes* depend on the kind of limitation under which the organism is growing. In their experiments the oxygen consumption rate under phosphate limitation was significantly higher than under carbon-

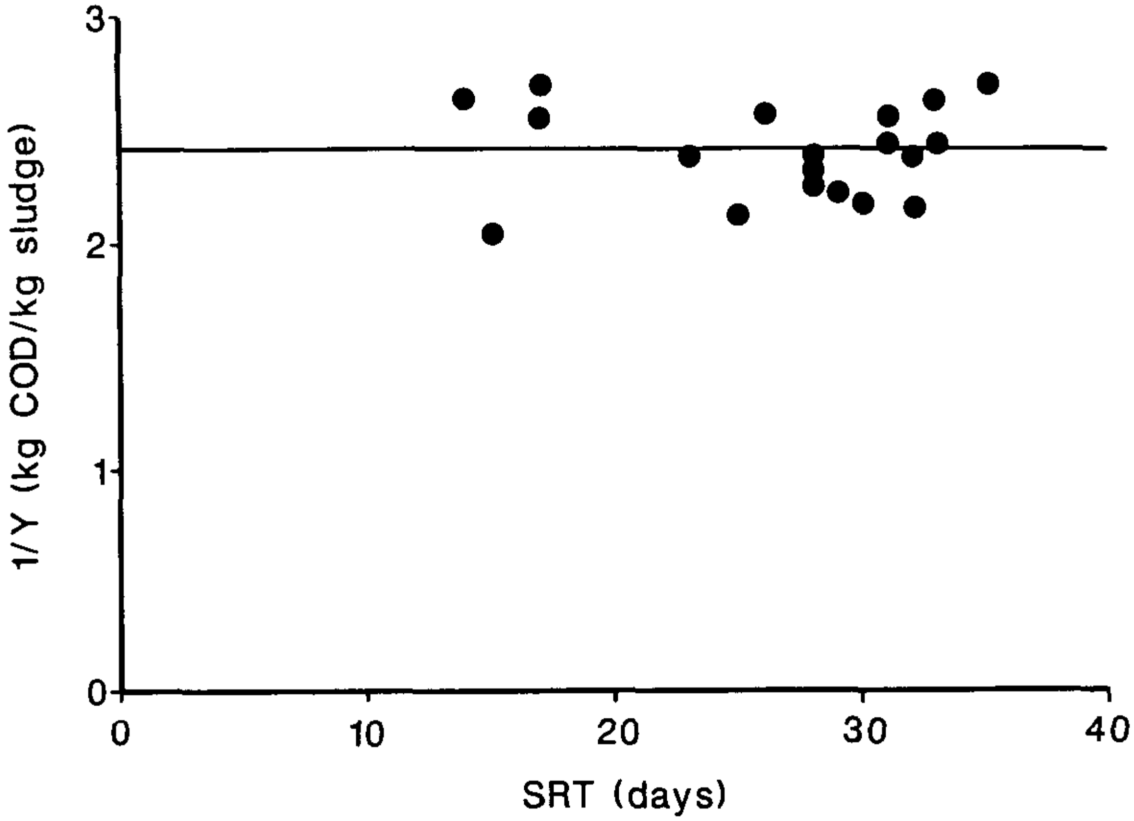

Figure 2.1 **Relationship between sludge age and (specific) sludge** production in dutch municipal waste water treatment systems (Data from Centraal Bureau voor de Statistiek 1988).

and energy limitation. Assuming that similar phenomena also occur in activated sludge, this suggests a way to maximize the specific activity of activated sludge in a system with complete biomass retention by specifically removing a compound (e.g. phosphate or sulfate) from the waste stream before the waste comes into contact with the activated sludge.

Another important point in this context is that there are large fluctuations in the composition and flux of the waste water through the treatment system. These fluctuations imply that the organisms in such a waste treatment system continuously experience different conditions. This may very well put extra stress on the organisms and make their metabolic behaviour, and especially their maintenance requirements, different from the behaviour of the model organisms studied so far (Bulthuis et al. 1989).

2.2.3 Experimental approaches

The general remarks made above indicate that most of the answers to the important kinetic questions about the effect of complete biomass retention on the activity and behaviour of activated sludge can only be learned from long term experiments with activated sludge systems to which complete biomass retention is applied. For a proper understanding subsequent studies with pure cultures or with model systems are obviously a must, but for an immediate and adequate evaluation of the phenomena which deserve the most attention, studies under conditions that reflect the real-life situation as closely as possible are advisable.

To our knowledge nothing has been reported in the open literature about such an approach with systems operated with real waste water. There are however some promising model studies with artificial waste water. The first in this field were the model studies by the group of Gaudy (Gaudy et al. 1970, 1971, and 1976). This laboratory picked up the hypothesis put forward by Porges (1953) that it should be possible to achieve complete oxidation of a biodegradable waste stream, i.e. to eliminate the production of surplus sludge, by imposing complete biomass retention. In such a system new growth of the biomass should be counterbalanced by autodigestion (endogenous metabolism) of the biomass. At first Porges' hypothesis was met by a lot of criticism (Kountz and Forney 1959; Busch and Myrick 1960; Symons and McKinney 1958). It was claimed that complete oxidation is biologically impossible because part of the newly formed biomass would be non-biodegradable. This turned out to be for a large part armchair criticism, and to the extent that the criticism was based on experimental evidence, the results were influenced by experimental problems in that part of the biological solids were inadvertantly lost over the weir of the final clarifier.

In Gaudy's experiments complete biomass retention was obtained by centrifugation of the effluent, thus assuring return of all biological solids to the aeration tank. In a first series of experiments he showed that he was able to continuously operate an activated sludge system on a glucose based artificial waste water for a period of more than 3 years, without having to remove any surplus sludge. The purification efficiency was more than 90 % and there were no signs of the accumulation of a biologically inactive fraction, while the sludge concentration in the reactor never reached a real steady state but oscillated around a value of about 16 kg/m^3 (Fig. 2.2). The specific activity of the biomass operating under this kind of pseudo-maintenance condition was 50 gBOD/kg/day, i.e. close to the value postulated above for the dutch situation. Interestingly, the endogenous oxygen uptake of the sludge was 36 gO_2/kg sludge/day, but the oxygen uptake immediately after a shock load increased to values as high as 1440 gO_2/kg sludge/day, indicating that the system was well adapted to handling shock loads.

The oscillations in the sludge concentration observed by Gaudy suggest that the maintenance concept is not very useful, or at least not the only factor necessary to describe the behaviour of activated sludge at very

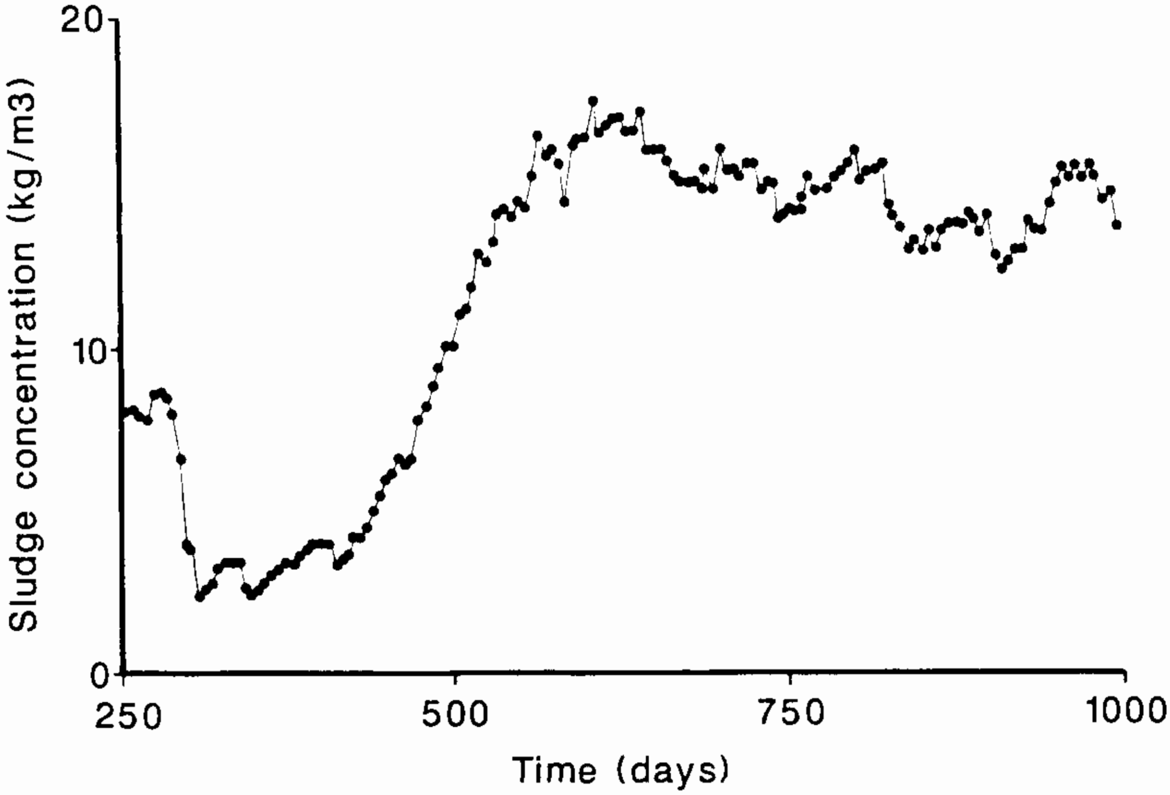

Figure 2.2 Sludge concentration in an activated sludge system with complete sludge retention (after Gaudy et al. 1970, 1971).

high sludge ages. Cryptic growth and predation may also come into play under such conditions, and indeed terms like autolysis and autodigestion may prove more meaningful for understanding the behaviour of a mixed population than the term maintenance energy.

2.2.4 Structure of sludge under various experimental conditions

Oscillations in the sludge concentration, and periods of inadequate settling behaviour of the sludge were the main problems encountered in Gaudy's study. The bad settling behaviour was caused by the development of small flocs, not by development of filamentous sludge. Complete nitrification first occurred after about two years and remained complete for the remainder of the experiment (one year). The experiment described above was performed with a completely soluble substrate, and therefor extrapolating from these results to municipal waste water that contains a significant fraction of non-dissolved material is not possible. To evaluate the effect of such a non-dissolved fraction a second experiment was done by Gaudy's group. This time the influent was enriched with hydrolyzed sewage sludge from a trickling filter. This addition contained about 50 % inorganic material. Also with this addition, the system operated stably for a long time, more than 1.5 years. Again the sludge concentration stabilized at 15-20 kg/m^3, and the properties of the biomass were not noticeably influenced by the presence of the entrapped material. The ash content in the sludge increased to 50 % and remained stable at this level. There is however one important annotation that should be made to this experiment: on a weekly basis part of the sludge in the reactor (10-20%) was removed, hydrolyzed, and returned to the reactor. In addition hydrolyzed sludge was added to the reactor to model the effects of primary sludge. This hydrolytic assist was incorporated into the reactor system to enable the operators to expand the natural autolytic processes in the reactor at times when these processes seemed unable to keep the growth of the sludge in check. Unfortunately, a control experiment without a hydrolytic assist was not done, so it is not clear to what extent this assist is really necessary. From this experiment it is however clear that entrapment of non-biodegradable inorganic material should not be a problem in a municipal waste water treatment with complete sludge retention. For slowly degradable or even non-degradable organic material, however, this question cannot yet be answered. It remains a question of course whether this approach is also economically attractive, as complete oxidation of the waste will result in a higher oxygen demand of the treatment process.

2.2.5 Summary: known characteristics of aged sludge

Not much information is available on the behaviour of activated sludge at long sludge retention times. Extrapolation of data obtained at short retention times may lead to erroneous conclusions. From the few data available, however, it can be concluded that there are no theoretical reasons why complete biomass retention should be impossible in waste water treatment. The specific activity of the biomass under those conditions is likely to be low, but there may be ways to uncouple the specific activity of the biomass from the stringencies imposed by the non-growth conditions. The economics of a waste treatment system operating under no growth conditions, may however be such that it is desirable to allow for some growth in order to obtain a higher specific activity of the biomass. This consideration can however only be made if reliable data are available for the relationship between specific activity and growth rate of activated sludge at high sludge ages, i.e. measured at these ages, and not obtained by extrapolations. In the discussion presented above emphasis has been placed on the maintenance concept as the idea behind the hypothesis that below a certain food over microorganism ratio no net sludge growth will occur. Another important side of complete sludge retention is however that death and (auto)lysis become important aspects of the overall metabolism of the sludge community at low or zero growth rates. These phenomena may be as important as the maintenance concept for a better understanding of the behaviour of activated sludge under those conditions. Recent reviews (Mason et al. 1986; Bryers and Mason 1987) revealed that essentially nothing is known about this subject, and discrimination between the two views is currently mainly academic. Furthermore, it seems possible to reconcile the two approaches by arguing that after a detour death and autolysis lead to the same result as maintenance: rather than having a constant maintenance requirement the cell population degrades part of its mass at a constant rate.

2.3 Nitrogen removal

In the current treatment systems nitrogen removal is achieved by manipulating the oxygen concentration in the waste stream(s) (Kunst and Mudrack 1988). Recirculation and alternating processes are used to the same degree (Henze 1991). Replacing the settling tank by a membrane system to achieve sludge/water separation does not affect these options.

Complete nitrification should be easily achievable in a sludge retention system, since there is no danger that the relatively slow growing nitrifyers will be washed out of the reactor, or wasted with the surplus sludge. Table 2.1 shows that this is indeed the case. In model studies with complete biomass retention complete nitrification was achieved at hydraulic retention times as low as 4 hours. In the two japanese studies complete nitrification was achieved already within a few days after the start of the experiments, while in Gaudy's studies it took two years before complete nitrification was achieved. Nitrogen balance studies suggest that under a proper aeration regime more than 50 % of the ammonium nitrogen can simultaneously be converted into nitrogen gases.

Table 2.1 Nitrogen removal in laboratory scale waste water treatment systems with complete biomass retention

Biomass retention	Nitrification (%)	Denitrification (%)	HRT^ (h)
Cross flow filtration*	100	50	16
Dead-end filtration**	97	60	4
Centrifugation***	>90	–	16

^: HRT = hydraulic retention time. *: Suwa et al. 1989; **: Yamamoto et al. 1989; ***: Yang and Gaudy 1974.

Biomass retention by means of membrane systems therefore appears to improve the possibilities for nitrogen removal.

2.4 Phosphorus removal

Techniques specifically aimed at removing phosphorus from municipal waste water are not yet applied on a large scale in the Netherlands. The classical precipitation techniques with iron and aluminum are indeed far from ideal, since they result in the generation of large additional quantities of surplus sludge.

Simultaneous precipitation and complete biomass retention are incompatible. This does however not imply that extensive phosphate removal cannot be achieved in systems which employ membrane filtration to achieve biomass retention. Phosphate removal by means of a Crystalactor® (Rensink et al. 1991) remains a posssibility, although the (unknown, but probably not very favourable) settling characteristics of activated sludges selected for in a membrane reactor may interfere with a smooth operation of such a process.

2.5 Removal of recalcitrant compounds

For many hydrophobic compounds, especially those with log K_{OW} >5 (where K_{OW} stands for octanol/water partition coefficient), sorption to biomass is the main elimination route in waste water treatment plants (Matter-Müller et al. 1980; Drescher-Kaden et al. 1989). Complete biomass retention will therefore result in accumulation of these compounds in the treatment system, and eventually they will pass through the system without any appreciable elimination unless a subpopulation develops in the activated sludge that is able to degrade them. The concentrations that will be reached in the activated sludge in systems with complete biomass retention depend on the concentrations in the influent and on the log K_{OW}, and no data are currently available to predict whether these concentrations may be toxic to the activated sludge.

The inorganic micropollutants that are eliminated via sludge removal are mainly heavy metals. The removal efficiency of this group is about 50 %. Thus it seems unlikely that this category will pose any problems in systems with complete biomass retention.

Activated sludge reactors with complete biomass retention will provide an excellent habitat for the development of (slow growing) organisms specialized in the degradation of recalcitrant xenobiotics (van Luin and van Starkenburg 1984; McIntyre and Lester 1984), or the possibility to inoculate a system with such organisms and indeed retain them in the system. Whether such organisms will develop or retain their activity is presently an open question (Dwyer et al. 1988; McClure et al. 1989).

3 MEMBRANE ENHANCED BIOMASS RETENTION IN BIOTECHNOLOGY

3.1 Introduction

Membrane enhanced biomass retention is currently being applied successfully in a variety of biotechnological processes, especially in the production of industrially important extracellular metabolites such as ethanol, lactate, butanol-acetone, and acetic acid. Small molecules like these pass through the membrane readily, do not accumulate to undesirably high concentrations in the fermentor, and may be recovered from a cell-free filtrate, while the cell-recycle culture system allows increased microbial cell concentrations and dilution rates, and hence metabolic productivity.

The practical application of membrane enhanced biomass retention has been made possible by two technological innovations: the development of asymmetric membranes, and the development of cross flow filtration. Both innovations are crucial to the achievement of the high fluxes necessary to make membrane enhanced biomass retention an economically viable process.

3.2 Types of membranes and membrane modules

Membranes can be classified in three general groups according to their operating characteristics: microfiltration (MF), ultrafiltration (UF), and reverse osmosis (RO). Each of these groups of applications has its own characteristics, the most important ones being the pore sizes of the membranes and the type of particles retained. Microporous membranes are defined by pore sizes between 0.1 μm and 10 μm, while ultrafiltration membranes have pore sizes between 0.001 and 0.05 μm. In reverse osmosis pore sizes are below 0.001 μm. (In specifications of reverse osmosis membranes the separation characteristics are usually given as cut off in Daltons, i.e. in the units of molecular weight of the molecules retained by the membrane, rather than as the pore size.)

There are no fundamental differences between the three classes of membranes. In fact membranes belonging to different classes can consist of the same material and are sometimes made by the same process. Asymmetric membranes were first developed for ultrafiltration and reverse osmosis, but are currently also commercially available with pore sizes in the microfiltration range (Le et al 1984, Hsieh et al 1988). With respect to the operating conditions there are again no fundamental differences, the practical difference being that reverse osmosis is usually operated at 3000-6000 kPa, while the other processes operate in the pressure range of 50-700 kPa (100 kPa = 1 atm).

For successful and useful filtration the membrane must possess the following characteristics: (1) high hydraulic permeability, that is, the membrane must allow the passage of water at high rates per unit membrane area under modest pressure; (2) high fouling resistance, that is, no tendency to adsorb or retain solutes in the pore network as this reduces hydraulic permeability; (3) long membrane life; (4) good mechanical durability, chemical and thermal stability; and (5) easily cleanable.

The emphasis placed on a high hydraulic permeability and a good resistance against fouling already suggests that modern large scale filtration processes are not operated in the classical dead end mode, i.e. that the slurry is not directed "dead end" into the filter, as this will result in retention of all the filtered material on and in the filter, and therefor in a dramatic flux decay. A more sophisticated mode of operation is to employ cross flow filtration, where a high fluid circulation rate tangential to the filtration barrier (the membrane) is used to sweep particulate material away from the membrane surface. Cross flow filtration, sometimes also called tangential filtration, was already known in the sixties, but has only gained widespread recognition as an attractive separation technology in the seventies thanks to the work of Henry (Henry 1972; Henry and Allred 1972).

Table 3.1 Commercially available polymeric microfiltration membranes (after Defrise and Gekas 1988, and Roesink 1989)

Material	Resistance (thermal/ chemical)	Geometry*	Applications
Hydrophilic			
Cellulosics	poor	F C K	bacterial analysis air filtration pharmaceutical
Nylon	good	F C K	–
Polyethersulfone	–	F C	biotechnology
Polyetherimide	–	F C	process industry biotechnology
Hydrophobic			
Nylon	–	F	–
PVC	poor	M	air filtration clarification
PTFE (teflon)	good	F C K	sterilization gas filtration
Polyethylene	fair	T	–
Polysulfone	good	F C K H	sterilization
Polypropylene	–	F C K	pharmaceuticals food industry

*: F=flat; C=cylindrical; K=cartridge; M=cast on non-woven polyolefin; H=hollow fibre; T=tubes.

Nowadays a wide variety of membrane materials (Table 3.1) and membrane modules (Table 3.2), all with their own advantages and disadvantages, are available for use in cross flow filtration units. Asymmetric membranes are preferred for virtually all applications. Such membranes have a thin dense skin layer supported on a much more open microporous sublayer. This combination not only provides significantly higher fluxes than symmetric membranes do, but it also offers significantly better flux stability, because the skin acts as a true surface filter. The particles are retained at the surface, where they can be removed by shear forces provided by the flow of the feed solution tangential to the surface. In the older symmetric membranes particles tended to lodge in the interstices of the structure, and this resulted in plugging of the membrane (Singh 1989). Filtration rates are also greatly increased since the major flow resistance, the skin layer can be extremely thin (in the order of 2-10 μm) and is supported by a more porous support matrix with a low hydraulic resistance (Hsieh et al. 1988).

Table 3.2 Membrane module concepts (after Strathmann 1984)

Module type	Membrane surface per module (m2/m3)	Capital cost	Operating cost	Flow control	Ease of cleaning in place
Tubular	25-50	high	high	good	good
Plate and frame	400-600	high	low	fair	poor
Spiral Wound	800-1000	very low	low	poor	poor
Capillary	600-1200	low	low	good	fair
Grooved rods	200-300	low	low	poor	fair

For more detailed information the reader is referred to reviews by Strathmann (1984) and Belfort (1988).

3.3 Flux through membranes

3.3.1 Membrane flux decay

Flux stability is perhaps the most critical factor determining process and economic viability of membrane separation processes, as flux decay can be a serious problem. Flux decay is usually a direct result of an increase in the hydraulic resistance of the membrane due to fouling, i.e., excessive accumulation of solutes at the membrane surface or in the pores. Most if not all liquid streams in biotechnology contain extraneous matter in the form of small particles, macromolecules etc. During the filtration operation, these substances are often concentrated near the surface as well as in the pores. The phenomenon of membrane fouling is only partially understood (Milisic and Ben Aim 1986), but there are ways to control flux decay, and obtain a stable flux for extended operation (Schulz and Ripperger 1989).

Three processes play a role in flux decay: sorption of solutes on the membrane, sorption of solutes in the membrane, and concentration polarization.

Sorption of solutes on the membrane is the outcome of a series of physico-chemical steps with as the result that particles or molecules stick permanently to the surface of the membrane. It can be minimized by choosing a membrane with optimal physico-chemical surface characteristics in order to minimize specifically the sorption of certain proteins or carbohydrates present in the filtrate.

Sorption of particles in the membrane occurs when particles are caught in the web-like pore structure of the membrane. It can be minimized by choosing the right pore size. When the size of the particles is too close to the pore size of the membrane they may get trapped in the pores.

Concentration polarisation is the phenomenon that the concentration of the particles that are retained by the membrane is higher close to the membrane than it is in the bulk of the solution. This is due to the fact that these particles are dragged to the surface of the membrane by consequence of the water flux through the membrane. This accumulation of particles at the surface of the membrane is counterbalanced by a diffusion away from the membrane, and as a result of these two partial processes a dynamic equilibrium will develop, resulting in a concentration gradient perpendicular to the membrane surface. The high concentration of particles close to the membrane surface may result in the formation of gel-like structures, which can become very stable and dense, especially when different interacting solutes are present. In this way layers can develop that have a higher flux resistance than the membrane itself. Concentration polarisation can be discouraged by increasing the cross flow velocity and by promoting turbulence at the surface of the membrane. In contrast higher transmembrane pressures can be counterproductive as they will not only enhance the flux through the membrane, but also compress the cake layer, which results in an increase in the specific resistance of the cake layer (Riesmeier et al. 1987, 1989; Nagata et al. 1989).

The classical model for concentration polarisation is based on the assumption that the dissolved solutes do not sorp or attach to the membrane surface, and that the solute layer is reversibly established. Recently, Belfort and coworkers (Nagata et al. 1989) formulated a more comprehensive model in which back migration of particles from the solute layer or the membrane surface is negligible and where particles that reach the solute-solution interface attach (stick) completely. The data presented by Belfort and coworkers do not favor one model over the other, probably because both models are extreme simplifications.

3.3.2 Membrane flux restoration

Backflushing and membrane cleaning are the most widely used methods for flux restoration of fouled membranes. In backflushing controlled pulses of either permeate or gas are pressed from the permeate side of the membrane through the pores (Galaj et al. 1984). The effficiency of this type of cleaning depends on the type of suspension to be filtered and the type of fouling that occurs. In industrial practice a variety of cleaning solutions is used for periodic cleaning of the membranes. For example with particulate foulants acid cleaning is generally effective, whereas for oily substances alkaline cleaning reagents are generally recommended. Protein deposits on the membrane surfaces can be removed by the use of suitable enzymatic cleaners. Many membrane devices will not withstand the use of strong cleaning agents. In some cases the membrane may be cleaned mechanically by a spongeball cleaning device (Takadono et al. 1984). Ceramic membranes can withstand harsh chemical environments and this is a definite advantage for certain applications (Hsieh et al. 1988).

The necessity for and frequency of membrane cleaning depend on the speed with which membrane fouling occurs and the level at which the flux deterioration stabilizes. Frequently flux decline due to concentration polarisation proceeds rapidly during the first minutes or hours after start up of the process, but after this rapid initial flux decline the flux stabilizes at a steady state level, and membrane cleaning remains superfluous. When flux decline is due to a gradual formation of a deposit on or in the membranes the time scale of flux decline can be different and periodic application of flux restoration methods can be useful.

3.3.3 Predicting flux decay from first principles

More information on the principles and phenomena that play a role in cross flow filtration can be found in handbooks and specialized journals like Desalination and the Journal of Membrane Science. From this literature it is clear that in spite of the special attention paid recently to the influence of various solutes, including proteins, salts, colloids, and particulates (microbial cells) on membrane fouling (McDonogh et al. 1989; Rautenbach and Schock 1988; Riesmeier et al. 1987; Visvanathan and Ben Aim 1989, Hanemaaijer et al. 1989), it is still virtually impossible to predict from first principles how a previously untested solution can be optimally processed by membrane filtration (Gatenholm et al. 1988; Singh 1989; Schulz and Ripperger 1989).

Table 3.3 gives a summary of the variables that influence the transmembrane flux in cross flow processes.

Table 3.3 Summary of factors influencing the transmembrane flux in cross flow filtration processes

Primary factors influencing the transmembrane flux

1. pore size of the membrane
2. surface characteristics of the membrane
3. porosity of the membrane
4. shear forces at the membrane surface
5. cross flow velocity
6. particle size
7. nature of the particles/solutes
8. concentration of the particles/solutes
9. transmembrane pressure
10. pressure drop along the membrane
11. temperature

Secondary factors (processes) influencing the transmembrane flux

1. concentration polarisation
2. gel layer formation
3. adhesion of solutes at the surface and/or in the pores of the membrane
4. compaction of the gel layer

3.4 The application of membranes for biomass retention in biotechnology

A major application of cross flow filtration in biotechnology is its use to improve the volumetric productivity of bioreactors. A fermentation system equipped with a cross flow unit allows the continuous removal of inhibitory metabolites while retaining a high concentration of cells. This concept has been successfully applied by Kobayashi and coworkers in Japan. This group works on lactic acid fermentation, an important microbial process in the food industry. In fed batch cultures lactic acid accumulates to toxic levels thus limiting growth and activity of the cells. The application of cross flow filtration overcomes this problem: lactate is continuously being removed, thereby enabling further growth and activity of the cells. In this way biomass concentrations of 50-80 g/l were achieved. Unrestrained accumulation of biomass, however, resulted in a steady decrease in the specific activity of the cells. This problem was solved by continuously bleeding part of the biomass from the system, thus maintaining the cells under steady well defined growth conditions (Wang et al. 1988). These studies showed that cross flow filtration can be successfully applied to achieve high cell densities and a high volumetric activity. The membrane flux at a cell density of 81 g/l was 25 $l/m^2/h$. Table 3.4 summarizes some of the results obtained by Kobayashi and coworkers with various fermentations operated for 17 hours at 37°C.

Table 3.4 **Operating conditions in microbial fermentations with membrane enhanced biomass retention employing ceramic membranes with a pore size of 0.2 μm.**

Organism	Cross flow rate (m/sec)	Flux ($l/m^2/h$)	Biomass (g/l)
*S. cremoris**	0.7	25	81
*L. casei**	--	25	49
*B. longum***	0.7	2	54
*E. coli****	--	20	66

*: Taniguchi et al. 1987a. *S=Streptococcus, L=Lactobacillus;*
-- = not published.
**: Taniguchi et al. 1987b. *B=Bifidobacterium*
***: Iijima et al. 1987. *E=Escherichia*

Propionic acid fermentation is another example where the performance of the bioreactor was increased by coupling of the fermentor with a cross flow filtration unit. Working with *Propionibacterium acidi-propionici,* Blanc and Goma (1987) were able to work at a biomass concentration of 112 g/l. This concentration was 9 times higher than could be obtained in batch experiments. Under these conditions the specific activity of the biomass in the cell recycle experiment dropped about 50 %, an observation that could not be fully explained. The occurrence of cell damage induced by the high shear forces applied in the filtration unit (Nipkow et al. 1989) cannot be ruled out as the cause of the decline in specific activity in this case. Hoffmann et al. (1987) showed that in their system yeast cells were not damaged by cross flow filtration. This group studied the application of cross flow filtration for the production of ethanol (Hoffmann et al. 1987, 1988). Another successful application of cell retention via cross flow filtration was reported by Holst et al. (1985), who used *Streptococcus lactis* to produce superoxide dismutase in such a system. These authors too could not observe damage to the microorganisms from the filtration step. Another possible cause of a decrease in the specific activity in cell recycle systems is the accumulation of toxins. Damiano et al. (1985) present evidence for the occurrence of this phenomenon in their ethanol fermentation. Furthermore they present a general method for determining the best recycle ratio. In their case a balance among fermentor productivity, specific productivity, and wasted substrate needed to be made to approach an optimal operational design for the overall system.

From the papers cited above it is clear that cross flow filtration can be successfully applied in industrial fermentations, and that the optimal operational parameters need to be established by experimentation for each specific case. There is no systematic preference for a certain type of membrane or membrane module. Also the choice of the pore size of the membrane and the cross flow velocity generally seems to be arbitrary, although exceptions to this observation exist (Hoffmann et al. 1987). The main conclusion of the present survey is thus that biomass retention by means of cross flow filtration can be beneficial for the improvement of the volumetric activity of bioreactors. Biomass concentrations of more than 100 g/l can be achieved in such systems.

4 A BRIEF HISTORY OF THE USE OF MEMBRANE ASSISTED BIOMASS RETENTION IN WASTE WATER TREATMENT

4.1 Introduction

Filters have been used in waste water treatment for decennia, and the use of reversed osmosis for the preparation of drinking water from sea water is a well established technology. In the wake of this technology other membrane separation applications for the treatment of specific waste streams have been developed, and are currently applied successfully on an industrial scale (Cheryan 1986).

The use of cross flow technology in waste water treatment has been pioneered by Dorr Oliver Inc., an engineering firm, that obtained a patent on the application of cross flow technology for biomass retention in waste water treatment in 1967 (Dorr Oliver 1967, Okey 1970, Stavenger 1971), but the process never lived up to its potential and the use of cross flow filtration for biomass retention in waste water treatment has thus far remained an underdeveloped field. The main application of the system has been in small scale treatment plants for the purification of municipal waste water in large buildings and office blocks in Japan (Arika 1977), i.e. in places where space is extremely expensive.

In addition to these specialty applications, Dorr Oliver has focused on the application of membrane enhanced biomass retention for anaerobic systems (Li et al. 1984, Li and Corrado 1985). This approach is not illogical, as anaerobic bacteria grow much more slowly than aerobes. Their retention in treatment systems is therefor likely to be more rewarding, and for the treatment of waste water where sludge develops that does not settle well, filters are especially useful. Furthermore, since anaerobic systems require no oxygen, the oxygen supply cannot become limiting, as may be the case in aerobic systems where high volumetric activities are desired.

The position of membrane assisted anaerobic systems has however been jeopardized by the development of other advanced high rate bioreactors with good sludge retention, or at least good biomass hold-up, such as the UASB system, and the anaerobic fluidized bed and filter systems. Japan has failed to develop these technologies, and is currently trying to catch up by focusing on the development of more efficient biomass retention systems with the use of membrane technology. This research is coordinated in the Biofocus and Aqua Renaissance programs (see appendix 3).

4.2 Anaerobic systems

Membrane techniques for biomass retention are reputed to be associated with high energy costs, and have consequently seen only a few practical applications in waste water treatment. As recently as 1985 Saw et al. claimed that their concept of operating digesters using cross flow filtration units for biomass retention represented a new development. Although this claim was slightly exaggerated, theirs is indeed one of the few papers in which a systematic search was made of the optimal conditions for membrane assisted sludge retention.

Saw et al (1985) concluded that the optimal membrane grade cannot be predicted from first principles. Instead choices must be made empirically. In their experiments the flux through the membrane was dependent on the cross flow velocity. The correlation between the two indicated the existence of two distinct regions, one for the laminar flow regime, and one for the turbulent flow regime. The transition between the flow regimes occurred at a cross flow velocity of 3.0 to 6.0 m/s, corresponding to a Reynolds number of 1200 to 2400.

In experiments with a duration of 11 days Saw et al found that the flux dropped sharply during the first day, after which it remained stable over the remaining 10 days. This suggested that in the long run membrane fouling by anaerobic sludge reaches a limiting level. The optimum membrane grade for this particular sludge sample was a 0.45 µm Asypor membrane with an asymmetric structure.

Shimizu and Kayawake (Shimizu et al. 1988, 1989 a,b,c; Kayawake 1989) have studied ceramic membranes with pore sizes between 0.1 and 0.2 µm. In the experiments 0.1 µm turned out to be the optimum pore size (Shimizu et al. 1989b). With respect to long term flux stability it was found that the permeation flux of an aluminum membrane with a pore size of 0.2 µm decreased with time (Shimizu et al. 1989c). After 30 days at a cross flow velocity of 0.6 m/s the flux had dropped to 22 % of the value measured after 5 hours.

In a subsequent paper by the same group but with a different waste stream (cellulose rather than glucose) and a different ceramic membrane (pore size 0.1 µm) the flux could be stably maintained at 0.4 m^3/m^2/day at a cross flow velocity of 1 m/s, even though during this period the biomass concentration increased from 5 to 15 g/l (Kayawake et al. 1989).

The most important observations reported thus far (see also appendix 4) are:

-the existence of an optimum pore size,
-the possibility to stably operate a filtration system without fouling problems for 150 days,
-the occurrence of different fouling mechanisms at different cross flow velocities,
-the possibility to effectively abate fouling problems to a certain extent by membrane cleaning.

The level of the membrane fluxes reported, approximately 0.4 m^3/m^2/day, is however still below the value reported by Saw et al. (1985) of 0.7 m^3/m^2/day. Comparing these numbers is not completely fair. Both groups worked with biomass concentrations of 15 g/l, but the cross flow velocities, the pressures applied and the waste streams were different, as illustrated in Table 4.1.

Table 4.1 Operational characteristics of cross flow filtration applied as biomass retention technique in the anaerobic treatment of waste water.

Waste stream	Cellulose*	Brewery waste**
Biomass conc.(g/l)	15	15
Membrane type	Ceramic	Mixed ester
Pore size (µm)	0.1	0.45
Cross flow velocity	1 m/s	2 m/s
Pressure (kPa)	100	150
Flux (m^3/m^2/day)	0.4	0.7

* data from Kayawake et al. 1989
** data from Saw et al. 1985

In the Netherlands, DHV Consulting Engineers (1984) has a patent on the application of microfiltration for enhanced treatment of waste water. The firm reports a flux of 1.7 m^3/m^2/day at a sludge concentration of 8 g/l for the anaerobic treatment of textile bleaching water (Eggers et al. 1986).

4.3 Aerobic systems

In a review on the application of membrane processes in the treatment of sewage Sammon and Stringer (1975) fully concentrate on effluent polishing and water reuse. Biomass retention by means of cross flow ultrafiltration was known by these authors, as one reference was made to this possibility, but back in 1975 the process apparently was deemed too expensive to warrant further discussion of this application. Three years later Harris et al. (1978) published a paper in which they showed that ultrafiltration could be effectively used for the shipboard treatment of waste water, but their discussion suggests that they consider this treatment method as physical rather than a combined biological-physical method. These authors estimate the power consumption of the system as 6.4 kW/m^3, which is much too high for general application in sewage treatment plants. A few years later Christensen and Plaumann (1981) estimated the typical minimal energy requirement for the filtration of secondary effluent with a polysulfone ultrafiltration membrane to be 4.6 kWh/m^3.

In the meantime however the Dorr-Oliver system had been picked up in Japan (Arika et al. 1977) where it is now marketed by the Sanki Engineering Corporation. The process as originally developed has some characteristics that make it attractive for specialty applications like the treatment of waste streams in large office buildings where space is scarce. For such applications the following requirements have to be met:

1. The system should be compact,
2. Sludge formation should be kept at a minimum,
3. The system should be easy to operate and maintain,
4. The system should be able to absorb variations in influent characteristics, and
5. The overall reclamation costs should be low.

Sanki Engineering claims that its system provides an optimum solution to these requirements [see also appendix 5].

4.4 Membrane fouling

In 1980 the group of Fane published a study on the factors affecting ultrafiltration flux in a combined ultrafiltration-activated sludge waste water treatment system. Long-term experiments showed that the most dramatic decrease in flux occurred during the first 24 hours and that the degree of flux decline was a function of the cross flow velocity and/or sludge concentration. In an experiment over 30 days the flux decreased by a factor of 33. This decrease was completely caused by the formation of a gel layer on top of the membrane. Fane et al. (1980) also reported that stopping the substrate flux to the activated sludge reactor for several days resulted in an increase of the flux and hypothesized that under those conditions the cells within the gel layer lose their slime layer and their cohesive flocculant properties and become more susceptible to scour.

In the experiments of Krauth and Staab (1988) long term flux stability was no problem. These authors did not observe any decrease in the membrane flux during an operation period of 6 months. The membrane of choice in their experiments was the E 11 membrane of Hoechst, a membrane with a cut-off of 25 kDalton. The membrane was superior to two other membranes (HFM 251 and HFP 276 from Abcor) with cut-offs of 18 kDalton and 35 kDalton respectively. At cross flow velocities of 5-8 m/s the E 11 membrane allowed fluxes between 3 and 10 m^3/m^2/day at pressures of 200 and 300 kPa. The sludge concentrations in these experiments ranged between 2 and 3 g/l. The pressure in these experiments was higher than usual because their reason for these experiments was the development of a system in which the activated sludge process itself is operated at elevated pressure. The idea behind this approach is that aeration is facilitated under elevated pressures, and that the surplus sludge production under these conditions is lower than under the normal atmospheric pressure. This claim could indeed be substantiated with experimental evidence. Another interesting observation was that in these experiments a membrane with a pore size of 0.2 µm became irreversibly clogged after an operational period of only 60 hours.

4.5 Alternative approaches to avoiding high filtration energy costs

An extreme solution for the high energy costs inherent to biomass retention by means of cross flow filtration may be to directly insert the membranes into the aeration basin, i.e. to dispense with the idea of cross flow filtration, and to fall back on conventional dead-end filtration. This was indeed the approach taken recently by Yamamoto et al. (1989) [see also appendix 6].

By applying intermittent suction on hollow fiber membranes directly inserted into a laboratory scale activated sludge plant fed with a synthetic waste these authors were able to obtain a steady flux of about 2 $l/m^2/h$ against energy costs of only 0.007 kWh/m^3. The sludge concentration and volumetric loading rates obtained in this sytem were about three times those of conventional activated sludge systems, which is also quite attractive. At the current membrane prices of Dfl 150/m^2 (Delgorge and Eggers 1990) this approach is however too expensive: either the price of the membranes must drop considerably (by a factor of 100), or the achievable flux must be increased with a factor of 100 before this approach becomes economically feasible.

Another approach to bring down the costs for energy consumption may be to directly incorporate the membranes into more advanced biorectors of e.g. the airlift type, where superficial velocities of several meters per second are applied anyway, and thus come free of charge.

In addition to the membrane assisted bioreactors discussed so far and the carrier-mediated sludge retention strategy under development in Delft (Kampf et al. 1987), sludge retention via auto-immobilization may be a viable option. In the japanese Biofocus project two types of aerobic upflow systems are currently being tested for their applicability in the treatment of (presettled) municipal waste water (Takahashi and Kyosai 1988; Mishima and Tochikubo 1989). In both systems the activated sludge flocs show the granulation phenomenon well known from anaerobic systems (Dolfing 1987; Hulshoff Pol 1989). The authors of these Biofocus studies claim that in their experiments no surplus sludge was produced and that external settlers were superfluous. The volumetric loading rates in these systems were not better than those in conventional activated sludge systems, but there seem to be distinct possibilities for further optimization of their systems. The japanese waste water is however different from the dutch waste water in that it is more dilute, and therefor it is difficult to predict how such systems will respond to dutch conditions.

4.6 Conclusions

Although the idea of applying cross flow filtration for biomass retention in waste water treatment systems has been around for more than 20 years the technology has not yet been fully developed. This is mainly due to the high energy demand associated with obtaining enough turbulence along the membrane to prevent flux decline. In the last 5 years, however, the first steps have been taken to obtaining more systematic information on the relevant parameters that influence flux and flux decline, aimed at the development of membranes that are specifically tailored to waste water treatment applications [see appendix 7 for details]. Currently the fluxes obtained in small scale experiments are in the order of magnitude of about 0.4-0.7 $m^3/m^2/day$ at sludge concentrations of 15 g/l and an energy consumption of 1-2 kWh/m^3 (Kimura 1991). In short term experiments the fluxes appear to be linearly correlated to the logarithm of the sludge concentration, but in long term experiments this correlation is not always recognizable. The sensitivity of the various membrane systems to fouling is not straightforward either: in some cases severe flux decline occurred over time while in other cases no further flux decline could be observed after the first 24 hours of operation. The effect of the cross flow velocity in preventing flux decline was clearcut in short term experiments, but long term experiments showed that high cross flow velocities cannot prevent a gradual plugging of microfiltration membranes. This may turn out to be different for ultrafiltration membranes. Another interesting observation was that systematic cleaning of the membranes could prevent the build-up of a flux-demoting gel layer.

5 ECONOMIC ASPECTS OF MEMBRANE ASSISTED SLUDGE RETENTION IN WASTE WATER TREATMENT

5.1 Introduction

In previous chapters the technical feasibility of the application of membrane assisted sludge retention has been discussed, based on the present state of the art. The potential economic advantages of membrane assisted sludge retention are:

1. Elimination of the settling compartment
2. High volumetric activities
3. Low surplus sludge production

The costs for the implementation of this technology consist of:

1. The membrane modules
2. The membranes
3. Extra energy consumption
4. Extra labour- and cleaning costs

These posts will be quantified below. The estimates have been made for a waste water treatment plant with a capacity of 100.000 p.e. Such a plant must be able to handle a waste water flux of 4000 m^3/h. The average waste water flux through such a plant is 1200 m^3/h. Other characteristics are given in appendix 1. The costs and benefits are expressed per population equivalent per year and compared to present costs and associated levies.

5.2 Costs

A sensitivity analysis of the costs of the implementation of membrane assisted sludge retention is given in Table 5.1. The values presented in this analysis will serve as the basis for a discussion on the economic feasibility of the process. For comparison: the current waste water treatment levies are generally Dfl 50-75/p.e./year (Schoot Uiterkamp personal communication 1989), while the actual treatment costs are somewhat lower at Dfl 43/p.e./year.

The calculations are based on a flux of 1 $m^3/m^2/h$. At a waste water flux of 4000 m^3/h the surface to be installed will then be 4000 m^2. The investment costs for the modules and pumps for an installation of 600 m^2 are Dfl 1 million. This price is based on the actual price of a membrane unit with a surface area of 600 m^2 installed recently in a dairy factory. Write off time is ten years with an annuity of 15 %. Advantages of scale are incorporated via a power of 0.7. For the membranes the calculations are based on a price of Dfl 300/m^2, a life time of 3 years, and an annuity of 40 %. Here there are no economies of scale due to the installation of larger surface areas, although increased membrane use is likely to reduce membrane prices in the longer run. Energy costs are estimated based on a present cost of Dfl. 0.20/kWh, and a waste water flux of 55 m^3/p.e./year. Energy requirements are assumed to be proportional to the surface area of the membranes. This assumption implies that a lower specific flux through the membranes has a three-fold effect on the costs: on the costs for the modules, on the costs for the membranes, and on the costs for energy. This is illustrated in Table 5.1 which is based on energy requirements of 0.5 kW/m^2.

Table 5.1 Sensitivity analysis of the costs of membrane assisted sludge retention as a function of the transmembrane flux and the installed membrane area.

Flux ($m^3/m^2/h$)	1.0	0.5	0.25	0.125
Membrane area (m^2)	4000	8000	16000	32000
Energy demand (kW/m^2)	0.5	0.5	0.5	0.5
Energy costs (kWh/m^3)	0.5	1	2	4
		Costs (Dfl/p.e./year)		
Installation*	7.48	12.16	19.75	32.08
Membranes	4.80	9.60	19.20	38.40
Energy	5.50	11.00	22.00	44.00
Total costs	18	34	61	114

*: This figure includes a surcharge of 20 % for engineering plus 10 % for unforeseen.

This analysis indicates that at energy requirements of 0.5 kW/m^2 the installation, the membranes, and energy contribute about equally to the total costs.

Appendix 8 gives a sensitivity analysis of the costs of membrane assisted sludge retention as a function of the energy requirements of the system and the price of the membranes. Case A shows the effect of an energy requirement of 0.2 kW/m^2 rather than the 0.5 kW/m^2 used in table 5.1. The values currently quoted by Dutch membrane supplyers are between 0.4 and 0.6 kW/m^2 (Delgorge and Eggers 1990). The value of 0.2 kW/m^2 is taken from the work of Beaton and Steadly (1982). The extra energy needed to realize a sufficiently high cross flow velocity along the membrane is currently in the order of 3-6 kWh/m^3 (Aqua Renaissance Research Association 1989; DHV 1986).

At energy requirements of 0.2 kW/m^2 energy costs of 1 kWh/m^3 correspond to a specific flux of 200 l/m^2/h, while energy costs of 3-6 kWh/m^3 correspond to fluxes of 35-70 l/m^2/h.

In appendix 8 (case B and C) the energy costs per m^3 of effluent are kept constant at 1 kWh/m^3. This is done in order to be able to evaluate the specific effect of the price of the membrane and the surface of the membranes.

In appendix 8 (case C) a sensitivity analysis for the price of the membranes is presented. The price for the membranes used in these calculations is Dfl. $1500/m^2$, i.e. 5 times higher than the price used in the estimates presented in Table 5.1. Currently the prices for membranes vary between Dfl. $500/m^2$ and Dfl. $1500/m^2$, but it is expected that these prices will drop in the future.

Sewage treatment plants with a capacity of 100.000 p.e. are generally engineered to accomodate daily fluctuations in the waste water flux to a maximum of 4000 m^3/h, even though the average flux through such a system is only 1200 m^3/h. At fluxes well below the peak value a part of the installation can be shut down if this proves to be beneficial to membrane life. Daily fluctuations in the influent fluxes will not affect the energy consumption per m3 of waste water.

To summarize these four variants presented in appendix 8 Table 5.2 gives the high and low estimates for fluxes of 1 $m^3/m^2/h$ and 0.125 $m^3/m^2/h$ respectively.

Table 5.2 Best and worst case estimates for the costs of sludge retention by means of cross flow filtration.

Flux ($m^3/m^2/h$)	1.0		0.125	
	Costs (Dfl/p.e./year)			
	best*	worst**	best	worst
Installation	7.48	7.48	32.08	32.08
Membranes	4.80	24.00	38.40	192.00
Energy	2.20	66.00	17.60	66.00
Total costs	14.48	97.48	88.08	290.08

*: best: membrane price Dfl $300/m^2$; energy demand 0.2 kW/m^2.

** worst: membrane price Dfl. $1500/m^2$; energy consumption 6 kWh/m^3.

5.3 Potential advantages of using membrane systems to retain sludge

5.3.1 Elimination of the settling compartment

The building costs of the settlers for a treatment plant with a capacity of 100,000 p.e. are Dfl 3.5 million. This amounts to 14 % of the total investment costs of such a plant. Assuming a write off period of 30 years for the civil part and 15 years for the electro-mechanical part the annuity of the settlers (including engineering and unforeseen) equals Dfl 4.50/p.e./year. Savings on the investment for and operation of a sludge return device adds another Dfl 1.25 to this amount for a total of Dfl 5.75/p.e./year.

5.3.2 Increased volumetric activities

The building costs of an aeration tank for a treatment plant with a capacity of 100,000 p.e. are Dfl 3.5 million. Increased volumetric activities in the aeration tank will mainly influence the size of the reactor and not the investments in the electro-mechanical part of the reactor. The annuity on the building costs of the aeration tank is Dfl 2.43/p.e./year. This figure includes 20 % engineering and 10 % unforeseen. Savings of 50 %, i.e. Dfl 1.20/p.e./year seem to be the maximum that can be achieved.

5.3.3 Low surplus sludge production

The current costs of sludge disposal are 10 % of the total costs of waste water treatment, or about Dfl 4.30/p.e./year. These costs are expected to rise sharply in the next decade. Various authors give different estimates for the costs of sludge disposal in the near future. Heide and van der Graaf (1986) expect additional costs of Dfl 10/p.e./year. A report by DBW/RIZA (Anonymous 1988a) came to a similar figure, with the annotation that the authors explicitly stated that in their report costs for waste gas cleaning and value added taxes were not included.

With the current treatment technology a municipal waste water treatment plant with a capacity of 100,000 p.e. produces 4000 kg primary sludge and 2500 kg surplus sludge daily, for a total of 6500 kg/day. Complete elimination of the biological production of surplus sludge will therefor result in a reduction of the amount of sludge by at most 38 %.

5.3.4 Potential savings

Application of membrane assisted sludge retention in aerobic municipal waste water treatment systems results in the folllowing possible savings:

	Dfl/p.e./year
Elimination of the settler	5.75
Increased volumetric activities	0.00- 1.20
Lower sludge production	0.00- 8.00
Total possible savings	5.75-14.95

These estimates indicate that the actual savings will strongly depend on the savings due to lower surplus sludge production. These savings will depend both on the degree to which material savings on surplus sludge production can be realized and on the future costs of sludge disposal.

Elimination of the settler yields only Dfl 5.75/p.e./year, and savings on the reactor size would add only a fraction to that number. Savings on the costs of sludge disposal (burning) may have the largest impact on the balance sheet. Estimates vary somewhat between different authors, but it is clear that the potential savings are between Dfl 1 and Dfl 2 for every 10 % of sludge not produced. Assuming that 60 % of the sludge currently produced is primary sludge and 40 % is biologically produced surplus sludge, the potential savings on sludge disposal costs are maximally Dfl 4-8/p.e./year, if it is possible to run the system fully under no-growth conditions.

Unfortunately total oxidation in the aeration tank will result in a lower biogas yield and higher aeration costs, but these hidden costs are canceled out by elimination of the sludge digester (see appendix 9 and 10).

5.4 Summary and conclusions

Based on the currently available data it is not possible to produce a reliable estimate of the costs and benefits of the introduction of membrane assisted sludge retention in waste water treatment systems. The estimates made above nevertheless allow some important conclusions. On the level of capital costs the benefits will be between about Dfl. 5.75 and 6.95 per p.e. per year, as a result of savings on the investment costs for the settler and a smaller volume of the aeration tank. These savings are exceeded by the costs for membranes plus modules. Even if the membrane area to be installed can be limited to 4000 m^2 for a treatment plant of 100,000 p.e. the capital costs will be about two times as high.

The economic viability of membrane assisted sludge retention hinges therefor on the operating costs of the system and on the monetary benefits of a lower surplus sludge production. The estimates made above indicate that at an energy consumption of 1 kWh/m^3 the operational costs will roughly be balanced by savings in the sludge disposal costs. The current energy costs of 3-6 kWh/m^3 prohibit an immediate application of membrane assisted sludge retention in municipal waste water treatment systems, but if this energy demand can be brought down to 1 kWh/m^3 and fluxes in the order of 1 $m^3/m^2/h$ can be realized this technology will become economically viable.

6 GENERAL EVALUATION OF THE FEASIBILITY OF INTRODUCING MEMBRANE SYSTEMS FOR THE RETENTION OF SLUDGE IN WASTE WATER TREATMENT SYSTEMS

6.1 Introduction

The potential advantages of membrane assisted sludge retention for the development of high-performance bioreactors to be applied in the treatment of municipal waste waters have been discussed extensively. From this discussion it has become clear that further research is needed for a full assessment of the feasibility of such a strategy, and that the main economic advantage must be looked for in the area of reduced surplus sludge production. Complete elimination of the production of surplus sludge is not a realistic goal because a large part of the surplus sludge currently produced consists of primary sludge, i.e. sludge that is not produced as a result of the biological processes in the reactor. There are however distinct possibilities for the elimination of the secondary, or biological fraction of the surplus sludge, as shown by the promising results of Gaudy and coworkers. The other advantages, i.e. elimination of the settler and a smaller volume will grosso modo be eliminated by the capital costs of the membranes and the membrane modules. A major additional advantage is then the possibility to obtain simultaneous nitrification and denitrification in such systems.

The main points of concern with respect to the feasibility of the application of membrane assisted sludge retention in aerobic waste water treatment are the achievement of long term flux stability and the extra energy needed for cross flow filtration. Abandoning the technology of cross flow filtration and switching to solids-liquid separation via the application of membranes directly in the aeration compartment may be a viable alternative, provided that the price of membranes drops by a factor of ten, or that the flux through the membranes can be increased by a factor of ten, or by a combination of both improvements.

For an economical operation of membrane assisted sludge retention in municipal waste water treatment systems by means of cross flow technology, transmembrane fluxes of 1 $m^3/m^2/h$ have to be attained at energy costs of 1 kW/m^2, resulting in overall energy costs of 1 kWh/m^3. Cross flow filtration cell recycle systems have been applied successfully to the production of industrially important extracellular metabolites such as ethanol, lactate, butanol-acetone, and acetic acid, but the fluxes of 50 to at most 100 $l/m^2/h$ which are the limits of the current biotechnological applications are simply not good enough for aerobic waste water treatment systems. Thus current systems cannot be applied economically to aerobic waste water treatment, except under special conditions such as in large urban complexes or on ships, where space is at a premium. This does however not mean that there are no opportunities for membrane enhanced biomass retention to be developed to a viable technology for aerobic municipal waste water treatment systems.

Instead, given current fluxes of 50-100 $l/m^2/h$ under practical conditions, it is to be expected that further research on high flux microfiltration and ultrafiltration membranes may eventually result in the production of membranes with the required characteristics.

6.2 Future perspectives of membrane assisted sludge retention

In the next paragraphs the future of membrane enhanced sludge retention in waste water treatment systems will be evaluated from four different perspectives: technical, market, regulatory, and economic.

6.2.1 Technical perspectives for membrane enhanced sludge retention

Membrane separation technology has been introduced successfully in a variety of biotechnological processes in the last decennium. This technology is still evolving: new membrane materials are being developed for various specialty applications, and research projects like the japanese Aquarenaissance and Biofocus programs, and the dutch RWZI-2000 program may serve as catalysts for the successful development of membrane technology for application in waste water treatment systems. Many of the types of problems to be expected have been investigated before. As an example, one of the successful projects in the "Innovation Oriented Program on Membranes" started by the dutch government in 1983 was the development of a microporous hydrophilic capillary membrane and the design of a capillary membrane module (Roesink 1989). Research into a specialty membrane system for activated sludge systems should be based on the know-how generated by several of the projects in this program. Furthermore it is to be expected that much of the knowledge gained in this research will be applicable to other biotechnological processes.

6.2.2 Market perspectives for membrane enhanced sludge retention

The market for membrane filter equipment is currently growing at a rate of 10 to 15 % per year, and the market for cross flow filtration membranes in 1987 in Europe alone was estimated to be $ 80 million (Laidler 1988). Assuming the best case of Table 5.2, namely a life time of three years, a price of Dfl. 300/m^2, and a flux of 1 $m^3/m^2/h$, implementation of cross flow filtration for biomass retention in dutch waste water treatment systems would result in an annual market in the Netherlands alone of Dfl. 14 million or about 10 % of the total membrane market in Europe. The total investment costs for membrane equipment (modules plus other hardware) would be about Dfl. 200 mln. These estimates indicate that successful introduction of membrane assisted biomass retention in municipal waste water treatment would result in a significant market expansion for membrane technology.

The market increase for membranes might be 10 times bigger if non-fouling membranes at a price of Dfl. 300/m^2 can be developed that allow fluxes of about 100 l/m^2/h when directly immersed in the aeration tank.

The requirement for adequate and financially acceptable membrane systems should eventually result in the development of more advanced membrane systems with lower initial costs and substantially lower energy requirements per m3 of treated waste water. Research in this area may therefor ultimately lead to economically acceptable high-performance filtration and bioreactor systems which will also be useful in other fields such as in biotransformations of relatively inexpensive compounds (Witholt et al. 1990). Thus regardless of the characteristics and uses of future membrane systems, the potential market for such membrane systems is substantial, both in relative and in absolute terms.

6.2.3 Regulatory perspectives for membrane enhanced sludge retention

As stated briefly in chapter 2.4 essentially nothing is known about the possibilities to improve the degradation of recalcitrant compounds by employing membrane enhanced biomass retention. In theory it should be possible to add and retain specific organisms in membrane enhanced bioreactors, thereby improving the degradation of hitherto recalcitrant compounds. To what extent such organisms will remain active in the complex sludge environment is currently not known, but a good understanding of the ecophysiology of such organisms should make such an approach feasible. Timely research and development of systems to cope with the future tightening of effluent standards is warranted and membrane enhanced biomass retention is likely to be an important element in such systems.

Another potential point in favor of membrane enhanced bioreactors is that if they are effective in retaining specific degradative activities in the sludge biocoenosis, their presence will allow a relatively easy adjustment to new effluent standards, and avoidance of regulatory sanctions due to non-compliance with new standards. Systems that are already equipped with membrane enhanced biomass retention can be adapted to compliance with higher standards against minimal costs. Higher levies caused by such standards will also increase the cost-effectiveness of membrane assisted bioreactors. Finally membrane enhanced bioreactors may be helpfull as specialty reactors for the cultivation and preservation of biomass with special degradative capabilities. Research along this line has been started recently in Twente.

6.2.4 Economic and political perspectives for membrane enhanced sludge retention

From a purely economic point of view it is hard to predict the future of membrane enhanced sludge retention. Current fluxes and prices are close enough to the economic break even point of the envisioned new system to warrant further research, especially because the RWZI-2000 project should open up new horizons. The fact that the japanese government has a similar project in which membrane enhanced biomass retention is prominently present suggests that others have also recognized the potential of this technology. International cooperation between governments and industries in this field might be advisable. The time is ripe for a new dutch innovation in the field of waste water treatment after the development of the Pasveer ditch in the fifties and the UASB reactor in the seventies.

7 RECOMMENDATIONS FOR FURTHER RESEARCH

The coupling of modern filtration systems to bioreactors offers an opportunity for the development of high performance bioreactors for the treatment of municipal waste water. Whether this will result in practical systems must be investigated in model systems and pilot scale experiments.

The predominant reservations with respect to the viability of such systems are the sensitivity of the membranes to fouling, and the energy required for cross flow filtration.

Points for further investigation are:

- The purification characteristics of membranen assisted bioreactors: sludge concentration, sludge- and volumetric activities, and sludge production and removal efficiencies.
- Optimization of membrane filters, flux, reduction of fouling, and energy use.

Research on the improvement of waste water treatment systems should be directed along the two complementary lines described below.

7.1 Ecophysiological research

The objectives of the ecophysiological research are to establish:

1 - The feasibility of a total oxidation process with dutch municipal waste water. These experiments should be done with presettled influent, and sludge retention should be brought about by membrane filtration.

2 - The loading rates that can be applied to municipal waste water treatment systems operating under no-growth conditions.

3 - The feasibility of obtaining simultaneous nitrification denitrification in dutch municipal waste water treatment systems equipped with membrane enhanced biomass retention.

Conceptually these experiments are rather straightforward: the most logical approach is to simultaneously run a number of pilot plants with complete biomass retention at different volumetric loading rates of e.g. 0.5-1-2-4-8 kg BOD/m^3/day, i.e. at hydraulic retention times of 12-6-3-1.5-0.75 hours. These experiments will give information on what sludge concentrations and what purification efficiencies can be achieved at different loading rates and on the feasibility of total oxidation in such systems. Furthermore these experiments will give preliminary information on the degree of nitrification that can be obtained with this technology. In view of the experience of Gaudy and coworkers (1970, 1971, 1976) these experiments should run for at least a year and probably more than two years so that a proper evaluation of the results can be made. After a few months, however, the decision should be made at what hydraulic retention time a second series of reactors should be run. In this series it should be established under what conditions (oxygen concentration) nitrification-denitrification occurs optimally.

Both series of experiments should preferable be done with real waste water in order to obtain information that can be directly used for the evaluation and development of membrane assisted sludge retention strategies. The soundness of the basic concepts behind these ideas has already been proven and therefor no time should be wasted in repeating what has already been done. Furthermore this approach will give valuable information on the long term behaviour of membrane modules during the actual treatment of municipal waste water. The main objective of these experiments is to obtain information on the biological characteristics of the sludge that develops under these experimental conditions. Modular design of the membrane installation will ensure that the scheduled hydraulic retention time can be maintained independent from the specific transmembrane flux.

The size of the aeration tanks for these reactors is debatable. A volume of 100 liter per reactor seems appropriate. At a flux of about 100 liter/m^2/h a surface area of only a few square meters per reactor is required, while this reactor size will allow regular sampling from the reactor without disturbing the sludge concentration in the system.

7.2 Technological research

The objectives of the technological research are to establish:

1 - The state of the art in membrane technology with respect to the application of cross flow filtration for sludge retention in municipal waste water treatment systems.

2 - The relationships between energy consumption, cross flow velocity, biomass concentration, and transmembrane flux for various membrane filtration systems.

The recommended strategy for the technological research involves an initial screening on laboratory scale of a number of currently available membranes made of different materials and with different pore sizes in order to establish the most promising candidates for further in depth research. This first screening can be limited to short term experiments with a time scale of hours to days. This research can be done in the laboratory with small batches of activated sludge.

With the most promising candidates longer term experiments should be done to establish the behaviour of the membranes under various flow conditions, especially the degree of flux decline. It would be recommendable to have the possibility to evaluate the same membrane in different module configurations in order to be able to evaluate the effect of this variable. Other factors to be evaluated include the optimal module length, the energy use of the various modules and the possibility to reduce the energy demand by applying turbulence promotors or to use unorthodox feed flow approaches.

For this research it is recommended to approach one or more membrane manufacturers at an early stage in order to come to a vigorous research project. The advantages of industrial participation are a reduction of the costs for equipment and probably experimentation time. In order to attract industrial attention it is however advisable to first obtain some experimental data which show what the current non-optimized membrane technology is able to do for sludge retention in municipal waste water treatment systems.

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APPENDIX 1 Design characteristics of the typical dutch municipal waste water treatment plant*

Capacity	100,000 p.e.
Type	activated sludge plant
Effluent quality	drastic BOD removal nitrification partial denitrification

Design properties

Hydraulic loading rate	
daily	13,000 m^3/day
average loading rate	1200 m^3/hour
maximum capacity	4000 m^3/hour
BOD load	5400 kg BOD/day
after settling	3500 kg BOD/day
Kjeldahl-nitrogen	1000 kg Kj-N/day
after settling	800 kg Kj-N/day

Aeration tank

Biological loading rate	3500 kg BOD/day
Volume	6700 m^3
Hydraulic retention time	12 hours
Sludge concentration	3.5 kg/m^3
Sludge loading rate	0.15 kg BOD/kg sludge.day
Volumetric loading rate	0.52 kg BOD/m^3/day

Sludge production

Primary sludge	4000 kg/day
Surplus sludge	2500 kg/day
Total	6500 kg/day
After sludge digestion	4450 kg/day

*: After Heide and van der Graaf 1986.

APPENDIX 2 Estimation of the "maintenance coefficient" for dutch municipal waste water treatment systems

Table 1 **Sludge characteristics of municipal waste water treatment systems operated on pre-settled waste water at different sludge retention times (de Vries et al. 1985).**

Sludge age (days)	Loading rate (g COD/kg sludge/day)	Yield (g sludge/gCOD)
30	140	0.24
17	280	0.33
5.3	400	0.48
4.0	600	0.58

The data presented in Table 1, compiled by de Vries et al. (1985), have been used to estimate the maintenance coefficient for dutch waste water treatment systems. Two different approaches were taken.

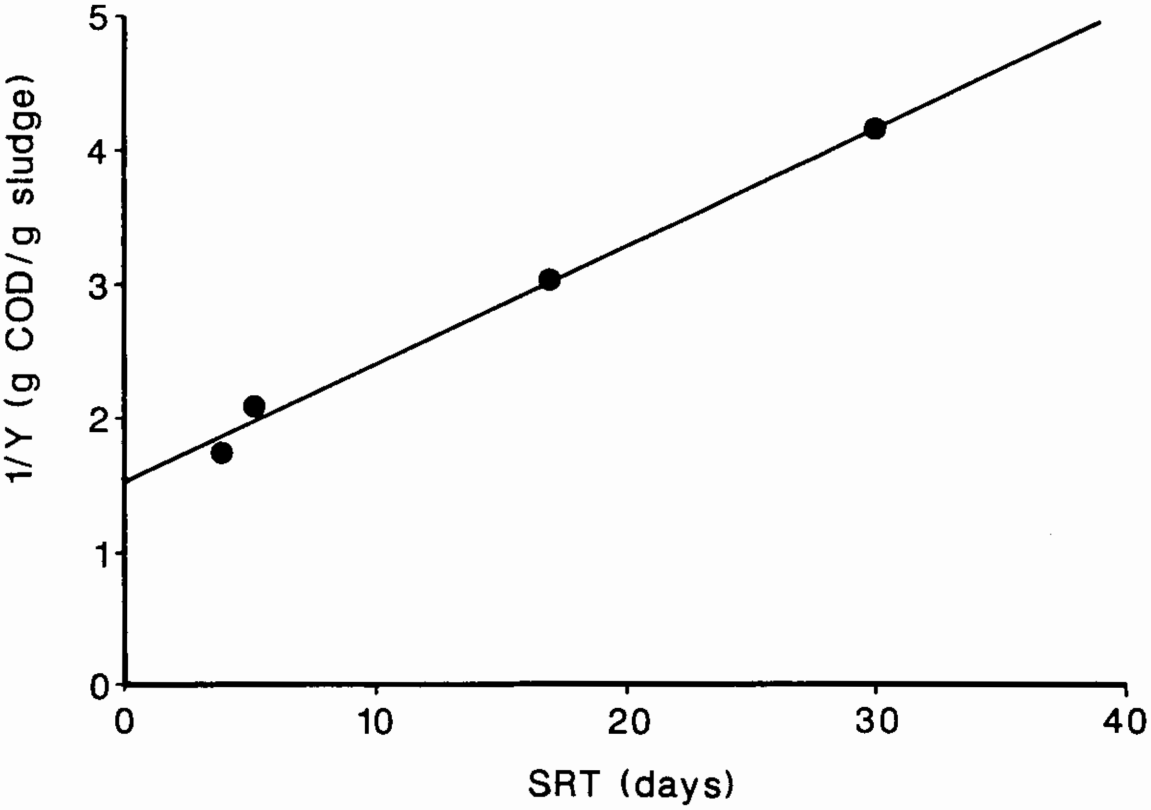

Figure 2.3 Relationship between sludge age and (specific) sludge production in dutch municipal waste water treatment systems operated on presettled municipal waste water (Dat are from de Vries et al. 1985).

The first was to plot the specific acivity of the activated sludge (actually it was the loading rate, but the COD-based efficiency of the various treatment systems does not generally differ much from 84 %) versus the inverse of the sludge age. For pure cultures a linear correlation between these two parameters would be expected. Linear regression of the data from Table 1 yields a maintenance coefficient of 60 gCOD/kg sludge/day ($r^2 = 0.978$). Fitting the data with an exponential curve yields a much better correlation ($r^2 = 0.997$) and an intercept of 117 gCOD/kg/day, but since there is no conceptual framework to support such a function this estimate may not be valid.

A second approach to estimate the maintenance coefficient is to plot the inverse of the sludge yield versus the solids retention time (Pirt 1965). The slope of this line (Figure 2.3) yields a maintenance coefficient of 90 gCOD/kg sludge/day ($r^2 = 0.996$). The second approach seems somewhat more reliable than the first one and thus the specific activity of activated sludge in a dutch municipal waste water treatment system under no-growth conditions is estimated to be about 90 gCOD/kg sludge/day. The upper limit to the volumetric loading rate in a system with complete sludge retention in which sludge densities of 100-150 kg/m^3 might be attained (Heijnen 1983, 1984), is then in the order of 9 to 14 kg COD/m^3/day.

To further illustrate the pitfalls of estimating the maintenance coefficient from published data Figure 2.1 (see chapter 2) was constructed. For this figure data tabulated by the Central Bureau of Statistics have been used. The data were collected over the period 1983-1986. It is clear that no correlation can be detected between sludge age and sludge yield (surplus sludge production). Apparently the primary sludge produced in the presettling tank masks any correlation between sludge age and sludge yield.

APPENDIX 3 Survey of the japanese research programs in the field of municipal waste water treatment

The japanese BIOFOCUS program is concerned with the aerobic treatment of municipal waste water (Kyosai and Pinnekamp 1989). It was started in 1985 and runs until 1990.

The main objectives of the program are:

-to bring down energy consumption
-to bring down operating costs
-the development of more compact systems
-to improve the effluent quality
-the recycling of reusable components.

The program is divided in 8 subdivisions:

1. Composing a database with information on microorganisms that can be used in waste water treatment
2. The applicability of genetic engineering
3. Methods to immobilize microorganisms
4. Bioreactors in the treatment of waste water
5. Bioreactors for the treatment of sludge
6. Biosensors
7. Sludge-water separation methods
8. Systematic evaluation of investigated and newly developed technologies and their integration into novel treatment systems.

The development and evaluation of novel treatment concepts occurs at a central test site. In this way all researchers work with the same waste stream and results can be easily compared.

Comparison with the dutch RWZI-2000 program shows a remarkable degree of similarity between the objectives of the dutch and the japanese program. In practice the japanese program seems to be slightly more ambitious in that it also pays attention to "high tech" approaches like genetic engineering and biosensors.

The Aqua Renaissance program is another government directed research program in the field of waste water treatment. For this program a special organization, the Aqua Renaissance Research Association was founded in 1985. It consists of 20 companies and two research organizations which are coordinated by the ministry of international trade and industry (MITI) and the new energy and industrial development organization (NEDO). The program has roughly the same goals as the Biofocus program with as the main difference that it emphasizes anaerobic treatment coupled with membrane assisted biomass retention. Techniques are being developed for the anaerobic treatment of not only high strength industrial waste streams, but also for the treatment of dilute waste streams and domestic sewage.

The objective for the membrane separation devices is to develop membrane modules with a power consumption of less than 1.5 kWh/m^3 at sludge concentrations of 10 g/l, and of less than 0.3 kWh/m^3 at biomass concentrations of 0.1 g/l.

In order to realize these targets, organic (plastic) and inorganic (ceramic) membrane modules are being developed using the 6 types of modules indicated in Table 1.

Table 1 Types of membrane modules studied in the Aqua Renaissance project.

Organic (plastic) membrane modules	Inorganic (ceramic) membrane modules
Immobilized microorganism	Tubular external pressure
Capillary	Tubular internal pressure
Hollow fiber	Flat sheet

Based on the basic research carried out on these types of modules 7 different types of field test plants are now in operation in Japan (Aqua Renaissance Research Association 1989).

APPENDIX 4 Experimental observations on the application of membrane enhanced biomass retention in anaerobic waste water treatment systems

Experiments by the group of Anderson in Manchester

Saw et al (1985) report on experiments with anaerobic sludge taken from a digestor in which high strength waste waters from a brewery were treated. The authors found that for membranes with pore sizes ranging from 0.2 to 3.0 µm, the flux increased sharply to 50-70 $l/m^2/h$ with pressures up to 120 kPa. At higher pressures the flux began to decline slowly. Ultrafiltration membranes with cut-offs between 8 kDalton and 20 kDalton behaved slightly differently in that above a pressure of 180 kPa the flux remained stable at a plateau value of 30-50 $l/m^2/h$ (concentration of suspended solids 11 g/l; cross flow velocity 3 m/s). It is apparent therefor that under identical conditions microporous membranes were more energy efficient than the ultrafiltratiom membranes.

The power indexes obtained in these experiments were close to the values predicted by the Dittus-Boelter relationship. As expected on theoretical grounds a distinct correlation between the logarithm of the biomass concentration and the flux was observed suggesting a limiting biomass concentration of approximately 100 g/l.

The optimum membrane grade for this particular sludge sample was a 0.45 µm Asypor membrane with an asymmetric structure. The membranes are bonded to replaceable parallel plates in so-called MEMSEP units. The authors conclude that both ultrafiltration and the new generation of highly asymmetric microporous membranes (in casu the MEMSEP system) can be used for biomass/effluent separation. On the average, microporous membranes yield about 40 % higher fluxes than ultrafiltration membranes, and they state that a new design of cross flow microfiltration equipment capable of high solids concentrations has been found suitable for biomass retention in anaerobic digestors. Unfortunately no information is given on the energy consumption or the economics of this technique.

Experiments by the group of Shimizu in Japan

The economics of the system are the central point in the current japanese Aqua Renaissance program. The goal is to come to systems with energy requirements of less than 1.5 kWh/m^3 at a suspended solids concentration of 10 g/l. From the reports published in the open literature it is not clear how far they have come along. In the more fundamental papers published so far by Shimizu et al. (1988, 1989 a,b,c) and Kayawake et al. (1989) the emphasis has been on ceramic membranes. A pore size of 0.1 µm was found to be optimal (Shimizu et al. 1989b). Below this value the resistance of the membranes was rate limiting and above this value the membranes were prone to plugging. It was also found that high salt concentrations, which may result when the effluent of improperly balanced acidification reactors is used as influent for methane reactors, adversely affected the membrane permeability by stimulating the formation of a gel on the membrane (Shimizu et al. 1988,1989a). The formation of a gel with the same resistance eventually occurred under both high and low salts conditions. Due to gel formation, the fluxes for high and low salt conditions which after 5 hours of operation were 0.25 and 0.55 $m^3/m^2/day$ respectively, had converged again after 10 days of operation to 0.24 $m^3/m^2/day$ (Shimizu et al. 1989a). Furthermore it was reported that high pressures result in an increase of the specific resistance of the membrane system, probably caused by deformation of particles present in the waste water as this can result in increased plugging and/or formation of a more dense gel layer on the membranes (Shimizu et al. 1988).

With respect to long term flux stability it was found that the permeation flux of an aluminum membrane with a pore size of 0.2 μm gradually decreased with time (Shimizu et al. 1989c). After 30 days at a cross flow velocity of 0.6 m/s the flux had dropped to 22 % of the value measured after 5 hours. The (methanogenic) biomass concentration in this experiment was 3 g/l. Operating the same system at a cross flow velocity of 3 m/s limited the decrease to 47 %. The decrease in the permeation flux at these two different cross flow velocities was caused by different phenomena. The low cross flow velocity of 0.6 m/s allowed the formation of a gel layer on the membrane, which caused a continuous decrease in the permeation flux. The higher cross flow velocity of 3 m/s limited the (resistance of) the gel layer to a constant value, which was reached within 5 days, but allowed for the gradual plugging of the membrane. After 30 days of continuous operation at cross flow velocities of 0.6 and 3.0 m/s the fluxes were 0.2 $m^3/m^2/day$ and 2 $m^3/m^2/day$ respectively. Washing the membrane at intervals of 24 hours with a sponge reduced the formation of the gel layer under the low cross flow velocity condition, and thereby doubled the flux that could be attained under these conditions to 0.4 $m^3/m^2/day$ (Shimizu et al. 1989c).

In a subsequent paper by the same group but with a different waste stream (cellulose rather than glucose) and a different ceramic membrane (pore size 0.1 μm) the flux could be stably maintained at 0.4 $m^3/m^2/day$ at a cross flow velocity of 1 m/s, even though during this period the biomass concentration increased from 5 to 15 g/l (Kayawake et al. 1989). The paper mentions the effect on the permeation flux of cleaning the membrane with a $NaClO_4$ solution but it is not clear whether this strategy was used in keeping the flux at this constant level. The paper does show however that, after cleaning, the membrane flux is dependent on the biomass concentration.

Other experiments within the Aqua Renaissance Research Program

A comparison by Imasaka and his collegues (1989) between a symmetric and an asymmetric ceramic membrane with a pore size of 0.2

µm showed that the equilibrium permeate resistance due to the formation of a cake layer and to plugging ($R_c + R_p$) was identical for both types of membranes. As a consequence of its thinner skin layer, the intrinsic membrane resistance of the asymmetric membrane was however lower than the resistance of its symmetric counterpart, resulting in a 30 % higher permeate flux for the asymmetric membrane. The linear increase of the permeate resistance of the membrane (R_m) with the logarithm of the pore size and the linear decrease of the permeate resistance of the cake layer and plugging ($R_c + R_p$) with the logarithm of the pore size observed by Imasaka et al. (1989) suggest that it may be possible to predict the optimum pore size and the resulting flux for a given set of experimental conditions.

Almost all japanese experiments have been done at 37 °C. The work of Matsumoto et al. (1988) has shown that at a temperature of 10 to 15 °C fluxes are a factor of two lower than at 37 °C. This result is in agreement with the rule of thumb that the fluxes increase with 2.5 % per °C (Fane et al. 1980).

The japanese data presented above are probably only the beginning of what is being learned about the application of membrane assisted biomass retention in the japanese Aqua Renaissance program. In addition to laboratory scale experiments the Aqua Renaissance program also entails the operation of a number of pilot plants. The membrane surfaces installed in these experiments are between 12 and 100 m^2 for flows of 0.5 to 20 m^3/day, and design fluxes between 0.02 and 0.5 m^3/m^2/day. No information is yet available on what the actual fluxes are in these pilot scale experiments.

APPENDIX 5 Experimental observations on the application of membrane enhanced biomass retention in aerobic waste water treatment

The Sanki Engineering Corporation is marketing the Dorr-Oliver system in Japan (Arika et al. 1977). During the test period the system, equipped with IOPOR XP-24 membranes with a cut-off of 24 kDalton and operated at a cross flow velocity of 1.8 m/s, was able to maintain stable fluxes of about 25 $l/m^2/h$ for at least 6 months, without any cleaning. In the start-up period of the pilot plant, with a capacity of 15 m^3/day and operated at a hydraulic residence time of 6 hours, the sludge concentration increased from 3 g/l to 25 g/l, but this did not affect the flux. It is interesting to note that a rotary screen (80 mesh, 110 r.p.m) was placed around the inlet to the filtration unit. No information was given about the economics or the energy consumption of the process, but the Aqua Renaissance Research Association (1989) states that this type of application has an energy demand of 4-6 kWh/m^3. The characteristics of the effluent were good at a BOD < 2 mg/l, but nitrification was incomplete (75 %) resulting in an effluent ammonium concentration of 4 mg/l. The sludge concentration achieved in this experiment was in the range of the concentrations reported by Dorr-Oliver in the beginning of the seventies, where sludge concentrations of 15 and 40 g/l were successfully applied (Stavenger 1971).

In 1980 the group of Fane also published a study on a combined ultrafiltration-activated sludge waste water treatment system in which the IOPOR XP-24 membranes from Dorr-Oliver were used. This study was performed with artificial waste water based on glucose. One goal was to determine the relative significance of the dissolved and suspended solids on the transmembrane flux. The experiments showed that for a given concentration the dissolved solids exert a greater resistance to flow than the suspended solids, but because analyses of the mixed liquor showed that the dissolved solids content is relatively constant at about 1.35 g/l, the authors were able to conclude that in practice it is reasonable to attempt to correlate flux against suspended solids rather than total solids. When doing so, the authors found a reasonably good correlation between the flux and the logarithm of the biomass concentration, which correlation further improved when they plotted both parameters on a logarithmic scale. Depending on the cross flow velocity and the biomass concentration the fluxes were between 15 and 80 $l/m^2/h$. These fluxes were however obtained after less then one hour of operation and had not yet been influenced by long-term flux decline. Long-term experiments showed that the most dramatic decrease in flux occurred during the first 24 hours and that the degree of flux decline was a function of the cross flow velocity and/or sludge concentration. In an experiment over 30 days the flux decreased by a factor of 33. This decrease was completely caused by the formation of a gel layer on top of the membrane. Plugging of the (ultraporous) membrane played no significant role in this phenomenon. Unfortunately it is not clear what percentage of the gel layer was already formed during the first 24 hours, and whether the fouling had reached a steady state, or was bound to continue after the experimental period of 30 days.

In spite of the fact that sludge-water separation is one of the key area's of the japanese Biofocus program only one publication has appeared from Japan recently that deals with membrane enhanced sludge retention for municipal waste water treatment (Suwa et al. 1989). In this paper the virtues of simultaneous organic carbon removal-nitrification are spelled out convincingly, especially because it turned out that under the right conditions more than 25 % of the nitrogen was apparently denitrified. The experiments were done with artificial waste water, and it has to be seen to what extent these features can be obtained with real municipal waste water, but the results are certainly promising. The system was operated at three different growth rates and extrapolation of the results suggests a specific activity of the sludge at zero growth of 0.11 kg BOD/kg VSS/day (VSS = Volatile Suspended Solids). Technologically the experimental set up for these experiments was surprising in that the contents of the reactor were recycled through a cross flow filtration unit at a relatively low ratio of about 50:1, while additional cross flow velocity was provided by a magnetic stirrer. The flux was about 0.2 m^3/m^2/day at a sludge concentration of 15 g/l, but it is not clear what type of filter was used in these experiments.

APPENDIX 6 Experiments on membrane-assisted sludge retention using hollow fiber membranes directly inserted in an activated sludge aeration tank

Operating conditions for experiments on membrane-assisted sludge retention using hollow fiber membranes directly inserted in an activated sludge aeration tank (Yamamoto et al. 1989)

Membrane type	Hollow fiber
Pore size	0.1 µm
Type of waste water	Artificial; based on glucose
Sludge concentration	3-15 kg/m^3
Volumetric loading rate	1.5 kg COD/m^3/day
Volumetric retention time	4 hours
COD removal	95 %
Nitrogen removal	60 % (total nitrogen!)
Nitrification	97 %
Denitrification	60 %
Aeration	Intermittent
Surplus sludge production	None
Energy consumption	0.007 kWh/m^3 (membranes only)
Suction time	1-2 minutes/10 minutes
Transmembrane flux	2 l/m^2/hour

At the current membrane prices of Dfl 150/m^2 (Delgorge and Eggers 1990) this approach is too expensive. This price results in an investment cost for membranes alone of Dfl. 300 million for a treatment plant of 100,000 p.e. (4000 m^3/h). At a write off time of 3 years (40 % annuity) this would result in costs of Dfl. 1200/p.e./year. Thus either the price of the membranes must drop considerably (by a factor of 100), or the achievable flux must be increased with a factor of 100 before this approach becomes economically feasible.

APPENDIX 7 The desirable features of membrane filtration units for biomass retention in waste water treatment plants (modified after Anderson 1986)

1. High fluxes
2. Low energy consumption-economical to operate
3. High mechanical robustness and resistance to abrasion
4. Low fouling properties-resistant to adhesion/adsorption of feed materials
5. High membrane area/volume configurations which still allow a low pressure drop while maintaining high tangential velocities
6. Continuous operation with minimum supervision
7. Easy to maintain and simple to inspect for membrane replacement
8. The unit is backflushable
9. The membranes are chemically resistant to a wide range of feed and cleaning solvents
10. Low capital costs

APPENDIX 8 Sensitivity analysis of the costs of membrane assisted sludge retention as a function of the transmembrane flux at energy costs of either 0.2 kW/m^2 or 1 kWh/m^3 and membrane prices of Dfl. 300-1500/m^2

Case A.

Installation: 4000 m^2
Membrane costs: Dfl. 300/m^2
Energy costs: 0.2 kW/m^2

Flux (m^3/m^2/h)	1.0	0.5	0.25	0.125
Membrane area (m^2)	4000	8000	16000	32000
Energy demand (kW/m^2)	0.2	0.2	0.2	0.2
Energy costs (kWh/m^3)	0.2	0.4	0.8	1.6
		Costs (Dfl/p.e./year)		
Installation	7.48	12.16	19.75	32.08
Membranes	4.80	9.60	19.20	38.40
Energy	2.20	4.40	8.80	17.60
Total costs	14.48	26.16	47.75	88.08

Case B. Same as above but at a constant energy demand of 1 kWh/m^3.

Installation: 4000 m^2
Membrane costs: Dfl. 300/m^2
Energy costs: 1 kWh/m^3

Flux (m^3/m^2/h)	1.0	0.5	0.25	0.125
Membrane area (m^2)	4000	8000	16000	32000
Energy demand (kW/m^2)	1	0.5	0.25	0.125
Energy costs (kWh/m^3)	1	1	1	1
		Costs (Dfl/p.e./year)		
Installation	7.48	12.16	19.75	32.08
Membranes	4.80	9.60	19.20	38.40
Energy	11.00	11.00	11.00	11.00
Total costs	23.28	32.76	50.05	81.48

Case C. Same as case B but at a membrane price of Dfl. 1500/m^2.

Installation: 4000 m^2
Membranes: Dfl. 1500/m^2
Energy costs: 1 kWh/m^3

Flux (m^3/m^2/h)	1.0	0.5	0.25	0.125
Membrane area (m^2)	4000	8000	16000	32000
		Costs (Dfl/p.e./year)		
Installation	7.48	12.16	19.75	32.08
Membranes	24.00	48.00	96.00	192.00
Energy	11.00	11.00	11.00	11.00
Total costs	42.48	71.16	126.75	235.08

APPENDIX 9 Energy costs of cross flow filtration processes

The energy needed to obtain sufficiently high cross flow velocities is difficult to predict. This parameter will depend on a variety of factors including the module configuration (Cheryan and Kuo 1984) and the recycle ratio.

Handbooks on membrane technology are pretty vague about how to predict power costs. Rogers (1984) assumes a linear relationship between recycle ratio and energy consumption, but nevertheless gives a value of 2.6 kWh/m^3, i.e. a value with no dependency on the recycle ratio.

Cheryan (1986) states that the energy consumption is linearly correlated to the recycle ratio and the pressure difference along the membrane. (Note: not over the membrane!). The numerical values that can be calculated from Cheryans data are very interesting. He gives an example of an energy consumption of 11.500 kJ/m^3 (3.5 kWh/m^3) obtained for a recycle value of 120:1 at a pressure difference of 1 atm. An energy consumption of less than 1 kWh/m^3 therefor implies that at a pressure drop of 0.2-0.5 atm recycle ratios of 70-170 are the maxima that are permitted. If the pump efficiency is 80 % these recycle ratios drop to 55-135. Thus the challenge is to develop a system that does not foul too much and has a reasonable flux at a recycle ratio of 135 with a pressure drop of 0.2 atm.

Beaton and Steadly (1982) claim that they are able to estimate operational costs as a function of the membrane surface area. They use a power consumption value of 0.2 kW/m^2. At an energy price of Dfl. 0.20/kWh this would, at an installed membrane area of 600 m^2 amount to energy costs of Dfl 2.15/p.e./year. According to these estimates the annual costs for operating ultrafiltration systems amount to $ 400/m^2/year, including costs for write off, personnel, and cleaning. For a plant of 1200 m^2 this would imply annual operating costs of $ 10/p.e. Although care should be taken in translating this figure directly to the dutch situation this figure is still useful in outlining in what order of magnitude the operational costs for membrane assisted sludge retention are expected to be, and this order of magnitude is certainly promising.

The extra energy needed to realize a sufficiently high cross flow velocity along the membrane is currently in the order of 3-6 kWh/m^3 (Aqua Renaissance Research Association 1989; DHV 1986).

APPENDIX 10 Hidden costs of lower secondary sludge production

Anaerobic digestion of the 6500 kg surplus sludge (4000 kg primary and 2500 kg secondary sludge) produced daily in a treatment plant with a capacity of 100,000 p.e. reduces the final amount of sludge to 4450 kg/day. Sludge digestion results in the formation of biogas which is subsequently converted into electricity, in casu 14 kWh/p.e./year. It is not known what the contribution of either sludge fraction is to this production of energy. The extreme cases are that both fractions contribute equally to the production of biogas, or that the biogas originates only from the digestion of the biologically produced surplus sludge. Thus the loss in energy obtained via the formation of surplus sludge is estimated to be between 6 and 14 kWh/p.e./year.

Another effect of the complete elimination of surplus sludge production in a total oxidation process is that the amount of energy needed for aeration will roughly double. This estimate is based on the assumption that currently 50 % of the COD removed results in oxygen consumption, while the other 50 % is converted into biomass. The amount of energy needed for aeration is currently 10 kWh/p.e./year.

Thus total oxidation will result in an additional power consumption of 16-24 kWh/p.e./year, which at an electricity price of Dfl. 0.20/kWh, represents a monetary value of Dfl. 3.20-4.80/p.e./year. These costs would however be balanced by elimination of the sludge digestor, since this would save Dfl. 6.50/p.e./year.

Below an estimation is made of the possible savings of a complete elimination of secondary sludge production (40 % less total sludge production) at three price levels for the cost of sludge disposal: Dfl. 3 (the present cost), 10 and 20/p.e./year respectively.

Table 5.3 Effect of the costs of sludge diposal on the cost-benefit analysis of the elimination of surplus sludge production in membrane assisted sewage treatment plants.

	Dfl/p.e./year Costs of sludge disposal		
	present	10.00	20.00
Cost reduction			
Total cost reduction	**14.65**	**17.45**	**21.45**
Elimination of the settler	5.75	5.75	5.75
Increased volumetric activity	1.20	1.20	1.20
Less surplus sludge	1.20	4.00	8.00
Elimination sludge digestor	6.50	6.50	6.50
Cost increase/lost income			
Total cost increase/lost income	**4.80**	**4.80**	**4.80**
No production of electricity	2.80	2.80	2.80
Higher aeration costs	2.00	2.00	2.00
Total savings	**9.85**	**12.65**	**16.65**

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