MEMBRANE BIOREACTORS FOR WATER REPURIFICATION - PHASE I

FINAL TECHNICAL REPORT

City of San Diego, CA
Metropolitan Wastewater - Public Works

by
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Paul Gagliardo, P.E. (City of San Diego)

Assistance Agreement No. 1425-97-FC-81-30006J

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13. ABSTRACT *(Maximum 200 words)*

This report evaluates the feasibility of Membrane Bioreactors (MBRs) for water repurification projects. The MBR process uses membrane filters to substitute for the sedimentation and filtration processes in conventional suspended growth biological treatment. Thus, the MBR effluent can be adequate for the subsequent reverse osmosis membranes typically employed in water repurification projects.

The study has shown that the MBR process is cost competitive with other conventional wastewater treatment processes and offers several advantages. It was also concluded that a parallel comparison of several commercially available MBR systems needs to be performed at pilot-scale in order to adequately demonstrate the effectiveness of the MBR technology for water repurification.

A preliminary plan for the pilot-scale evaluation study has been developed. This plan identifies the MBR manufacturers to be evaluated, which are Mitsubishi Rayon Corporation, Zenon Municipal Systems, and Suez-Lyonnaise-des-Eaux. The plan also includes a description of the pilot test site located at the Aqua 2000 Research Center in Escondido, California. It is projected that 24 months will be required to conduct Phase II of the project, with 12 months allocated for the operation of the pilot units.

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- Mitsubishi Rayon Corporation
- Zenon Municipal Systems
- Suez-Lyonnaise-des-Eaux/IDI
- Kubota Corporation.

Finally, the authors would like to extend their appreciation to the Bureau of Reclamation for their support in the implementation of this study.

Bureau of Reclamation
Mission Statement

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

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Mission Statement

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ACRONYMS AND ABBREVIATIONS

AWT	Advanced water treatment
BOD(5)	biochemical oxygen demand
°C	degrees Celsius
cfu	colony forming unit(s)
C.G.E.	Compagnie Générale des Eaux
COD	chemical oxygen demand
CSTR	continuous stirred tank reactor
d	day(s)
DO	dissolved oxygen
F/M	food-to- microrganisms ratio
GAC	granular activated carbon
gfd	gallons per square feet per day
gpd	gallons per day
gpm	gallons per minute
HF	hollow fiber
HFF	hollow fiber filter
HRT	hydraulic retention time
IAWPRC	International Association on Water Pollution Research Center
IDI	Infilco Degremont Inc
$Kg/m^3 \bullet day$	kilogram per cubic meter-day
KPa	kiloPascal
KWh/m^3	kilowatt-hour per cubic meter
L	liter(s)
LDE	Lyonnaise-des-Eaux
MBR	membrane bioreactor
MF	microfiltration
µm	micron(s)
MGD	million gallons per day
m/day	meter(s) per day
m/s	meter(s) per second
mg/L	milligrams per liter
mL	milliliter(s)
mm	millimeter
m^3	cubic meter(s)
m^2	square meter(s)
m^3/kg	cubic meter per kilogram
m^3/min	cubic meter per minute
MLSS	mixed liquor suspended solids
MLVSS	mixed liquor volatile suspended solids
NH,-N	ammonia nitrogen
NTU	nephelometric turbidity unit
NWRI	National Water Research Institute
O&M	operation & maintenance
PVC	polyvinylchloride
PAN	polyacrylonitrile
Q	flowrate
Q_e	effluent flowrate
Q	flowrate in recirculation line
Q_w	flowrate to waste
RAS	return activated sludge
RO	reverse osmosis
S	effluent substrate
S_o	influent substrate
SRT	solid retention time
SS	suspended solids
q_c	mean cell residence time
TAC	technical advisory committee
T-N	total nitrogen
Total-P	total phosphorus
TOC	total organic carbon
TKN	total Kjeldahl nitrogen
TDS	total dissolved solids
TSS	total suspended solids
U	substrate utilization rate
UF	ultrafiltration
V	volume
WAS	waste activated sludge
X	biomass in reactor
X_e	effluent biomass
X_r	biomass in recirculation line
yr	year
ZMS	Zenon Municipal Systems

EXECUTIVE SUMMARY

The City of San Diego is in the process of conducting a major pilot testing program at Aqua 2000 Research Center for the evaluation of water repurification to augment a local water supply, in order to reduce their reliance on limited imported water supplies. Desalting membranes play an important role in nearly every water repurification project since these membranes are the best available technology for removal of inorganic salts, trace metals and organic compounds. In addition, they have the potential for removal of all classes of microorganisms.

As part of the Aqua 2000 Research Center program, the City of San Diego is also interested in evaluating the new and emerging technologies currently on the market for municipal wastewater treatment which might provide a cost advantage for future water repurification projects, particularly those that employ desalting membranes. Prominent among these technologies are the Membrane Bioreactors (MBRs), in which membrane filters are substituted for the sedimentation process in conventional suspended growth biological treatment.

Hence, the City of San Diego was awarded a cooperative agreement by the Bureau of Reclamation, as part of their Desalination Research and Development Program, to conduct a preliminary study to evaluate the feasibility of the MBR process for water repurification projects. One year was allocated for the completion of the feasibility study, which included the following tasks: literature review of MBRs, worldwide survey of MBRs, preliminary costs estimates, and preparation for a pilot scale investigation.

The literature review and the survey have shown that the MBR process offers several benefits over the conventional activated sludge process, including: smaller space and reactor requirements, better solids removal, disinfection, increased volumetric loading, andlesssludge production. The preliminary cost evaluation has also shown that the MBR process is cost competitive with otherconventional wastewater treatmentprocesses. Considering the above, it is the overall conclusion of the project team that a parallel comparison of several commercially available MBR systems needs to be performed at pilot-scale in order to adequately demonstrate the effectiveness of the MBR technology for water repurification. The principal focus will be to assess the MBR performance for producing water suitable as feedwater to RO membranes in an adequate, reliable and cost effective manner.

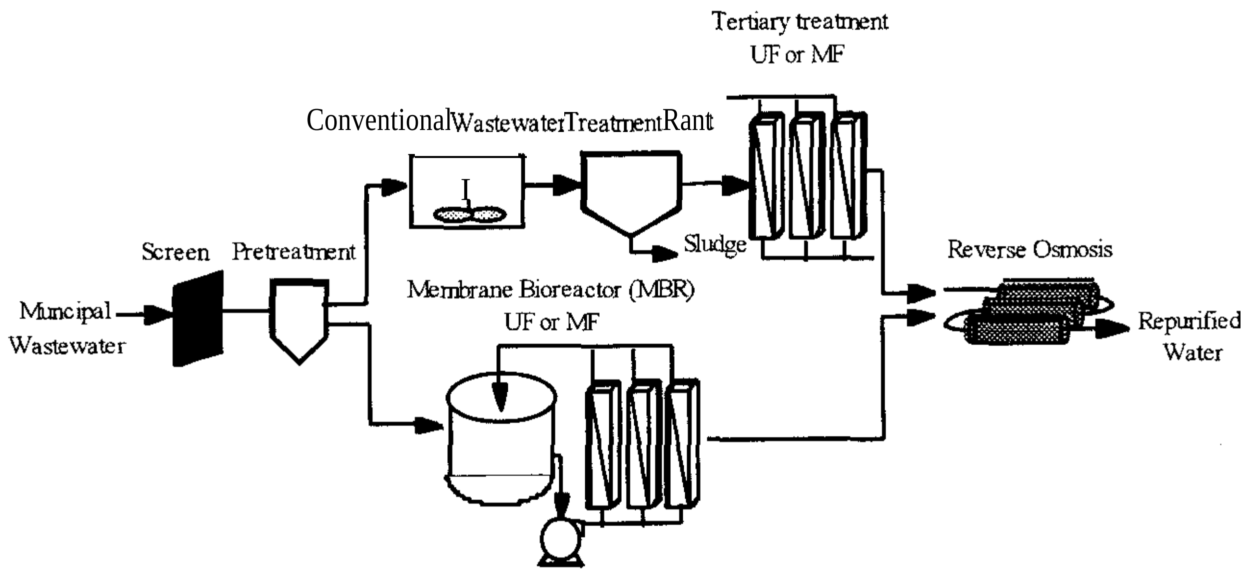
A preliminary plan for the pilot-scale evaluation study was developed. The plan identifies MBR manufacturers to be evaluated which are Mitsubishi Rayon Corporation, Zenon Municipal Systems, and Suez-Lyonnaise-des-Eaux. The plan also includes information about pilot capacity, schematic diagrams, and a description of the pilot testing site at the Aqua 2000 Research Center in Escondido, California. Finally, aproposed approach for implementing the pilot study is discussed. It is projected that 24 months will be required to conduct Phase II of the project, with 12 month allocated for the operation of the pilot units.

1. BACKGROUND AND INTRODUCTION

In an effort to reduce San Diego County's reliance on limited imported water supplies, the City of San Diego has been promoting the development of alternative water sources. Water repurification, a process in which reclaimed water receives additional advanced level treatment prior to its discharge to a potable water supply: is one of the alternatives being implemented. Desalting membranes play an important role in nearly every water repurification project since these membranes are the best available technology forremoval of inorganic salts, tracemetals and organic compounds. In addition, they have the potential for removal of all classes of microorganisms. Hence, the City of San Diego has been conducting a major pilot testing program since 1995 at their Aqua 2000 Research Center in Escondido, California to demonstrate the feasibility and reliability of water repurification via double membrane treatment [microfiltration (MF) or ultrafiltration (UF) followed by reverse osmosis (RO)]. From this study, design parameters for a full-scale [23 MGD (1 m^3/s)] advanced water treatment (AWT) system will be projected.

As part of the Aqua 2000 Research Center program, the City of San Diego is also interested in evaluating the new and emerging technologies currently on the market for municipal wastewater treatment which might provide a cost advantage for future water repurification projects. Prominent among these technologies is the Membrane Bioreactor (MBR) process, in which membrane filters (such as MF or UF membranes) are substituted for the sedimentation and filtration in conventional suspended growth biological treatment.

Membrane filters typically cost more than secondary clarifiers of comparable hydraulic capacity. As a result, up until the present time, MBRs have been most successful in the treatment of concentrated wastes where the biological reactor is large but the hydraulic capacity (i.e., the size of the membrane system) is small. Repurification changes the rules of this game since RO membranes are typically required for the AWT. Studies at both Aqua 2000 Research Center and the Water Factory 21 in California have confirmed that membrane filtration is the most cost-effective and reliable treatment process for preparing treated wastewater for the RO process. With membrane filtration already required, the economics shift to make the MBR process attractive for treatment of domestic sewage. That is because the MBR technology can replace multiple processes with a single membrane process as presented in Figure 1-1.



MBR Versus Conventional Treatment Process
Figure I-I

The Bureau of Reclamation awarded the City of San Diego a cooperative agreement to conduct a feasibility study on the application of the MBR process for water repurification projects. The project duration was one year (October 1997 - October 1998) and includes several tasks: literature review of MBRs, worldwide survey of MBRs, preliminary costs estimates, and preparation for a pilot scale investigation. This report provides the findings of these tasks.

2. CONCLUSIONS AND RECOMMENDATIONS

2.1 Conclusions

The following are the main conclusions formulated from the Phase I feasibility study:

- Recent interest in the MBR technology for domestic wastewater treatment has occurred due to an increasing number of water repurification projects and continuing advancement in membrane technology.
- The MBR process offers several benefits over the conventional activated sludge process, including: smaller space and reactor requirements, better solids removal, disinfection, increased volumetric loading, and less sludge production.
- The MBR process can exist in two different configurations, one with the low-pressure membrane modules replacing the clarifier downstream of the bioreactor (in-series), and the second with the membranes submerged within the bioreactor. No direct comparison between the two configurations was found in the literature.
- Only four companies are currently active in marketing the MBR system. The active companies that are marketing the submerged MBRs are: ZENON Municipal Systems (Canada), Mitsubishi Rayon Corporation (Japan), and Kubota Corporation (Japan). The active company that is marketing the in-series MBRs is: Suez-Lyonnaise des Eaux/Degremont (France/USA).
- Each manufacturer utilizes a unique combination of membrane materials and membrane configurations. For the submerged systems, there are also differences in the aeration systems and the cycling frequency of the suction pump, which are critical to flux maintenance through the membranes.
- Currently, the majority of the installed MBR systems are being used for the treatment of wastewater from the automotive, cosmetic, metal fabrication, food and beverage processing, landfill leachate, and other industries.
- While many installations can be found for small capacity industrial waste plants, there are only a few operating municipal installations. Municipal installations in the 1.0 to 2.0 MGD (0.0435 to 0.087 m^3/s) ranges are currently under construction in Canada, Egypt and the United States.
- The MBR process operates in a considerably different range of parameters than the conventional activated sludge process. Comparable chemical oxygen demand (COD) removals were observed for the two processes.
- The median value for membrane flux was observed at 15 gfd (25.46 $L/h/m^2$). This value is less than the nominal flux for drinking and reclaimed waters microfiltration (MF) applications (60 gfd and 40 gfd, respectively).
- A preliminary cost analysis was conducted for the MBR process as compared to oxidation ditch and conventional activated sludge processes on the bases of equivalent effluent water quality. The MBR process was shown to be very competitive with these processes, Hence, there appears to be a serious market potential for such technology in the United States (US).
- The effluent water quality from the MBR exceeds the quality of a conventional activated sludge system. The MBR effluent appears to be adequate as a feedwater to the RO process.

- The application of the MBR process for water repurification has, however, some unique challenges. One potential problem of this application would be the loss of membrane integrity during operation, which may release relatively high concentrations of biomass to the subsequent RO system resulting in membrane fouling.

2.2 Recommendations

Considering the above, it is the overall conclusion of the project team that in order to adequately demonstrate the effectiveness of the MBR technology for water repurification, a parallel comparison of several commercially available MBR systems needs to be performed at pilot-scale. This will allow evaluating their performance for producing water suitable as feedwater to RO membranes in an adequate, reliable and cost effective manner. In addition, evaluation of methods for continuous monitoring of the membrane integrity will be necessary.

2.3 Commercial Viability

There is a definite need to demonstrate the viability of MBRs for water repurification in the US, via pilot and/or demonstration-scale projects, especially for the municipal services industry. Initially, residents of the greater San Diego area would be the end users of water, which could be treated using MBRs. However ultimately, the entire wastewater and desalting industries are a potential marketplace for this technology and MBRs should be included as an alternative in the planning stages of facility expansions and for meeting site specific treatment goals. If MBRs were shown to be feasible for water repurification, their application would include more conventional water reclamation processes as the cost competitiveness of this technology continues to improve. Validation of the technology from a project such as the San Diego Repurification Project is a necessary first step, however, towards demonstrating that the MBR technology is an economically viable treatment process.

3. PROJECT FINDINGS

The following section describes the findings of each task implemented in this feasibility study. These tasks include: literature review of MBRs, worldwide survey of MBRs, preliminary costs estimates, and preparation of a plan for the pilot-scale evaluation study.

3.1 Task 1. Conduct a Literature Search on the Performance of MBRs for Wastewater Treatment

A literature search was conducted to evaluate the performance of MBRs for municipal wastewater treatment. The literature review document is included as Appendix A of this report. Below are selected main points from the review:

- Recent interest in the MBR technology for domestic wastewater treatment has occurred due to an increasing number of water repurification projects and continuing advancement in membrane technology.
- The MBR process can exist in two different configurations, one with the low-pressure membrane modules replacing the clarifier downstream of the bioreactor (in-series), and the second with the membranes submerged within the bioreactor. No direct comparison between the two configurations was found in the literature.
- In membrane processes, eventual accumulation of a cake layer on the membrane surface will increase the pressure requirements to maintain the flux at acceptable levels. The important parameters to maintain adequate flux for MBR processes with in-series membrane configurations are the cross-flow velocity and the operating pressure generated by the recirculation pump. For submerged membranes, the uplifting air in the bioreactor provides shear forces at the membrane surface. The airflow value and the aeration time appear to be critical operational criteria. Aeration without suction may also be useful as an on-site membrane washing procedure.
- The MBR process operates in a considerably different range of parameters than the conventional activated sludge process. While solid retention time (SRT) falls in the range of 5-30 days for a conventional system, SRT values frequently exceed 30 days for the MBR. The loading rate or Food/Microorganisms (F/M) ratio falls in the range of 0.05 - 1.5 d^{-1} for a conventional system, but is usually < 0.1 d^{-1} for an MBR. The low F/M ratio occurs due to the high mixed liquor suspended solids (MLSS) in the bioreactor, which typically range from 5,000 to 20,000 mg/L for MBRs as compared to 2000 mg/L in conventional processes.
- Low temperatures (below 13°C) adversely impact the overall removal of contaminants by the MBR process.
- A summary of key operational parameters and the performance characteristics of some bench- and pilot-scale case studies are provided in Table 3-1.

Table 3-1
Summary of Experimental Conditions and Process Performance for Bench-Scale and Pilot-Scale MBR Studies

Study Author	Country	Water Type	MBR Type	Bioreactor Size	Air Flow Rate (m^3/min)	Membrane Type	Pore Size (microns)	Flux (m/day)	Pressure (kPa)	Suction (minutes)	Velocity (m/s)
Ueda	Japan	Domestic	Submerged	21400 L	0.7	HF polyethylene	0.1	0.29	20	8 on / 2 off	
Bodzek	Poland	Domestic	In Series	25 L	0.007	Tubular PVC,PAN,WINICET	<0.05	0.6 to 1.0	200	No	2
Kishino	Japan	Domestic	Submerged	80 L		Chlorinated polyethylene cartridge	0.4	0.5		8 on/ 2 off	0.2 to 0.5
Chiemchaisri	Thailand	Domestic	Submerged	1000 L	0.0075	HF STN0314	0.03	0.1	13 to 40	10 on/10 off	
Ishiguro	Japan	Glucose	In Series	350 L		Spiral wound polysulfone	0.004	0.7	100	No	0.5
Shimzu	Japan	Domestic	Submerged		0.07	HF polyethylene, Tubular alumina	0.1, 0.5	0.4 to 0.6	4 to 50	0.14 m3/h	
Chaize	France	Domestic	In Series	4.5 L	0.001	Plate & frame polysulfone/cellulose	50,000 d*		0.01	No	1.5
Fan	France	Municipal	In Series	1500 L		Ceramic UF module	0.02			No	3 to 4
Urbain	France	Groundwater	In Series	1000 L		HF cellulosic derivate	0.01	1.4-1.7	120	No	0.9
Cote	USA	Municipal	Submerged	Single Tank	12 Nm^3/h/2 mods**	HF (Zeeweed ZW-150)	200,000 d*	0.84	20		
Cote	France	Municipal	Submerged	Two Tanks	5 Nm^3/h/1 mod**	HF (Zeeweed ZW-150)	200,000 d*	0.6	20		
Cicek	USA	Casein/starch	In Series	40 L		Tubular ceramic	300,000 d*			No	
Vera	Spain	Municipal	In Series	25 L		Tubular Carbosep composite	0.14	0.1	1	No	3
Urbain	France	Municipal	In Series	1000 L		Ceramic MF module	0.1		<2	No	1.5 to 3.5
Roncken	Rotterdam	Leachate	Submerged					2.4	3		

* d= dalton units

** Nm^3/h stands for Normalized m^3/h

Study Author	MLSS (mg/L)	HRT (hours)	SRT (days)	TSS percent removal	BOD percent removal	T-N percent removal
Ueda	8,000-12,000	13 to 16	125	100%	99%	83%
Bodzek	5,300	12 to 16		100%	99% (COD)	85%
Kishino	20,000	8	60 to 70	100%	98%	95% for NH3
Chiemchaisri		24		<1 NTU***	80 - 98% (COD)	>80%
Ishiguro	4,000-12,000		2 to 35		99% removal	
Shimzu	1,000 - 20,000	12				
Chaize	8,000-10,000	2 to 8	50 to 100	100%	>95% (COD)	>99% for ammonia
Fan		7.5 to 15	5 to 20	100%	>94% (COD)	>99% for ammonia
Urbain	NA	2.5	5	NA	NA	NA
Cote	5,000-15,000	2	5 to 10	>99%	>97% ; 96% (COD)	36%
Cote	15,000	9	50	>99%	>98%; 98% (COD)	80%
Cicek		6	30	>99%	99% (COD)	99.2 for ammonia
Vera				>99%	60%(COD)	
Urbain		24	25	>99.9%	>99.9%	97% for ammonia
Roncken					99.70%	99.8 for ammonia

**** TSS concentration expressed as turbidity units*

- The MBR process offers several benefits over the conventional activated sludge process, including: smaller space and reactor requirements, better solids removal, disinfection, increased volumetric loading, reduced sludge production, system reliability throughout hydraulic and solids load variations, a higher and more consistent quality effluent, potential reduction in capital expenditures, and potential reduction in energy requirements.

3 The MBR has been shown to produce less sludge with poorer settling characteristics, which might increase the difficulty of sludge disposal.

- The activated sludge formed in the MBR is characteristically different from the sludge formed in the conventional suspended growth reactor. The MBR contains a higher viable fraction resulting in faster decomposition of organic substances than the conventional suspended growth reactor.
- With submerged MBRs, optimization of the packing density of the hollow fiber membrane elements, the type of aerators used, and the specific placement of the aerators over the floor area of the bioreactor may be critical design elements.
- Research is ongoing to elucidate the relationship between permeate flux and sludge concentration at different biochemical oxygen demand (BOD) loading rates and to develop specific yields for these processes. None of this work is sufficiently developed to allow its use in full-scale applications.
- To adequately demonstrate the effectiveness of this technology, a parallel comparison of a conventional suspended growth reactor, a MBR with in-series configuration, and a MBR with submerged configuration needs to be performed at pilot-scale.

3.1.1 *Active Manufacturers of Membrane Bioreactors, Their Applications and Their Installations*

More than ten manufacturers of MBR processes were identified in 1992. Only four companies are currently active in marketing the MBR system, as shown in Table 3-2. The active companies are: Zenon Municipal Systems (Canada), Mitsubishi Rayon Corporation (Japan), Suez-Lyonnaise-des-Eaux/Infilco-Degremont (USA), and Kubota Corporation (Japan). While many installations can be found for small capacity industrial waste plants, there are only a few operating municipal installations. Municipal installations in the 1.0 to 2.0 MGD (0.0435 to 0.087 m^3/s) ranges are currently under construction in Canada, Egypt and the United States. A selected list of some of these worldwide MBR installations having capacities of 50,000 gpd (7885.42 L/h) and greater can be found in Appendix A.

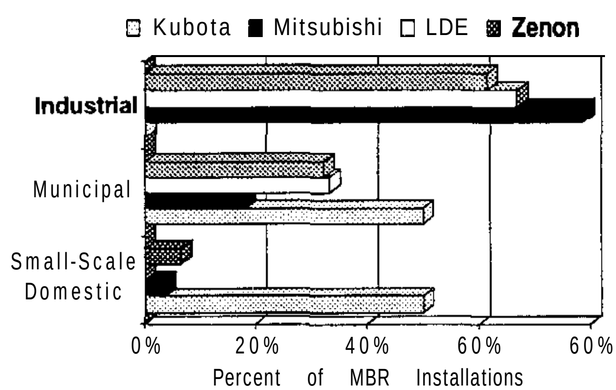
Zenon Municipal Systems (ZMS), Mitsubishi Rayon and Kubota Corporation market submerged MBRs with polymeric hollow fiber membranes while Suez-Lyonnaise-des-Eaux/Infilco-Degremont (Suez-LDE/IDI) market in-series MBRs with tubular ceramic membranes. Detailed information relating to the four active manufacturers is included in Appendix A.

Currently, the majority of the installed MBR systems are being used for the treatment of wastewater from the automotive, cosmetic, metal fabrication, food and beverage processing, landfill leachate, and other industries. Figure 3-l illustrates the distribution of MBR installations by treatment category.

Table 3-2
MBR Vendors

Trade Name	Company	Country	Wastewater	Current Status
MSTS	Dorr Oliver	USA	Domestic	No longer active
UBIS	Rhône Poulenc	France	Domestic	No longer active
ASMEX	Mitsui Petroc	Japan	Domestic, Industrial	No longer active
CYCLE-LET	Thetford Syst.	USA	Domestic	Acquired by Zenon
MEMBIO	Memtec	Australia	Domestic	Developing new product
BIOREM	Kubota	Japan	Domestic	Still active
STERAPORE.	Mitsubishi Rayon	Japan	Domestic, Industrial	Still active
MARS	Dorr Oliver	USA	Industrial	No longer active
ADUF	Ross/Membratek	S. Africa	Maize factory	No longer active
BIOMEMBRAT	Wehrle Werk AG	Germany	Lixiviat	No longer active
ZENOGEM	Zenon Env. Inc.	Canada	Oil	Still active
BIOSEP	C.G.E.*	France	Domestic	Employs Zenon technology
BRM	Suez-LDE/IDI**	France	Domestic, Industrial	Still active

*C.G.E: Compagnie G&&ale des Eaux
**Suez-LDE/IDI: Group Suez-Lyonnaise des Eaux/Infilco Degremont Inc.



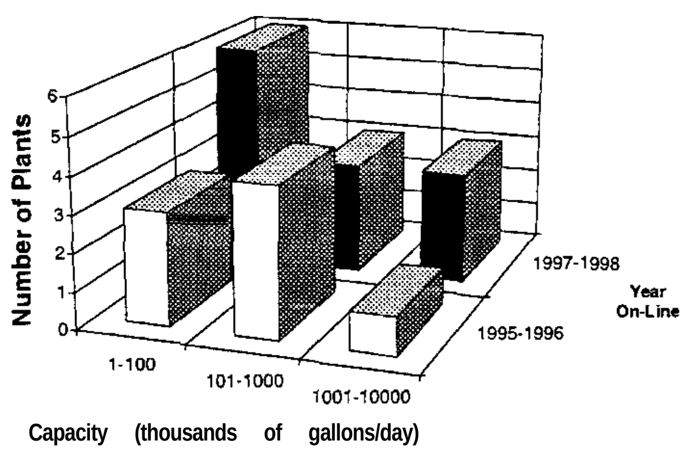
Distribution of MBR Installations by Wastewater Type
Figure 3-l

3.2 Task 2. Conduct a Worldwide Full-scale Survey of Existing MBRs

A Membrane Bioreactor plant survey questionnaire was developed to collect global full-scale design, operational and cost data. A copy of the survey questionnaire is included in Appendix B of this report. The survey questionnaire covers several issues, including: (i) MBR general information such as location, capacities, wastewater type, configuration (submerged or in-series), and startup date; (ii) membrane characteristics and operational data, including pore size, surface area, flux rate, backwash and chemical cleaning parameters; (iii) bioreactor configuration, hydraulic and operational parameters, sludge production, and aeration rate; (iv) MBR performance for the removal of organic contaminants, ammonia-nitrogen, phosphorus, and microbiological contaminants (coliform bacteria); and (v) cost performance, including capital costs of membranes and the plant, O&M costs of labor, energy, sludge disposal and other.

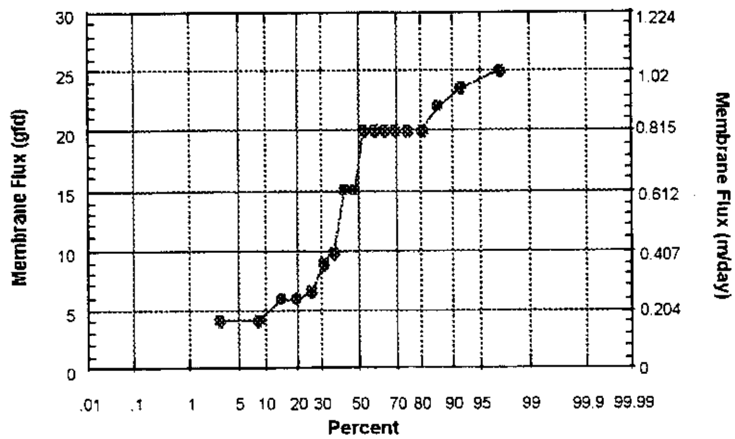
Forty-five questionnaires were distributed among the four major manufacturers, and twenty completed survey forms were received. Eleven completed survey forms were received from ZMS, seven from Mitsubishi Rayon, one from Suez-LDE/IDI, and one from Kubota Corporation. The following is a summary of the main conclusions drawn from the analysis of the survey data received from twenty full-scale operating MBR plants:

- Figure 3-2 illustrates the number of MBR plants versus capacity and year on-line. While the data is limited, it shows increasing implementation of the MBR process and expansion into higher capacity applications. Presently, the majority of the MBR plants are in the capacity range of less than or equal to 100,000 gpd (15,770.84 L/h), but the number of plants ranging between 1 and 5 MGD (0.0435 to 0.22 m^3/s) are increasing.



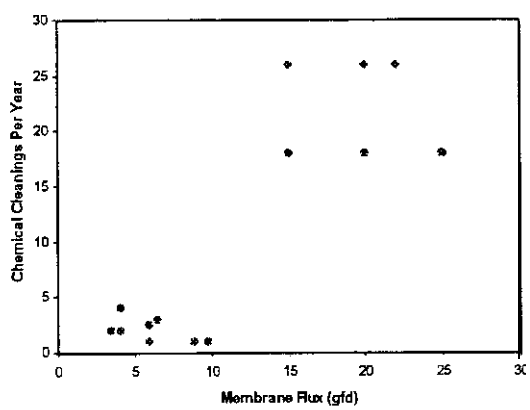
Number of MBR Plants Versus Capacity and Year On-line
Figure 3-2

9 Figure 3-3 provides the probability plot for membrane operational flux for the MBR systems. The 50th percentile of the membrane flux values is 15 gfd (25.46 $L/h/m^2$ or 0.61 m/d). As expected, this values is lower than the nominal membrane flux in drinking water and reclaimed water applications which are 60 gfd and 40 gfd, respectively. The reported flux range of 4 to 25 gfd (0.16 to 1 m/d) is very similar to the range of values reported in Table 3-1.



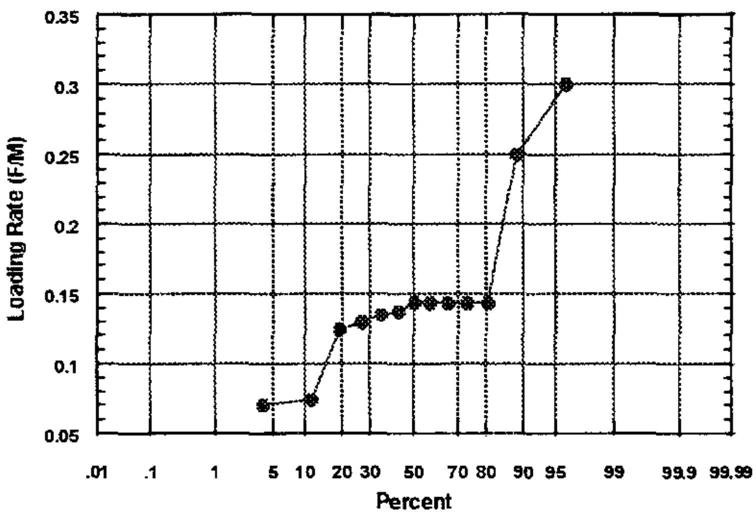
Membrane Flux Probability Plot
Figure 3-3

9 The variation of membrane flux versus chemical cleaning has been plotted in Figure 3-4. The lower chemical cleaning frequency was found to be accompanied by a lower membrane flux, which is expected. Cleaning frequencies for drinking water microfiltration plants are less than 12 times per year for most facilities with an average plant. performing **4** cleanings per year.



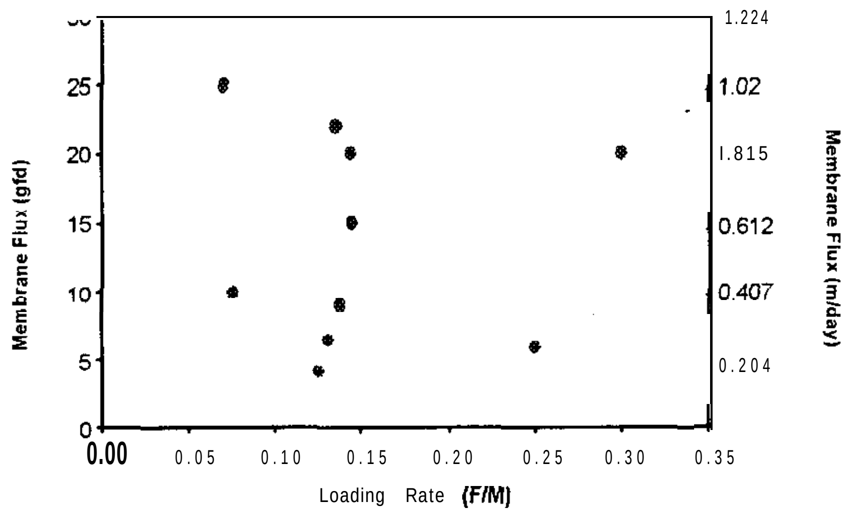
Variation of Membrane Flux With Chemical Cleaning Frequency
Figure 3-4

➢ The probability plot for loading rate (Food/Microorganisms) is illustrated in Figure 3-5. The F/M for MBR treatment of municipal wastewaters was observed to lie between 0. I and 0.3 d^{-1}, with the majority of the respondents operating close to 0.15 d^{-1}. One plant was observed to use a high F/M rate of 0.6 (data not shown). This plant consists of treating 100% industrial waste produced by a pig farm. Conventional activated-sludge processes operate in a F/M range of 0.2 - 0.5 d^{-1} with lower levels only achieved in extended aeration or oxidation ditch processes.



Loading Rate (F/M) Probability Plot
Figure 3-5

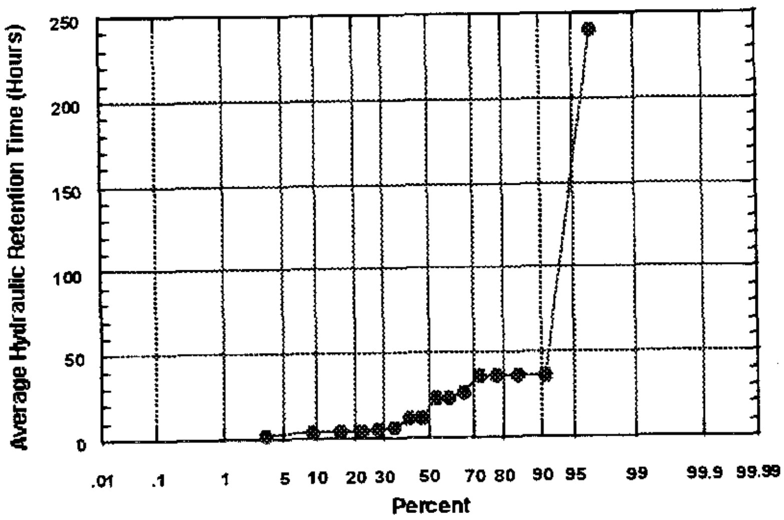
➢ The variation between membrane flux and loading rate (F/M) is illustrated in Figure 3-6. It appears that there is no direct relationship between these two parameters, possibly because the relationship is confounded by other parameters such as cleaning frequency that have not been considered here. Additional data needs to be analyzed to determine whether there are any trends.



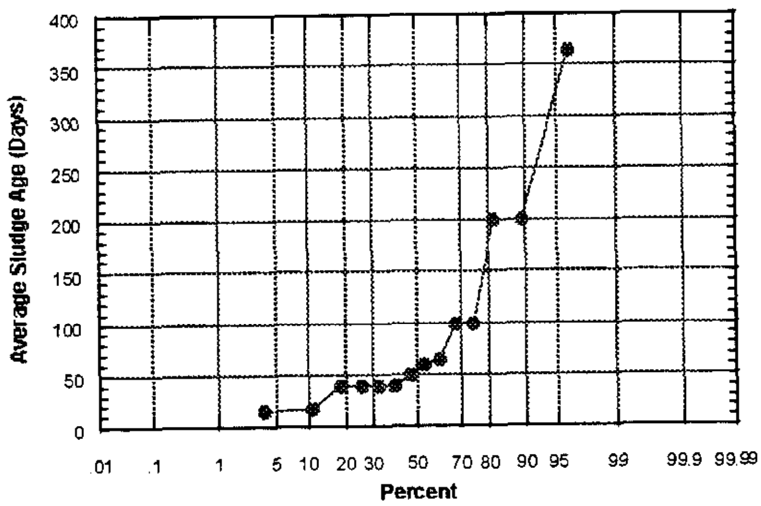
Variation of Membrane Flux With Loading Rate (F/M)
Figure 3-6

- The probability plot for hydraulic retention time (HRT) and the sludge age are illustrated in Figures 3-7 and 3-8. The 50th percentile for HRT was observed at 20 hours while that for the sludge age was observed at 50 days. While this process operates at an F/M ratio equivalent to an extended aeration process, it runs at a higher sludge age than an extended aeration process. This range of sludge ages also agrees with the values we presented in Table 3-1 of this report.

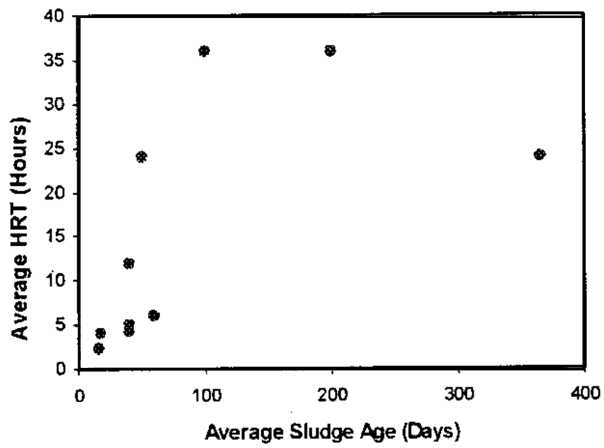
- The variation between HRT and sludge age is further illustrated in Figure 3-9. The higher the HRT, the higher the sludge age.



HRT Probability Plot
Figure 3-7

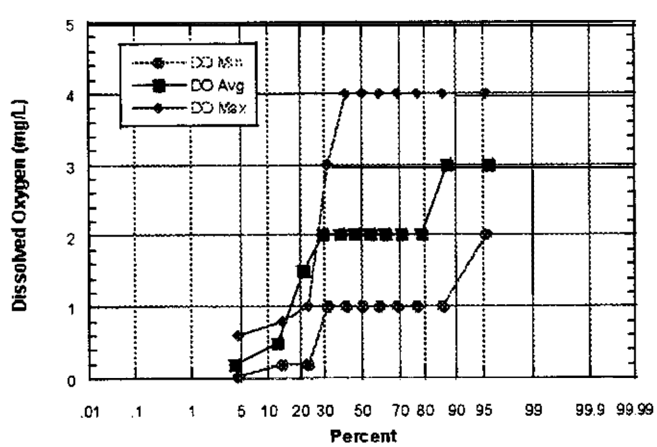


Sludge Age Probability Plot
Figure 3-8

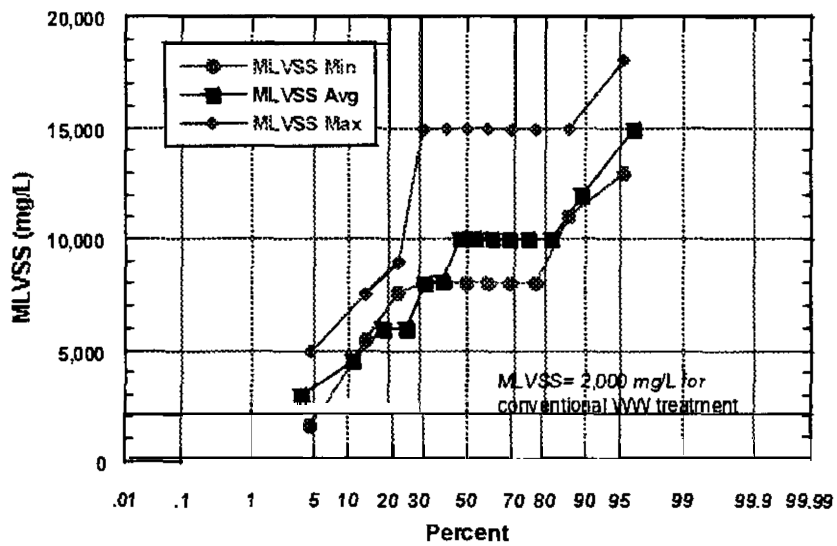


Average HRT Versus Average Sludge Age
Figure 3-9

- The probability plots for dissolved oxygen (DO) and mixed liquor volatile suspended solids (MLVSS) are illustrated in Figures 3-10 and 3-11. As far as bioreactor operation is concerned, the 50th percentiles for average DO and MLVSS content were observed at 2 mg/L and 10,000 mg/L, respectively. The maximum DO concentration was observed to have a median value of 4 mg/L. One plant treating domestic waste was observed to operate under a high DO concentration of 9 mg/L (data not shown). Compared to a conventional wastewater treatment facility, which operates at a MLVSS of 2,000 mg/L, the MBR incorporates five times the MLVSS concentration.

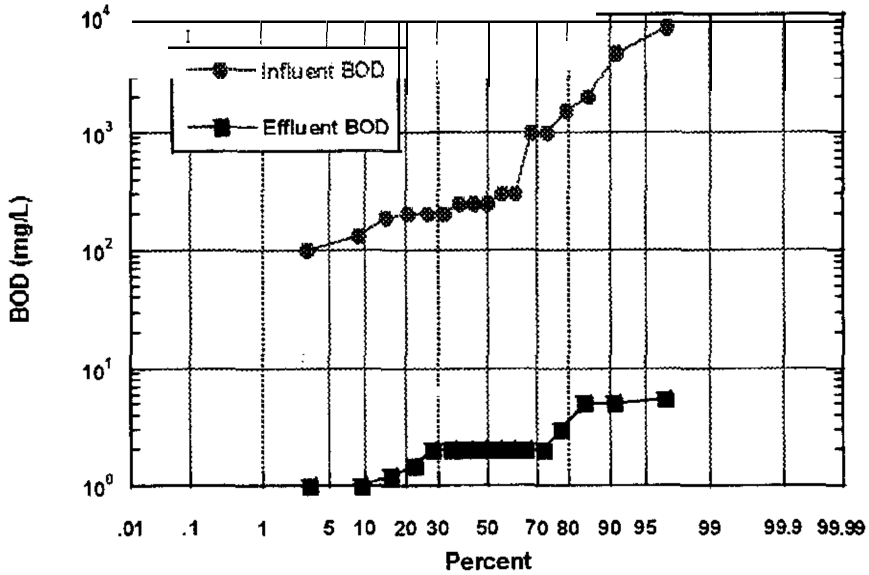


Dissolved Oxygen Probability Plot
Figure 3-10

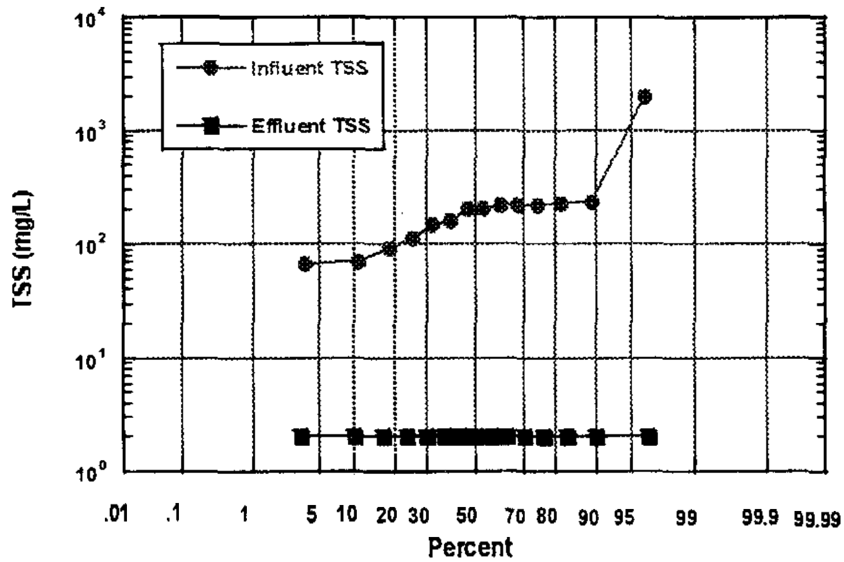


MLVSS Probability Plot
Figure 3-11

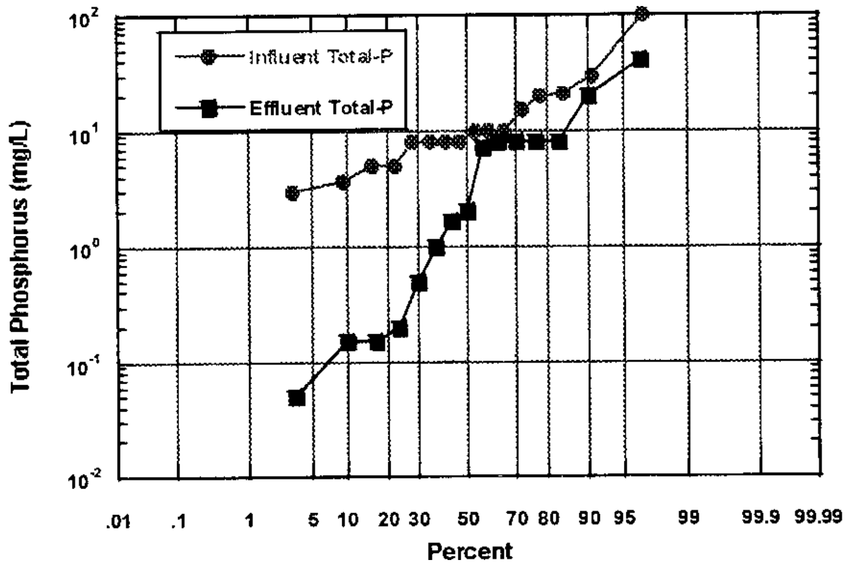
- The effluent water quality obtained from the MBR process is illustrated in Figures 3-12 to 3-16. The 50th percentile removals of biochemical oxygen demand (BOD) and total suspended solids (TSS) were observed to be in the order of 2 logs or 99%. BOD concentration in the effluent varied from non-detect to 4 mg/L. The effluent TSS concentration was in all cases less than or equal to 2 mg/L (below detection limit). A 1 to 2 logs total phosphorus removal was obtainedat half of the MBR plants. For the other half, only a small percentage of phosphorus removal was achieved. Insufficient data is available to determine why certain plants are achieving 50% or greater phosphorous removal. These plants may have a higher percentage of particulate phosphorous that is retained within the bioreactor are being operated under aerobic conditions leading to greater uptake by the microorganisms. The 50th percentile removal of ammonia-nitrogen was observed to be on the order of 2 logs or 99%. Effluent NH,-N concentrations ranged from 0.1 to 10 mg/L. Finally, the median for total coliform removal was observed at 5 to 6 logs. Only one plant provided their influent total coliform concentration, but a 10^6 to 10^7 cfu/100 mL was assumed as the typical total coliform concentration in a primary treated municipal wastewater.



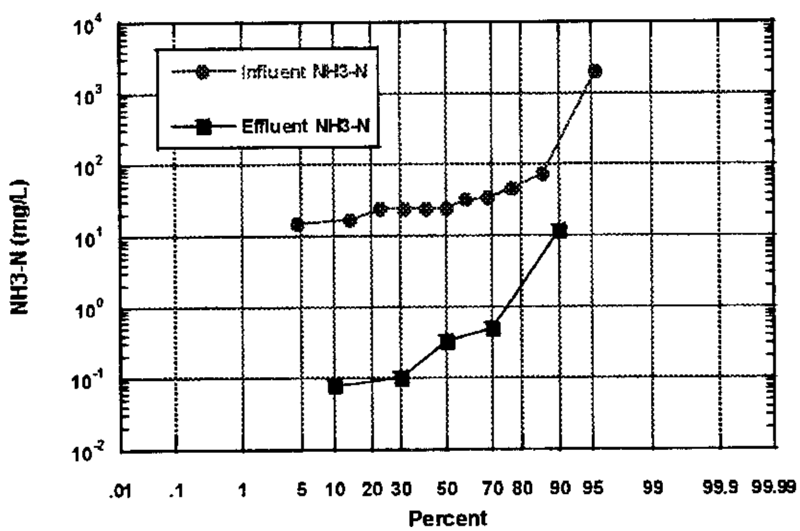
BOD Probability Plot
Figure 3-12



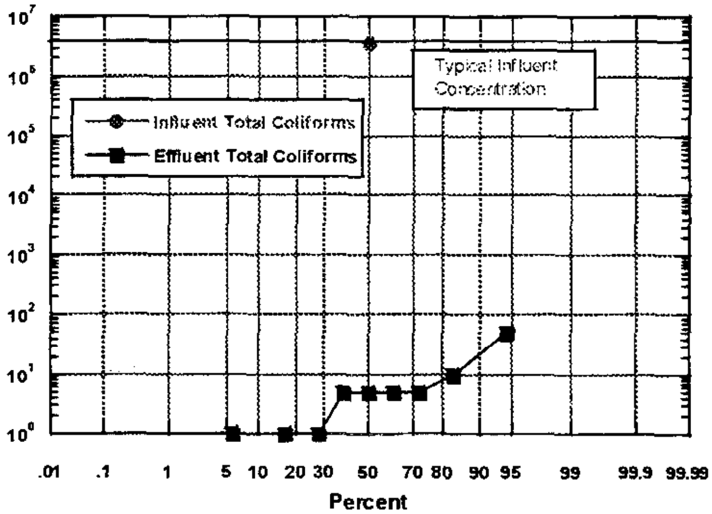
TSS Probability Plot
Figure 3-13



Total Phosphorus Probability Plot
Figure 3-14

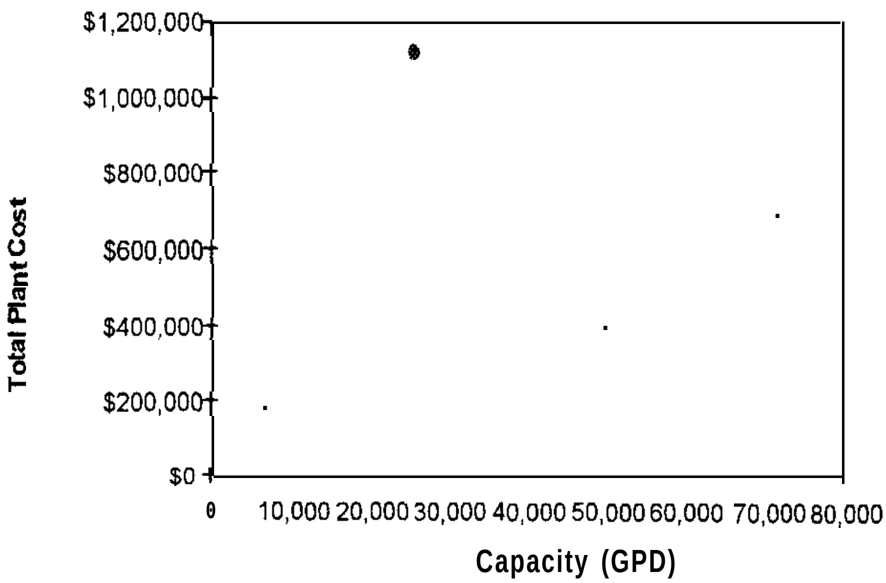


Ammonia-Nitrogen Probability Plot
Figure 3-15



Total Coliform Probability Plot
Figure 3-16

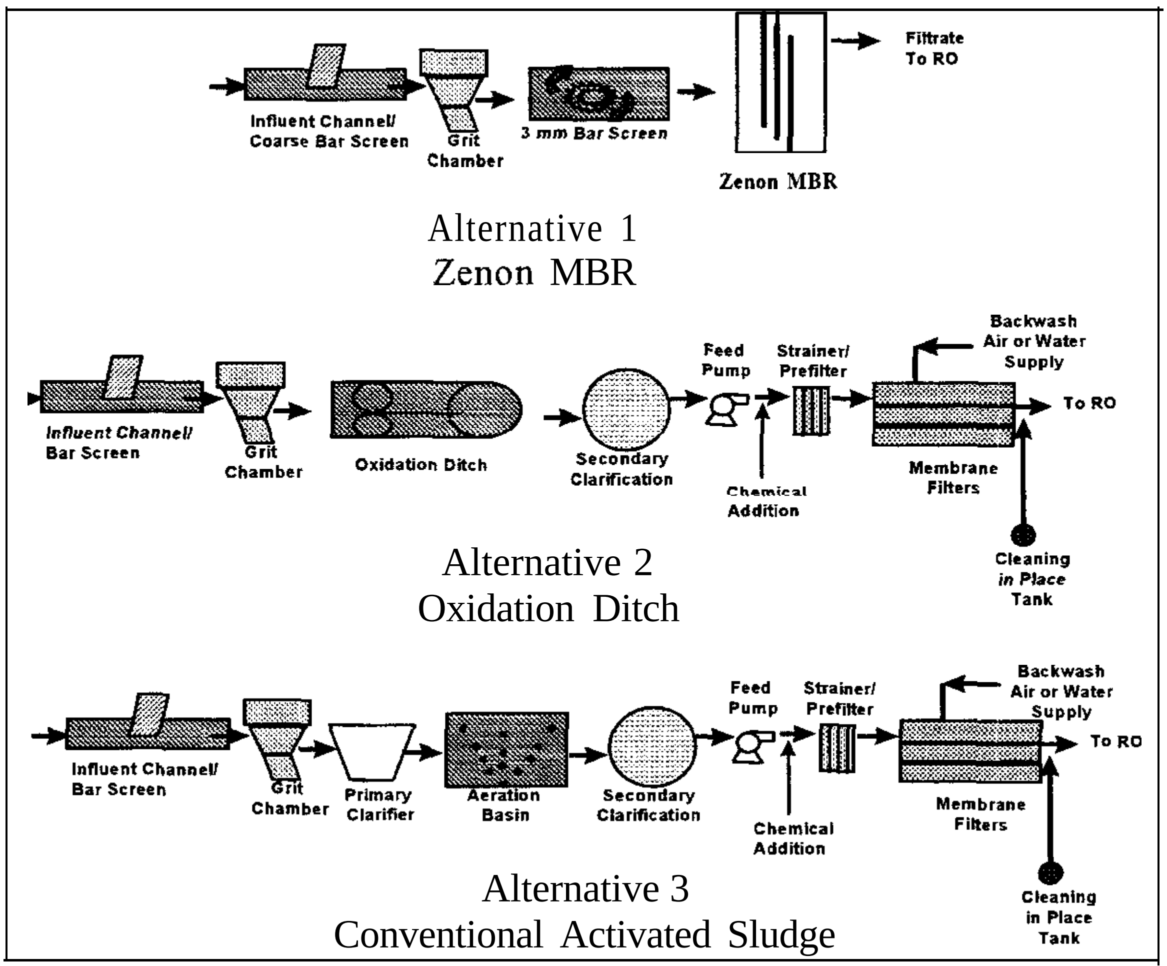
- The variation of total plant cost with plant capacity is illustrated in Figure 3-17. More data is required, particularly for larger capacity plants, to develop a cost curve for the process.



Total Plant Cost Versus Plant Capacity
Figure 3-17

3.3 Task 3. Perform a Preliminary Cost Analysis of MBRs

A cost analysis was conducted to compare three treatment processes: Zenon MBR (based on full-scale costs provided by the manufacturer), oxidation ditch, and conventional activated sludge. Figure 3-18 presents the process train schematics for each alternative. Each of the above alternatives was compared as pre-treatment to RO. The design capacity selected for cost comparison was 1 MGD (0.0435 m^3/s) since no actual data are available on MBRs with larger capacities. Also, this capacity is considered, at this time, one of the most viable for MBR applications in the municipal services water reclamation market.



Process Train Schematics
Figure 3-18

Tables C-l and C-2 in Appendix C present the capital and O&M costs for each alternative. The capital and O&M costs for the MBR alternative were obtained from Zenon Municipal Systems. Also, the size of the basins and the layout for the secondary treatment processes were based on a 1 MGD (0.0435 m^3/s) plant design on which Zenon had recently bid. The other processes and the associated costs in the MBR process train were based on predicted and expected requirements for the operation of the plant. The associated equipment, sizing, and required processes for both the oxidation ditch and the conventional treatment, were based on project experience. Capital and O&M costs were obtained from three references (Richard et al., 1992; Memcor, 1997; Montgomery Watson, 1998):

A summary of the cost comparison is presented in Table 3-3. It is important to remember that the costs presented are based on a conceptual design level and include amortized capital cost assuming a 20-year plant life and an 8% interest rate. It appears that the total cost of the MBR alternative is more favorable than the other alternatives. However, since the costs presented are approximate in nature based on a conceptual design level, it is prudent to conclude that costs for all three alternatives are comparable. Costs associated with land were not included. However, this could be an advantage since MBR's do not take up as much space as either a conventional or an oxidation ditch treatment plant. Finally, it should be noted that the O&M costs associated with MF could be greater because secondary effluent is being treated as opposed to tertiary effluent. What this exercise does illustrate is that the MBR is a viable alternative and should be seriously considered for specific projects. There is a serious market potential for such technology in many projects. Pretreatment to RO for water reclamation is one of those projects.

Table 33
Summary of Capital and O&M Costs

Alternative	Capital Costs	mor. Cap cost, $/yr	O&M Costs, /yr	Total Cost, $/yr	Total Cost, $11000 gal
Zenon	$5,068,600	$516,000	$267,000	$783,000	$2.15
Oxidation ditch	$5.587.800	$569,000	$307,000	$876,000	$2.40
Conventional activated sludge	$5,933,500	$605,000	$262,000	$867,000	$2.38

3.4 Task 4: Prepare a Preliminary Pilot Plant Design for Phase II of the Project

The objectives of this task include the following: identify the MBR manufacturers that will be included in Phase II pilot testing, determine the capacity of the MBR pilot units required, provide a description of the pilot testing site, determine the environmental impact of the pilot testing, provide detailed schematic diagrams of the pilot units, and identify the detailed approach to conduct the pilot study.

3.4.1 Identify the MBR Manufacturers That Will Be Invited to the Study

All four manufacturers were invited to participate in the pilot-scale evaluation study. Three manufacturers indicated an interest to be included in the study:

- Mitsubishi Rayon Corporation
- Zenon Municipal Systems
- Suez-Lyonnaise-des-Eaux/ IDI

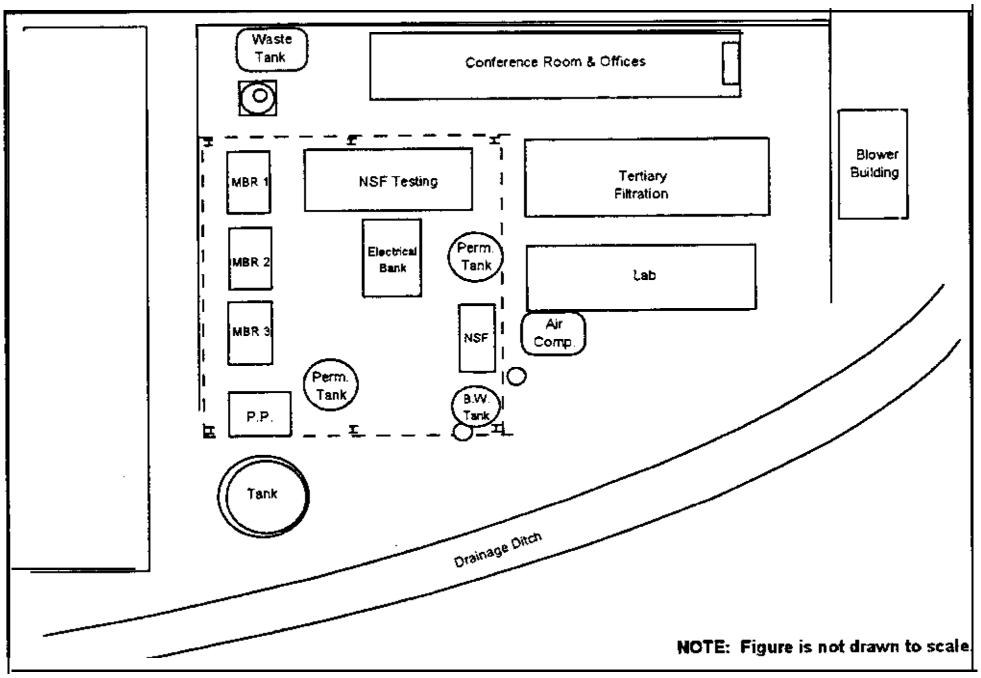
Letters of commitment were received from these manufacturers which were included in the proposal for Phase II of the study. These manufacturers represent the various configurations of the MBR process that are currently available.

3.4.2 Determine the Capacity of the Pilot Units Required

Based on discussion with the MBR manufacturers, it was concluded that a 2 to 5 gpm (454 to 1135 L/h) pilot capacity will be adequate to effectively evaluate the process and determine energy requirements.

3.4.3 Provide a Description of the Pilot Testing Site

The pilot testing site will be the Aqua 2000 Research Center located at the San Pasqual Reclamation Facility in Escondido, California which has a 1 MGD (0.0435 m^3/s) demonstration scale water hyacinth treatment system. Figure 3-19 provides a schematic diagram of the proposed pilot plant site and Table 3-4 shows the representative water quality parameters of the raw wastewater and primary treated effluent at the Aqua 2000 site. The influent to the MBR process will consist of primary treated effluent. More details about the proposed pilot site are provided in Appendix D.



Pilot Plant Site Layout
Figure 3-19

Table 3-4
Representative Water Quality Parameters of
the Aqua 2000 Raw and Primary Treated Effluents

Parameter	Raw Wastewater Quality	Primary Effluent Quality
BOD, mg/L	185	149
TSS, mg/L	219	131
TOC, mg/L	91	72
Turbidity, NTU	100	88
Ammonia-N, mg/L	22	21
Nitrate-N, mg/L	0.1	0.1
Phosphate-P, mg/L	6.1	5.1
TKN, mg/L	31.5	30.6

3.4.4 Determine the Environmental Impact of the Pilot Testing

The proposed study should not have any adverse environmental impacts since testing will be conducted in a wastewater treatment plant. On the contrary, there are potential environmental benefits from the proposed work. Below is a list of the environmental benefits of the MBR process as a pretreatment to RO:

- Less energy would be consumed since no additional RO pretreatment process would be required.
- Less waste would be produced as compared to the waste produced by activated sludge plus the RO pretreatment processes.
- Less space would be required as compared to the space required by activated sludge plus the RO pretreatment processes.
- Less chemicals would be used for RO cleaning as compared to chemicals used for RO cleaning after a lime pretreatment process.
- The feasibility of water repurification would be increased via desalting membranes to provide an indirect potable reuse.
- The feasibility of water reclamation would be enhanced.

3.4.5 Provide Schematic Diagrams of the Pilot Units

The pilot diagrams of the three manufacturers are included in Appendix E of this report. The electrical and plumbing requirements are also included with the pilot diagrams.

3.4.6 Identify the Detailed Approach to Conduct the Pilot Study

Approach:

The pilot-scale study will be designed to obtain the following information:

1. Baseline performance of three MBR systems operated in accordance with the manufacturer's specifications;
2. Optimization of each system to identify the range of operating conditions and critical parameters needed to obtain a suitable effluent quality for the subsequent AWT system and minimize process costs;
3. Verification of the optimized system performance under normal and stressed treatment plant conditions; and
4. Economic benefits of the optimized processes compared with conventional technologies.

The proposed actual pilot operation period is twelve months out of a twenty four-month overall study. During the first three months of pilot-operation, each MBR system will be operated according to manufacturer's specifications with each system being chemically cleaned at least once during that period using the manufacturer's procedure. This will demonstrate the baseline performance of each system, the effectiveness of the manufacturer's specified chemical cleaning protocols, and the presence of irreversible membrane fouling. Optimization of each process will occur from the fourth through the ninth month of operation. Each system will be operated under a range of values for each critical parameter in order to define a zone of acceptable performance and the optimal value for each parameter. The parameters to be considered during this phase of the pilot testing will include, but not necessarily be limited to: (1) membrane flux; (2) dissolved oxygen concentration: and (3) sludge age. A system is considered optimized when a set of operating conditions meets minimum effluent quality criteria at the lowest operating cost.

The optimized systems will then be pilot-tested for an additional three months to verify process performance under normal and stressed operating conditions. Stressed operating conditions will be designed to simulate increases in hydraulic and organic loading rates caused by storm events, plant maintenance and equipment failures, and peak month conditions. These experiments will therefore be performed under a range of hydraulic retention times and food to microorganism ratios. At the end of the pilot testing, the data generated from the optimized systems will be used to evaluate the regulatory compliance of the MBR process and to estimate the capital and operation & maintenance costs of this technology.

The applicability and suitability of the MBR effluent as a feed water to RO for water repurification will also be evaluated in the course of the pilot study. An RO unit will be included at the end of the treatment process to study the long-term impact of the MBR effluent on the fouling potential of the RO membrane. The RO pilot unit will be operated in a constant flux, variable pressure mode. RO membrane fouling will be evaluated by monitoring the increase in transmembrane pressure to maintain constant flux. The RO unit will contain two independent sets of pressure vessels that will allow parallel evaluation of two different RO membranes. At least two RO membrane manufacturers will be evaluated during the course of the pilot testing

4. REFERENCES

Beaubien, Andre', Trouve, Emmanuel, Urbain, Vincent, Aman, Didier, and Manem, Jacques. *Membrane Bioreactors Offer New Solution to Old Wastewater Treatment Problems.* Environmental Solutions, December 1994.

Behmann, H., Mouurato D. and Wingfield, H., T. *Upgrade of Municipal Wastewater Treatment Plants.* Literature provided by Zenon Environmental Inc. on November 4, 1996.

Bodzek, Michal, Debkowska, Zuzanna, Lobos, Ewa and Konieczny, Krystyna.. *Biomembrane Wastewater Treatment by Activated Sludge Method* Desalination, 107:83-95, 1996.

Chaize, S., and Huyard, A. *Membrane Bioreactor On Domestic Wastewater Treatment Sludge Production and Modeling Approach* Wat. Sci. Tech., 23:1591-1600, 1991.

Chiemchaisri, C., Yamamoto, K. and Vigneswaran S. *Household Membrane Bioreactor in Domestic Wastewater Treatment.* Wat. Sci. Tech. 27:1:171-178, 1993.

Choo, K-H. And *Lee,* C-H. *Membrane Fouling Mechanisms in the Membrane-Coupled Anaerobic Bioreactor.* Wat. Res. 30:8:1771-1780, 1996.

Çiçek, N., Franco, J., and Suidan, M. *Characterization and Comparison of a Membrane Bioreactor and a Conventional Sludge System in the Treatment of Wastewater Containing High Molecular Weight Compounds* Obtained directly from Nazim Çiçek in 1997.

Côte, P., Buisson, H., Pound, C., and Arakaki, *G. Immersed Membrane Activated Sludge for the Reuse of Municipal Wastewater.* Desalination 113: 189-196, 1997.

Fan, Xiao-Jun, Urbain, Vincent, Yi Qian, and Manem, Jacques. *Nitrification and Mass Balance with a Membrane Bioreactor For Municipal Wastewater Treatment.* Wat. Sci. Tech, 34:1-2:129-136, 1996.

Fane, A.G. *Membranesfor Water Production and Water Reuse.* Desalination 106:1-9, 1996.

Husain, H. and Mourato, Diana. *Application of Membrane Bioreactor Technology For Industrial and Municipal Wastewater Treatment.* Presented at the 1996 Air and Waste Management Association Conference, Nashville, TN.

Huyard, A., Trouve, E., and Manem, J. *Recent Advances on Membrane Bioreactors Applications to Water and Wastewater Treatment.* Proc. Euromembrane Interfiltra. Conf., Paris 6(21):189-193, 1992.

Ishiguro, K., Imai, K. and Sawada, *S. Effects Of Biological Treatment Conditions On Permeate Flux of UF Membrane in a Membrane/Activated-Sludge Wastewater Treatment System.* Desalination, 98:119-126, 1994.

Kimura, S. *Japan's Aqua Renaissance '90 Project* Wat. Sci. Tech., 23: 1573-1582, 1991

Kishino, H., Ishida, H., Iwabu, H. and Nakano, *1. Domestic Wastewater Reuse Using a Submerged Membrane Bioreactor. Desalination*, 106:115-119, 1996.

Manem, J., Trouve, E., Huyard, A., Urbain, V., and Beaubien, A. *Membrane Bioreactor For Urban and Industrial Waste-Water Treatment: Recent Advances.* Obtained directly from Jacques Manem, 1997.

Memcor. *Municipal and Industrial Wastewater Reclamation and* Reusecost manual, 1997.

Montgomery Watson. Traditional cost estimating techniques applied by the design engineers, Pasadena, California, 1998.

Richard D., Asano T., and Tchobanoglous G. *The Cost of Wastewater Reclamation in California.,* 1992.

Roncken, G.C.G. and Dijk, L. *van. Application of the Membrane-Bioreactorfor the Treatment of Highly Concentrated Wastewaters.* IAWQ Yearbook 1995-96:46-48, 1995.

Shimizu, Yasutoshi, Okuno, Yu-Ichi, Uryu, Katsushi, Ohtsubo, Sadami and Watanabe, Atsuo. *Filtration Characteristics of Hollow Fiber Microfiltration Membranes Used In Membrane Bioreactor For Domestic Wastewater Treatment.* Wat. Res., 30:10:2385-2392, 1996.

Smith, Clifford V. Jr., Gregorio, David Di., Talcott, Robert M. and Oliver, Dorr. The Use of *Ultrafiltration Membranes for Activated Sludge Separation.*

Trouve, E., Urbain, V., and Manem, J. *Treatment of Municipal Wastewater by a Membrane Bioreactor: Results of a Semi-Industrial Pilot-Scale Study.* Wat. Sci. Tech., 30:4:151-157, 1994.

Ueda, Tats&i, Hata, Kenji, Kikuoka, Yasuto and Seino, Osamu. *Effects of Aeration on Suction Pressure In a Submerged Membrane Bioreactor.* Wat. Res., 31:3:489-494, 1997.

Ueda, T., Hata, K., and Kikuoka, Y. Wat. Sci. Tech., 34:9:189-196, 1996.

Urbain, Vincent, Benoit, Raymond, and Manem, Jacques. *Membrane Bioreactor: A New Treatment Tool.* Journal AWWA, 88:5:75-86, 1996.

Vera, L., Villarroel-López, R., Delgado, S., and Elmaleh, S. *Cross-flow Microfiltration of Biologically Treated Wastewater.* Desalination 114:65-75, 1997.

SI METRIC CONVERSIONS

English Unit	Multiply by	SI Metric Unit
ft^2	9.29×10^{-2}	m^2
ft'	2.832×10^{-2}	m^3
MGD	0.0438	m^3/s
gal	3.785	L
gpm	227.1	L/h
gpd	0.1577	J-h
gfd	1.698	$L/h/m^2$
lb	0.4536	Kg
psi	703.1	Kg/m^2

Appendix A

APPLICATION OF MEMBRANE BIOREACTORS TO AEROBIC MUNICIPAL WASTEWATER TREATMENT

This literature review summarizes the present state of knowledge about the performance of the membrane bioreactor (MBR) for aerobic treatment of municipal wastewater. Included in the review are the results of bench and pilot-scale research and full-scale installations. The review is subdivided into the following sections:

SECTION 1

EXECUTIVE SUMMARY

Suspended growth biological treatment of municipal wastewater is accomplished using a community of microorganisms that metabolize the dissolved and colloidal carbonaceous organic matter into gases or cell tissue that is removed from the water by gravity separation. The process is optimized when the design and operating characteristics favor the kinetic decomposition of the organic waste and the microorganisms create a floc with effective settling characteristics. Unfortunately, in the activated sludge process, optimization of substrate utilization rates and bioflocculation occur under different sets of operating conditions and process optimization involves a trade-off between these two requirements.

A membrane bioreactor (MBR) consists of an activated sludge process which substitutes ultrafiltration or microfiltration membrane modules for the clarifier. The membranes serve as microbial barriers that can capture most of the biomass for recirculation inside the bioreactor. The MBR allows the activated sludge process to be optimized for solid-liquid separation and substrate utilization since bioflocculation is no longer an issue.

The high energy requirements needed to operate the filtration unit of the MBR at high suspended-solid concentrations historically restricted application of the MBR to high strength effluents or water recycling projects. Recent interest in this technology for domestic wastewater applications has occurred due to an increasing number of water reclamation projects and continuing advancements in membrane technology which have reduced the cost of membranes and provided a better understanding of the factors contributing to membrane fouling.

Treatment of secondary or tertiary effluents to meet standards for groundwater recharge or potable reuse may require final treatment with reverse osmosis. The conventional treatment tram to pre-treat effluent to a suitable quality for RO treatment consists of lime or ferric chloride precipitation followed by clarification and sand filtration or the application of ultrafiltration or microfiltration. The feasibility of replacing the conventional treatment tram with a membrane bioreactor is actively being studied. Although preliminary results are encouraging, there is still a need to fully demonstrate the comparability of the MBR process in achieving reuse effluent quality standards and to fully optimize MBR design and operational parameters to minimize costs.

The MBR process can exist in two different configurations. The MBR membrane modules may be placed downstream of the bioreactor (in-series) or submerged directly within the bioreactor (submerged). For either configuration, the MBR is typically operated in a considerably different range of parameters for the mean cell residence time (θ_c) and substrate utilization rate (U) than the conventional activated sludge processes. Due to tbis difference, the MBR offers several benefits over the conventional activated sludge process. These benefits include: (i) much smaller space requirements; (ii) better solids removal (elimination of bulking); (iii) disinfection; (iv) increased volumetric loading; (v) de-coupling of hydraulic and biomass retention time; (vi) production of less sludge due to high sludge age, (vii) high SRT which allows the development of slow-growing microorganisms such as nitrifying bacteria, and (viii) retention of high molecular weight organic compounds that can enhance the biodegradation process.

Submerged MBR systems typically utilize shell-less capillary or hollow fiber microfiltration membranes with pore sizes ranging between 0.1 to 0.4 µm. In-series MBR systems can utilize a variety of membrane configurations. Both systems exhibit COD removal rates that are as good or better than those observed for conventional suspended growth reactors and provide enhanced performance for reduction of total nitrogen, total phosphorous, and organic suspensions. While in-series and submerged MBR systems have been tested at pilot-scale and the submerged system has been shown to produce effluent quality that is suitable as feed water for reverse osmosis, no direct comparison of the two configurations could be found in the literature. The submerged MBR reduces the energy requirements of the system compared to an in-series MBR process, but the overall cost and operating efficiencies of the two systems has not been adequately demonstrated.

More than 10 manufacturers of MBR processes were identified in 1992. Today, only 4 companies actively marketing the MBR system could be identified. They consist of 1 French, 2 Japanese, and 1 Canadian firm. While many installations can be found for small capacity industrial waste plants and water recycling in high-rise buildings, there are only a few operating municipal installations. Municipal installations in the 1.0 to 2.0 MGD (0.0435 to 0.087 m^3/s) range are under construction in Canada, the United States, and Egypt.

Some important issues still need to be investigated for the MBR process. These include evaluating of the optimal operational conditions for maximizing the kinetic performance of the bioreactor and determining the impact of operational parameters on membrane flux and membrane fouling. The key operational parameters include primarily the mean cell residence time, and the food-to-microorganism ratio, and secondarily the type of membrane selected, the membrane pore size, the membrane velocity, the ah-flow rate, and the configuration of the membrane module (submerged within or downstream of the bioreactor). Identification of capital and O&M costs, design parameters and operational conditions of the MBR technology will lead to a proper balance between process productivity and product quality.

To fully demonstrate the effectiveness of this new technology, a parallel comparison of a conventional suspended growth reactor, a MBR with in-series configuration, and a MBR with submerged configuration needs to be performed at pilot-scale. These processes should be compared for critical ranges of influent loading, sludge retention times, hydraulic retention times, dissolved oxygen concentrations, membrane pressures and membrane fluxes. Preliminary bench-scale optimization work could be used to help identify the parameter ranges to consider for the pilot study.

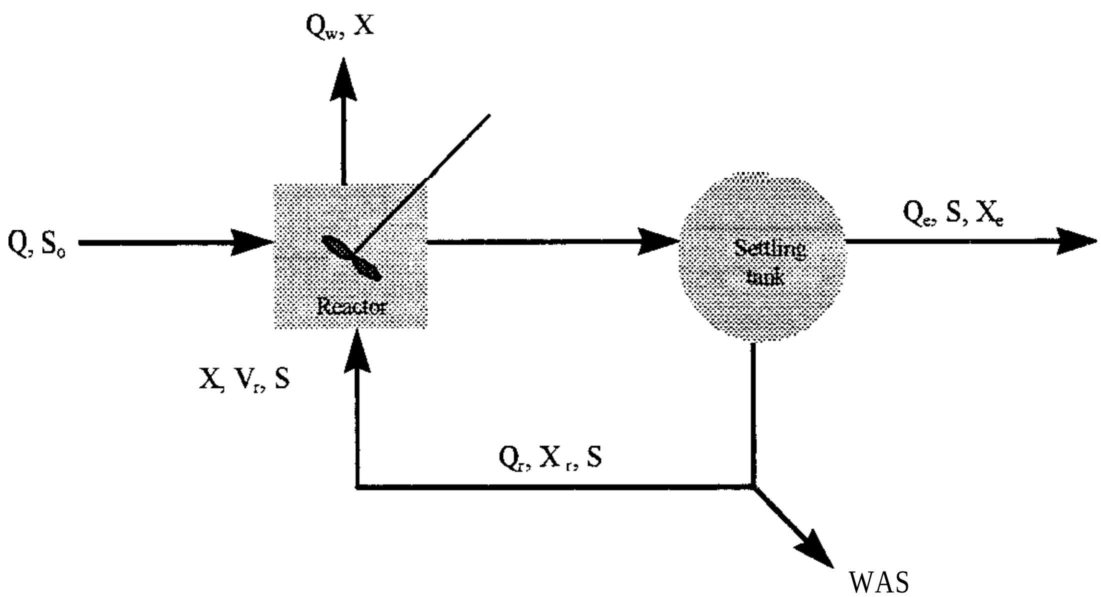
SECTION 2

BACKGROUND

Biological treatment of municipal wastewater is designed to remove nonsettleable colloidal solids, stabilize organic matter, and remove carbonaceous biochemical oxygen demand (BOD). This is accomplished using a community of microorganisms that metabolize the dissolved and colloidal carbonaceous organic matter into gases and cell tissue. The higher specific gravity of the cells then allows them to be removed from the water by gravity settling.

Conventional Treatment Process

The activated-sludge process is one of the most common conventional biological treatment methods employed. In this process, stabilization of municipal wastewater is accomplished aerobically. While many modifications of the process have been developed, operationally they all rely upon the suspension of an aerobic bacterial culture in aerated wastewater and subsequent separation and partial recycling of the suspended biomass. A schematic of the process is shown in Figure 2-1 for a complete-mix reactor. A description of the operational characteristics of different types of activated-sludge processes is provided in Table 2-l.



Schematic of Complete-mix Reactor
Figure 2-l

Table 2-1
Operational Characteristics of Activated-Sludge Processes

Process	Flow Model	Aeration System	BOD Removal Efficiency, %
Conventional	Plug-flow	Diffused-air, mechanical aerators	85-95
Complete-mix	CSTR	Diffused-air, mechanical aerators	85-95
Step-feed	Plug-flow	Diffused-air	85-95
Modified aeration	Plug-flow	Diffused-air	60-75
Contact stabilization	Plug-flow	Diffused air, mechanical aerators	80-90
Extended aeration	Plug-flow	Diffused air, mechanical aerators	75-95
High-rate aeration	CSTR	Mechanical aerators	75-90
Kraus process	Plug-flow	Diffused air	85-95
High-purity oxygen	CSTR in series	Mechanical aerators (sparger turbines)	85-95
Oxidation ditch	Plug-flow	Mechanical aerators	75-95
Sequencing Batch	Intermittent-flow STR	Diffused-air	85-95
Deep shaft	Plug-flow	Diffused-ah	85-95
Nitrification	CSTR or Plug-flow	Mechanical aerators. diffused air	85-95
Water Hyacinths	Plug-flow	Diffused-air	85-95

Taken in part from Metcalf & Eddy, Inc. (1991) Wastewater Engineering Treatment Disposal Reuse, Third Edition.

The two key objectives in the design and operation of a conventional activated sludge process are to: (1) optimize kinetic decomposition of the organic waste by the microorganisms; and (2) create a floc with effective settling characteristics. For a specified wastewater and set of environmental conditions, achieving specific effluent quality standards for carbonaceous BOD and TSS can be related to the mean cell residence time (q_c) and substrate utilization rate (U) of the reactor. The substrate utilization rate can be derived from the food-to-microorganism ratio (F/M) and the efficiency of the reactor in reducing the BOD concentration

$$U = \frac{F}{M}\left[\frac{S_o - S}{S_o}\right]100$$

where U = specific substrate utilization rate, (mg BOD utilized)/(mg MLVSS•d)
F/M = food-to-microorganism ratio, d^{-1}
S_o = influent BOD or COD concentration, mg/L
S = effluent BOD or COD concentration, mg/L

In order to maintain θ_c independent of the hydraulic retention time, it must be possible to separate the mixed liquor suspended solids and return a portion of them to the reactor.

Both F/M and θ_c are controlled by the volumetric loading rate, the design characteristics of the reactor, and the level of MLSS that can be maintained in the reactor. The level of MLSS in the reactor is in turn controlled by the return sludge recirculation rate, and the waste sludge disposal rate. Typical values for F/M reported in the literature vary from 0.05 (extended aeration) to 1.5 (high-rate aeration or high-purity oxygen). Mean cell residence times of 5 to 15 days typically result in production of stable, high-quality effluent and a sludge with excellent settling characteristics. Longer residence times on the order of 20 30 days are used for extended aeration and nitrification processes. Hydraulic detention times typically range from 4 - 8 hours and organic loadings typically vary from 0.3 to >3 $kg/m^3 \bullet day$. A summary of design parameters for the various activated sludge processes is provided in Table 2-2.

Table 2-2
Design Parameters for Activated-Sludge Processes

Process	θc (d)	F/M (lb BOD5 applied/lb MLVSS-d)	MLSS (mg/L)
Plug-flow	5-15	0.2-0.4	1,200-3,000
Complete-mix	5-15	0.2-0.6	2,500-6,500
Step-feed	5-15	0.2-0.4	1,500-3,500
Modified aeration	0.2-0.5	1.5-5.0	200-1,000
Extended aeration	20-30	0.05-0.15	1,500-5,000
High-rate aeration	5-10	0.4-1.5	3,000-6,000
Kraus process	5-15	0.3-0.8	2,000-3,000
High purity oxygen	3-10	0.25-1.0	3,000-8,000
Oxidation ditch	10-30	0.05-0.30	1,500-5,000
Sequencing batch	Not Applicable	0.05-0.30	1,500-5,000
Deep shaft	Not Available	0.5-5.0	Not Available
Nittification	8-100	0.05-0.25	1,500-3,500

Taken from Metcalf & Eddy, Inc. (1991) Wastewater Engineering Treatment Disposal Reuse, Third Edition.

Process optimization has typically been achieved by focusing on the processes involved in fixation of microorganisms and formation of good settling microbial flocs. Less focus has been placed on the techniques used for solid-liquid separation, until the development of the membrane bioreactor. Design parameters that must be specified for the bioreactor portion of the process are:

- the reactor type
- the reactor volume and volumetric loading
- the waste sludge production rate
- the return sludge rate, and
- the aeration and mixing requirements.

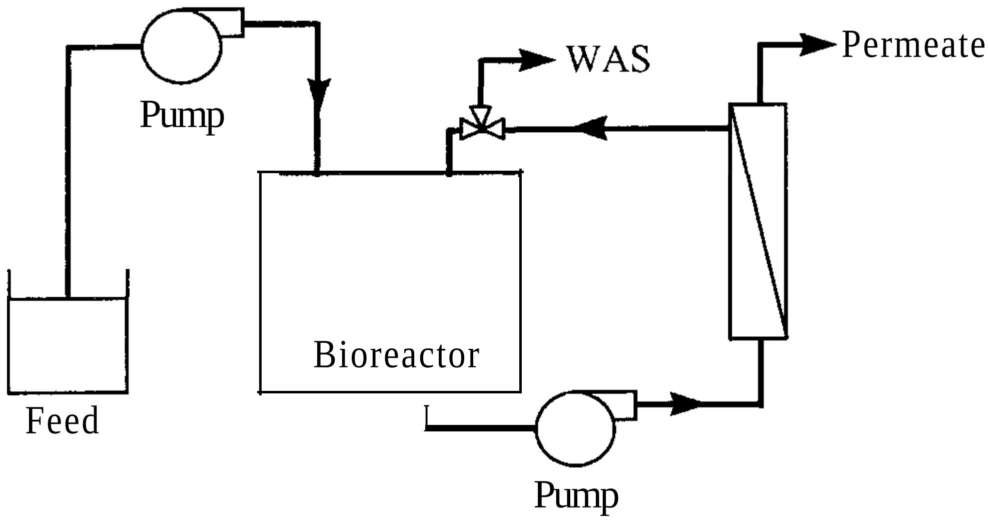
Reactors can be designed as continuous-stirred tank reactors (CSTR) or plug-flow reactors. Since the combined substrate removal rate for domestic waters is independent of the substrate concentration, the two types of reactors are typically run at similar hydraulic detention times. Plug-flow reactors are more susceptible to shock loads and frequently require incorporation of tapered aeration, step-feed, or contact stabilization to prevent oxygen deficiencies at the head of the reactor that can lead to sludge bulking and poor performance. A complete-mix reactor is better able to handle shock loads, but is more susceptible to filamentous growths due to low F/M ratios. This problem is sometimes addressed by the use of a "selector" which is a separate compartment used as the initial contact zone where the primary effluent and return activated sludge are combined. This zone enables the selective growth of floe-forming organisms by provision of a high F/M ratio at controlled DO levels. This permits the rapid adsorption of the soluble organics into the floe-forming organisms leaving little available for subsequent assimilation by filamentous organisms. *Nocardia* foam is another problem that arises due to a low F/M ratio or buildup of a high MLSS concentration and increased sludge age due to insufficient sludge wasting. This problem is typically handled by reducing the sludge age.

Theoretical oxygen requirements can be calculated based on the removal requirements for the carbonaceous organic matter and the conversion requirements for nitrogen. This, coupled with the oxygen-transfer efficiency of the aeration system, determines the air requirements for the process. Porous diffusers, jet aerators, and u-tubes have the highest transfer efficiencies but porous diffusers are more susceptible to clogging. The air supply must provide adequate mixing and maintain a minimum dissolved oxygen concentration of 1 to 2 mg/L throughout the aeration tank. For F/M ratios greater than 0.3, the air requirements for the conventional process amount to 30-55 m^3/kg of BOD removal for coarse bubble (nonporous) diffusers and 24-36 m^3/kg for fine bubble (porous) diffusers. Lower food-to-microorganism ratios increase air use to 75- 115 m^3/kg of BOD removed. For the extended aeration process, air requirements are 125 m^3/kg of B OD removed.

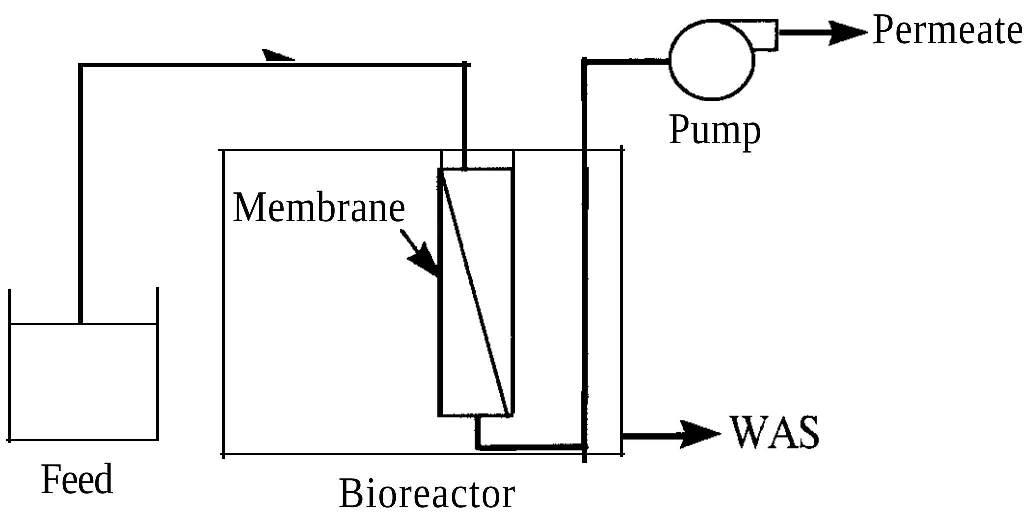
The Membrane Bioreactor Process

A membrane bioreactor (MBR) substitutes the clarifier with ultrafiltration or microfiltration membrane modules. Unlike the clarifier, the membrane is a microbial barrier that can capture the biomass for recirculation inside the bioreactor. The MBR was first developed and applied to domestic wastewater in the 1960's by Dorr-Oliver (Smith et al., 1969). The high energy requirements needed to operate the filtration portion of the MBR process at high suspended-solid concentrations restricted application, for the past 2 decades, to processes with high-strength industrial effluents or wastewater recycling in high-rise buildings in the US, Japan, South Africa, and Europe (Urbain et al., 1996). Serious interest in this technology for treating domestic wastewater has only occurred recently due to the approval of water reclamation projects and further advancements in membrane technology which have resulted in more favorable process economics.

The MBR process exists in two different configurations. A membrane unit can replace the clarifier downstream of the bioreactor as shown in Figure 2-2a or a membrane unit can be submerged directly within the bioreactor as shown in Figure 2-2b.



Schematic of a Downstream Membrane Bioreactor
Figure 2-2a



Schematic of a Submerged Membrane Bioreactor
Figure 2-2b

For either configuration, the MBR operates in a considerably different range of parameters for θ_c and F/M than the conventional activated sludge processes. While θ_c falls in the range of 5 - 30 days for a conventional system, θ_c values frequently exceed 30 days for the MBR and have been reported at levels as high as 125 days (Ueda, 1997). The F/M ratio falls in the range of 0.05 - 1.5 d^{-1} for a conventional system, but is usually $<0.1\ d^{-1}$ for an MBR. This lower ratio for the MBR should create higher aeration requirements unless a high percentage of the MLSS are in the endogenous phase of respiration. The low F/M ratio occurs due to the high MLSS values in the MBR, which typically range from 5,000 to 20,000 mg/L.

The MBR offers several benefits over the conventional activated sludge process. These benefits include:

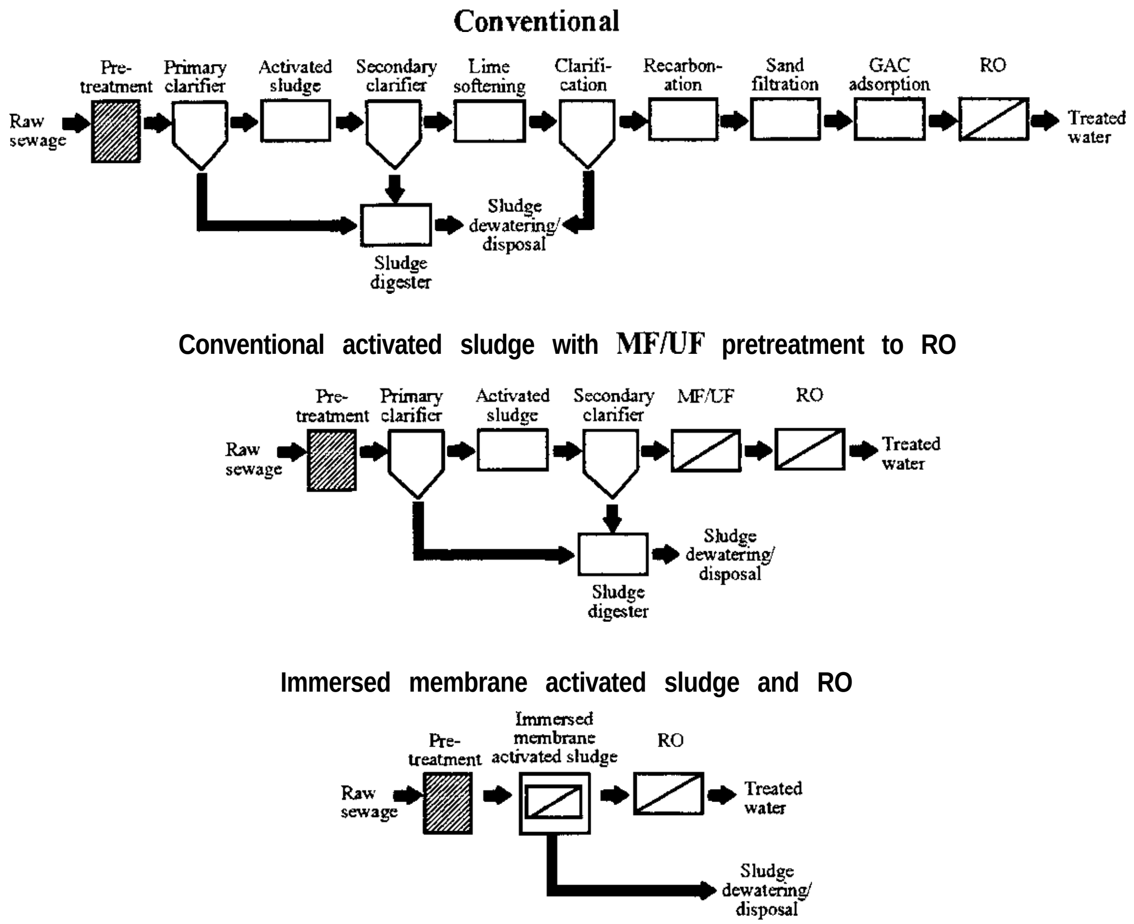
- much smaller space requirements
- better solids removal (elimination of bulking)
- disinfection
- increased volumetric loading
- greater de-coupling of hydraulic and biomass retention time
- production of less sludge due to high sludge age
- high SRT which allows the development of slow-growing microorganisms such as nitrifying bacteria, and
- retention of high molecular weight soluble compounds that improve biodegradation.

The long θ_c values and low F/M ratios which characterize the MBR, represent the range of operating parameters that can be problematic in a conventional reactor due to production of sludge with poor settling characteristics. This is not a concern with the MBR process because the membrane will still provide effective separation of biosolids, and effluent quality is no longer dependent upon the settleability of the biological floc.

Issues of Concern

Issues that still need to be elucidated for the MBR process include demonstration of the operational boundary conditions for maximizing the kinetic performance of the bioreactor and determining how operational parameters impact membrane flux and membrane fouling. The operational parameters of importance include not only θ_c and F/M, but also the type of membrane selected, the membrane pore size, the membrane velocity, the air-flow rate, and whether the membrane is submerged within or placed downstream of the reactor. Uncertainties still revolve around the economics of the process and determination of the design characteristics and operating variables that will create the proper balance between process productivity and product quality. As an example, the role of the MBR in the hydrolysis of TSS is still poorly understood (Manem et al., 1997).

Treatment of secondary or tertiary effluent to meet standards for groundwater recharge or potable reuse frequently requires inclusion of reverse osmosis. The conventional treatment train to pre-treat secondary effluent to a suitable quality for RO treatment consists of clarification with lime or ferric chloride followed by sedimentation and media filtration (Figure 2-3a) or use of MF or UF filtration (Figure 2-3b). Limited studies have been performed to investigate substitution of a membrane bioreactor (Figure 2-3c) as a pre-treatment for RO (Côté, 1997). Despite encouraging preliminary results, there still is a need to fully demonstrate the comparability of the MBR process in achieving reuse effluent quality standards and to optimize MBR design and operational parameters.



Schematic of Wastewater Treatment Trains to Produce Effluent which Meet Standards for Groundwater Recharge or Potable Reuse

Figure 2-3a,b,c

Demonstration of comparability is most readily achieved through performance of parallel studies of MBR and conventional activated sludge systems under similar experimental conditions. Little research of this type has been performed. Recent bench-scale work (Cicek, 1996) has directly compared the performance of a MBR and a conventional activated sludge process for a synthetic wastewater. These findings need to be expanded to consider the relative performance of a submerged MBR, evaluate the effectiveness of different types of membranes, consider the impact of varying operational parameters on reactor performance, and demonstrate the method's effectiveness at larger scale using real rather than synthetic wastewater.

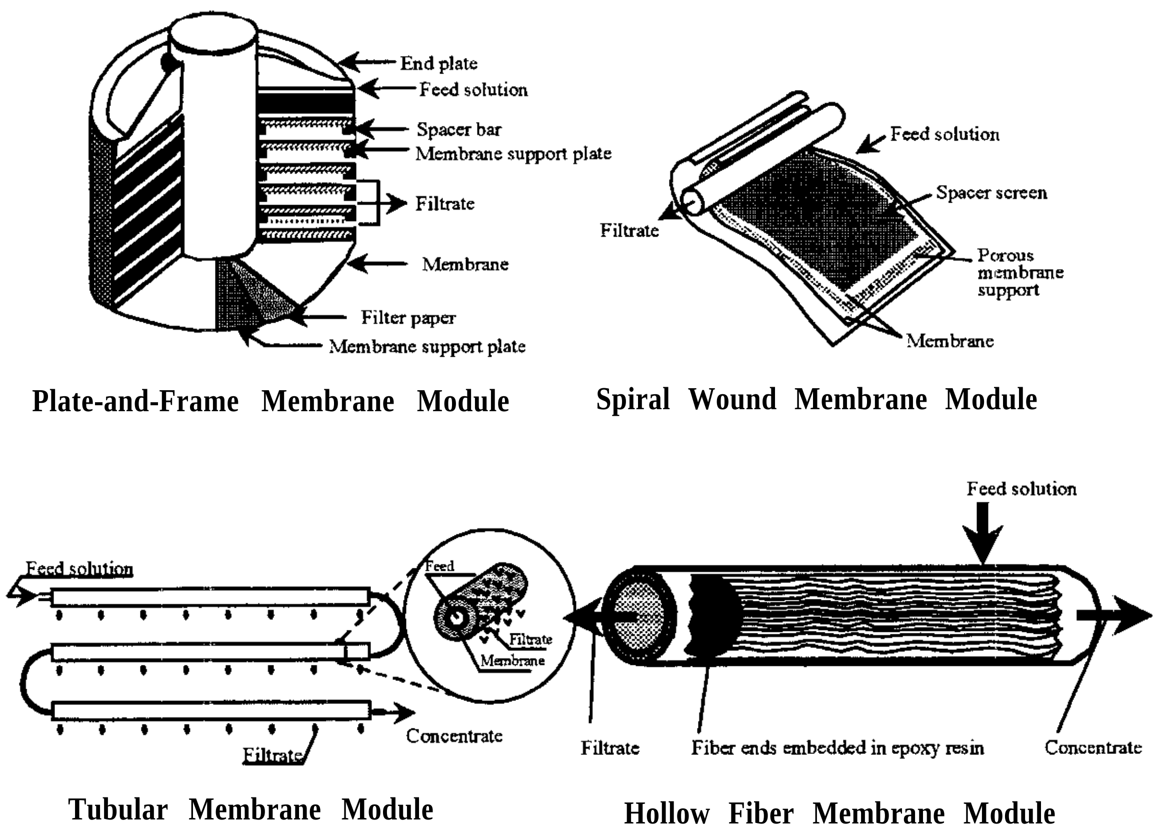
A parallel comparison of a conventional suspended growth reactor, a MBR with in-series configuration, and a MBR with submerged configuration needs to be performed at pilot-scale. Such a study could address the research objectives listed below:

- Determine the effluent quality produced by the MBR process and compare this to the quality produced by conventional secondary or tertiary treatment processes;
- Investigate the suitability of the MBR effluent as a feed water to the RO process. This will be achieved during the pilot study, with an evaluation of the fouling potential of the MBR effluent by monitoring of the increase in the transmembrane pressure to maintain the required flux;
- Determine the impact of several operational parameters on the performance of the MBR system. These parameters may include: sludge age, membrane flux rate, recirculation rate, and/or hydraulic residence time;
- Evaluate direct and indirect methods to monitor the integrity of the membrane system and treatment reliability;
- Develop preliminary estimates of the capital and operation and maintenance (O&M) costs of the MBR process; and
- Evaluate the potential for the MBR process to meet the regulatory requirements of wastewater reclamation, reuse and/or repurification.

SECTION 3

MBR PROCESS DESIGN AND PERFORMANCE

Four types of membrane configurations are in use today for full-scale application of microfiltration or ultrafiltration processes: plate and frame, tubular, hollow fiber modules, and spiral wound. The plate and frame and spiral wound membrane modules have a low packing density and utilize flat sheet membrane elements. The tubular and hollow fiber membrane modules have a high packing density and utilize small flexible elements. These configurations are shown schematically in Figure 3-1. For the high solids concentrations found in primary effluent, the plate and frame and spiral wound configurations may be too susceptible to fouling and therefore recent applications have employed hollow fiber configurations.



Types of Membrane Configurations for Microfiltration or Ultrafiltration Processes
Figure 3-1

The MBR membrane modules may be placed downstream of the bioreactor or submerged directly within the bioreactor. The submerged MBR, which was developed in the late 1980's, has been described in the literature as a system containing shell-less capillary or hollow fiber microfiltration membranes with pore sizes ranging between 0.1 to 0.4 pm. A submerged MBR is commercially available with shell-less hollow fiber membrane modules and 0.1µm pore size. The serial configuration typically utilizes UF membranes.

No direct comparison of the two configurations could be found in the literature. The submerged MBR has been tested at pilot-scale and shown to produce effluent quality that is suitable as feed water for reverse osmosis with a silt density index averaging 1.4 (Côté et al., 1997). The submerged MBR reduces the power consumption of re-circulation pumps because the mixed liquor is driven across the submerged module by a suction pump. This finding was substantiated by the low energy requirement of 0.3 kWh/m^3 determined by Côté *et al.*. Use of re-circulation pumps may also be undesirable because they can reduce the activity of the biocatalysts in the bioreactor due to the high volume of circulation feed required to maintain a high filtration flux and the possibility of damaging the biocatalysts due to the excessive shear stress generated by the pump (Shimzu *et* al., 1996).

For membrane processes, eventual accumulation of a cake layer on the membrane surface will increase the pressure needed to maintain the flux at acceptable levels. To prevent this, cake removal must occur continuously through the high shear forces created at the membrane surface. The important operating parameters to maintain adequate flux for MBR processes with in-series membrane configurations are the cross-flow velocity and the operating pressure generated by the recirculation pump. For submerged membranes, the uplifting air of the bioreactor provides the shear forces at the membrane surface. Therefore, the important operating parameters to maintain adequate flux for the submerged MBR are the air flow velocity and the cycling frequency of the suction pump. Aeration in a submerged MBR must, therefore, be optimized for both substrate utilization and maintenance of the required cross-flow velocity. Membrane cleaning usually also occurs intermittently by back-flushing with addition of appropriate chemicals. Bacterial regrowth was also observed on the permeate side of a submerged MBR during a pilot study in France and chlorine solution was recirculated on the permeate side of the membrane for 15 minutes once a week. The small amount of chlorine which permeated into the activated sludge tank had no visible effect on the biomass (Côté *et* al., 1997). The MBR should be designed and operated to minimize backwashing requirements and full automation of the backwashing process is desirable.

Most bench-scale and pilot-scale studies of the MBR process for treatment of domestic wastewater have occurred in Australia, Canada, Japan, France, the Netherlands, Poland, and the United States. A summary of the key operational parameters and the performance characteristics of these studies is provided in Table 3-l of the main report. Many of the MBRs investigated in these studies were bench-scale or small pilot-scale configurations assembled by the researchers. Therefore, some of the membrane modules and process configurations used may not be commercially available.

Comparative Performance of MBR and Conventional Suspended Growth Process

The MBR processes show removal of COD that is comparable to the removal rates observed for conventional suspended growth reactors, but the MBR shows enhanced performance for total nitrogen, total phosphorous, and organic suspensions. Very few parallel comparisons of the two processes have been performed and these results are not conclusive. No studies could be identified that directly compare the performance of the two different MBR configurations against the standard process used to pre-treat effluent prior to RO treatment for water reuse.

For the few studies we could find comparing the MBR process to the conventional activated sludge process, the comparison revealed increased turbulence and higher pressure in the MBR process which may affect the character of the biosolids. The activated sludge formed in the MBR had smaller floccules, more dispersed sludge, and no accompanying fauna, and it exhibited weak sedimentation capacity compared to the conventional system. While both systems exhibited similar stabilization times, there was a difference in the enzymatic activities of the two sludges indicating that decomposition of organic substances occurs faster in the MBR. Therefore, the improved performance from the MBR appears to be due to both the retention of impurities by the membrane and by the physiological state of the activated sludge. A study by Cicek *et* al., (1997) substantiated the different character of the MBR sludge (high in free swimming bacteria, production of small flocs, few filamentous or ciliate organisms, and no nematodes), but suggested potential difficulties in post treatment of MBR sludges due to measured resistance to vacuum filtration and poor sludge volume index test results. Manufacturers of submerged systems indicate that sludge recycle is maintained at a rate which produces a MLSS concentration of around 20,000 mg/L. Therefore, poorer settleability of the MBR sludge may be of small consequence if the plant typically operates at sludge disposal concentrations of 2%.

Another potential advantage of the MBR process is a reduction in sludge production. In a one-year French pilot study, the sludge production rate from a submerged MBR (0.25 kgSS/kgCOD removed) was about 50% less than the rate observed for an extended aeration activated sludge process (Côté *et* al., 1997). Low sludge production was corroborated by another French pilot study of an in-series MBR, which reported a sludge production rate of 0.23 kgSS/kgCOD removed (Urbain *et* al., 1993). This result was not substantiated by a parallel bench-top study of an MBR and an activated sludge process (Cicek *et* al., 1997). However, this study was performed at a very small scale using a non-submerged MBR and synthetic wastewater.

Comparative Performance of Membrane Modular Configuration and Composition

Few parallel studies have been performed directly comparing membrane modular configurations and membrane composition. Polysulfone membranes have lower initial permeability than cellulose membranes, and cellulose seems to give a higher flux with higher biomass concentrations. Polyvinylchloride (PVC) membranes with higher water permeability are characterized by smaller permeate flux than polyacrylonitrile (PAN) membranes due to structure characteristics of large macropores that are susceptible to pressure compaction.

Impacts of Temperature and Influent Quality on MBR Performance

Varying influent quality appears to have little impact on MBR performance for removal of BOD, COD, and TSS. As occurs with all activated sludge processes, removal is impacted by low temperatures < 13°C. Nitrification is slightly impacted by loading variations and removal decreases with the decrease of the BOD/T-N ratio. Complete nitrification is not achievable at low temperatures even at long SRT because other factors such as T-N/MLSS load ratio, NH,-N/MLSS load ratio, HRT and return ratio of nitrified liquid must also be optimized for nitrogen removal at low temperatures. Denitrification is dependent upon the inflow of raw sewage at the beginning of the anoxic period, the length of the aeration period, and the MLSS concentration.

Increases in reactor temperature have been reported with the use of in-series MBR processes due to the energy produced by the recirculation pump. Temperature increases were only reported for one submerged MBR process study which was unique in that the system was maintained under pressure as a means of preventing limiting oxygenation capacity within the reactor. To maintain the temperature of the reactor at a constant level, these systems employed a reactor cooling system.

Impact of Activated Sludge Characteristics on Membrane Fouling

No studies have systematically evaluated the impact of activated sludge characteristics on membrane performance. Changes in the MLSS concentration, sludge age, or sludge characteristics can be effected by varying the sludge return rate, the bioreactor temperature, or the type of pretreatment applied. Instead, much of the published research has focused on:

- verifying the effectiveness of the process under a specified set of conditions;
- demonstrating the robustness of the technology under a variety of loading rates:
- determining minimum backwash protocols needed to maintain system performance; and
- optimizing design criteria for aeration and membrane configurations.

Membrane performance is degraded by fouling which is caused by adsorption of organic species, precipitation of less soluble inorganic species, and adhesion of microbial cells at the membrane surface (Choo and Lee, 1996). The higher biomass concentration and smaller particle sizes found in MBRs are expected to reduce membrane permeability. However, there are still many unknowns regarding fouling mechanisms and how they relate to specific activated sludge quality characteristics.

Predictive Modeling of Permeate Flux from Sludge Conditions

Good correlation of permeate flux with the differential concentration of DOC in the influent and effluent of an MBR treating synthetic wastewater suggests that even with suspended solids, the gel polarization theory can be applied for the system. Prediction of permeate flux from a given sludge concentration at various BOD loadings showed promise, but needs further refinement. A model developed by the International Association on Water Pollution Research and Control (IAWPRC) task group on mathematical modeling for design and operation of biological wastewater treatment gave good prediction of effluent COD and TKN concentrations, but there was major disagreement with the MLVSS concentration. Studies performed with in-series MBRs have identified transmembrane pressure and crossflow velocity as the parameters governing filtration performance for a given concentration of suspended solids (Manem et *al.*, 1993). It was demonstrated that increasing cross-flow velocity leads to shorter production cycles, more cleaning operations, and no reduction in energy consumption (Urbain et al., 1994). Fane, 1996, states that economically viable fluxes are probably in the range of 1.2-2.4 m/day.

Impact of Aeration on Design and Operating Parameters for Submerged Reactors

Hollow fiber membranes are shaken by the uplifting airflow and the turbulence of this flow may impact the efficiency of the filtration process. Findings of Ueda, 1997, suggests that the cake-removing efficiency of the uplifting air was influenced by the turbulence of the flow, however, Shimzu, 1996, showed that the filtration flux of the hollow fiber membrane was not larger than that of the rigid membrane and so the improvement of flux caused by the vibration of membrane elements by turbulent flow of air bubbles may be small.

Ueda's findings are supported by the fact that jet aeration, using a series of air nozzles, improved the performance of the MBR by increasing permeate flux and reducing the HRT. If increasing aeration intensity is important for cake removal, it may be useful to increase aeration intensity by concentrating modules over a smaller floor area when designing a submerged MBR. Good agreement between measured and predicted cross-flow velocity as a function of superficial air velocity suggest that bioreactor height and total frictional resistance also appear to be key design parameters. Ueda's data suggest an air flow optimum value that should be considered to minimize power consumption. Reduction of the airflow rate below this value can result in a rapid increase in pressure that might not decrease to its former value when the airflow rate is restored to its previous value. Aeration without suction might also prove useful as an on-site membrane washing procedure. Operation of 2 pilot-scale submerged MBRs in France and the United States could be maintained with stable fluxes and operating pressures provided a 15 minute permeate backwash or a 15 minute chlorinated permeate recirculation was performed once a week.

Operationally, shorter aeration time requires shorter suction time which results in longer HRT under the same flux conditions. Excess sludge needs to be wasted at regular intervals to prevent accumulation of DOC in the aeration tank and an increase in sludge viscosity and suction pressure. The flexible properties of hollow fiber membrane elements were shown to cause crowding of elements that reduced the effective membrane surface area at high-rate filtration operation (high AP) or under low fluidity conditions such as high MLSS. A high density packing of hollow fiber membranes might not be optimum for wastewater where there are more particles and the packing density should be optimized to maintain effective use of membrane surface for activated sludge suspensions.

Operation of a pressurized submerged MBR has also been successfully piloted as a means of increasing oxygen transfer and preventing limiting oxygenation capacity within the reactor (Roncken, 1995). Utilizing this approach it was possible to transfer 2.5 kg $O_2/m^3 \bullet hour$.

Cost Benefit Analysis

Little cost information is available in the literature for the MBR process. The development of preliminary information was implemented under Task 4 of this project. This cost information should be validated with pilot study data. It appears that submerged systems reduce power consumption, but it is unclear whether this reduction approaches the consumption levels used by conventional suspended growth systems. Ueda et al., 1996, indicates an average power consumption of 2.0 kWh/m^3 of treated wastewater for a submerged MBR, about 3-4 kWh/m^3 for conventional cross-flow MBRs, and about 0.2-0.3 kWh/m^3 for a conventional activated sludge process, This differs from results reported by Côté, 1997, where the energy consumption required for filtration for two submerged MBR pilot was 0.30 kWh/m^3 of wastewater.

Chaize et al., 1991 states that re-circulation MBRs are not cost effective due to the high power consumption of the re-circulation pump and that the submerged MBR shows promise provided a balance between surface area, cost and energy input can be achieved. Manem et al., 1997 states that extensive research is in progress to overcome the high energy consumption required to operate the filtration unit at high TSS concentrations, and that second generation more intimately combined MBR processes could soon be developed.

SECTION 4

MBR VENDORS

The MBR process can be retrofitted to an existing activated sludge bioreactor or designed as a new installation. This survey focuses on vendors providing suspended growth MBR processes rather than membrane manufacturers of micro- and ultra-filtration membrane modules than can be coupled with existing activated sludge processes to provide an attached growth process.

A list of potential manufacturers was obtained from a 1992 proceedings paper (Huyard et al., 1992). This information has further been updated through communication with MBR manufacturers, and is summarized in Table 4-1 along with the current status of each manufacturer. More detailed information is then provided for those manufacturers still actively marketing the MBR process.

Table 4-l
Potential Manufacturers of MBR Processes

Trade Name	Company	country	wastewater	current status
MSTS	Dorr Oliver	USA	Domestic	No longer active
UBIS	Rhône Poulenc	France	Domestic	No longer active
ASMEX	Mitsui Petroc	Japan	Domestic, Industrial	No longer active
CYCLE-LET	Thetford Syst.	USA	Domestic	Acquired by Zenon
MEMBIO	Memtec	Australia	Domestic	Developing new product
BIOREM	Kubota	Japan	Domestic	Still active
STERAPORE	Mitsubishi Rayon	Japan	Industrial, Domestic	Still active
MARS	Dorr Oliver	USA	Industrial	No longer active
ADUF	Ross/Membratek	S. Africa	Maize factory	No longer active
BIOMEMBRAT	Wehrle Werk AG	Germany	Lixiviat	No longer active
ZENOGEM	Zenon Env. Inc.	Canada	Oil	Still active
BIOSEP	C.G.E.*	France	Domestic	Employs Zenon technology
BRM	Suez-LDE**/ Degremont Infilco	France	Domestic, Industrial	Still active

***C.G.E: Compagnie Générale des Eaux**
****Suez-LDE: Groupe Suez-Lyonnaise des Eaux**

(1) Zenon Environmental Inc., (CANADA).
ZenoGem®/ZeeWeed®
Cycle-Let@
BIOSEP®

ZenoGem® is the patented process that integrates a suspended growth activated sludge system(bioreactor) with a cross-flow membrane system (ZeeWeed® membranes). It was developed over the past 15 years and today there are over 100 installations treating sewage mostly in the US and Canada. The technology has been certified by the NSF, CA, CT, NJ, and other states for water recycle. To date, the largest existing MBR installation is 520,000 gpd (82,000 L/b). A 1.0 to 1.5 MGD (0.0435 to 0.0652 m^3/s) capacity plant is currently under construction in Arapahoe, Colorado.

ZeeWeed® are ultralow pressure, patented shell-less hollow fiber membranes with a nominal molecular weight cut-off of 200,000 daltons that allow any tank to become a ZenoGem® process. Facilities can be expanded by 3-6 times their original design loading without significant alterations to the existing civil works. The fibers are mounted on a frame, with permeate extraction from bottom and top headers. The membranes are continuously aerated at their base to renew the biomass to be filtered and to agitate the hollow fibers to minimize fouling. The hollow fibers can be backwashed with the permeate.

Cycle-Let@ was first developed by Thedford, Inc. to recycle flush water in remote locations. The process incorporated biological treatment, pressure-driven membrane filtration (tubular membranes), activated carbon and ultraviolet disinfection. The earlier system consisted of a cross-flow MBR, where the tubular membranes were placed after the biological reactor. The process has been purchased and patented by Zenon Municipal Systems (ZMS). Today, the Cycle-Let@ system is a modified ZenoGem® MBR system, which also incorporates vacuum-driven ZeeWeed® hollow fiber membranes, but is designed for unrestricted wastewater recycle use and long term sludge accumulation within the reactor.

BIOSEP®, which was developed by the Compagnie Générale des Eaux (CGE) Anjou Research Center, employs the Zenon MBR technology. This immersed membrane activated sludge process was applied to the treatment of raw sewage. It uses hollow fiber membranes (ZeeWeed®) or flat sheet membranes with a pore size between 0.1 um and 0.45 um. The common features of these MBRs are: (i) a direct immersion into the reactor where the biological treatment takes place, and (ii) an operation under an outside-inside filtration mode at a low transmembrane pressure (< 0.5 bar).

(2) Suez-Lvonnaise des Eaux /Deqrémont I SITA , (FRANCE)
BRM®

Aerobic and anaerobic MBR processes (BRM®) for industrial and municipal wastewater were first developed by the Centre International de Recherche *sur l'Eau* et l'Environnement (CIRSEE) in 1993. CIRSEE, which is operated by Suez-Lyonnaise des Eaux in collaboration with Degremont and FD Conseil, provide processes that use ceramic or organic membranes for ultra- or microfiltration (Beaubien, 1994). Infilco Degremont and SITA (subsidiaries of LDE) in collaboration with CIRSEE have developed and installed full-scale MBR processes to treat and recycle industrial and municipal wastewater and landfill leachate. Process applications have employed hollow fiber cellulosic (Aquasource) and ceramic membranes (Rhone-Poulenc).

(3) Mitsubishi Rayon Co. Ltd, (JAPAN)

STERAPORE™ L
STERAPORE™ F

Mitsubishi Rayon Co. is a manufacturer of Hollow-Fiber 0.1 pm Membrane Filters (HFF) for MBRs. Their patented HFF Sterapore-L&F tank-submerged type filter units have been used by municipal engineering companies for wastewater and water treatment since 1992.

Sterapore-L is a microfilter of a unique screen-like structure and is made of microporous hollow fiber membrane. This element does not need any pressure-resistant vessel. It has a unique screen-like configuration in which the HFF membrane is arrayed in the way of the screen, and in which both ends of the membranes are connected with pipes collecting treated water. The water flows outside of the hollow fibers and is then suctioned out of the pipes. The element is used in wastewater treatment applications. Typical dimensions of a wastewater treatment system would be 27 m^3 volume, 250 m^2 effective membrane surface area, and 27 m^3/day (7,133 gpd) capacity. Sterapore-L is mostly applied for industrial wastewater treatments in the range of 0.3 to 750 m^3/day (80 to 199,000 gpd) capacity.

Sterapore-F accentuates the special feature of HFF technology which can be used for compact filter design and is used in river water purification applications. Since Sterapore-F has a larger effective membrane surface area than the L module, and it can be easily scaled to a large capacity water treatment plant. Typical dimensions of a water purification system would be 50 m^3 volume, 100 m^2 effective membrane surface area and 50 m^3/day (13,210 gpd) capacity.

Both systems operate at pressures less than 30 kPa (4.35 psia), at pH ranges from 2 to 11, and at temperatures less than 40°C. Typical MLSS concentration is maintained between 8,000 and 15,000 mg/L.

(4) Kubota, (JAPAN)

BIOREM®
FILCERA®

Kubota Inc. has patented their submerged type ceramic membrane process, for treating domestic wastewaters, and today, eight wastewater treatment plants incorporating their MBRs are installed and operating in Japan. Two MBR systems, known as BIOREM® and FILCERA®, have been patented. These two are basically the same, but the difference lies in their application. One system (BIOREM) is intended for treating wastewaters, while the other (FILCERA) is intended for water purification. Both consist of a tank-submerged type membrane module, which brings together multiple external pressure tubular type ceramic membrane elements of an asymmetric two layer structure.

The BIOREM MBR system was developed 10 years ago, and the oldest system is still operating in good condition using the original ceramic membrane.

Retention time in the BIOREM reactor ranges from 6 to 8 hours, and is around 30 minutes in the FILCERA reactor. The MLSS concentration is greater than 10,000 mg/L.

(5) Memtec, (AUSTRALIA)
MEMBIO™

Membio (fixed-film bioreactor on anthracite) was tested, but the results showed that it was not better than conventional wastewater **treatment.** It is no longer manufactured, but they are testing other MBR configurations.

SECTION 5

MBR INSTALLATIONS

A survey questionnaire was created by Montgomery Watson, coveting all aspects of MBR technology, including qualitative, quantitative and cost issues. This survey was originally intended to be sent out world-wide to all the existing MBR plants. However, once communications were established with the MBR vendors, it was decided that the survey questionnaires be sent out to the main MBR manufacturers (i.e., Zenon Municipal Systems, Kubota Corporation, Mitsubishi Rayon Co. Ltd, and the Group Suez-Lyonnaise des Eaux/Degremont) who agreed to distribute the survey form among their clients or to complete directly the questionnaire, by April 10, 1998.

The following section is a general description of the existing world-wide MBR plants installed by the different manufacturers, Table 5-1, which follows the general description section, presents a selected list of some of these world-wide MBR installations having capacities of 50,000 gpd (7885 L/h) and greater.

Zenon Municipal Systems

There are over 100 MBR (ZenoGem® and Cycle-Let@) installations today.

ZenoGem® facilities are mainly found in Canada and the United States. Other installations are found in Europe (Italy, France, the Netherlands, and Belgium), North Africa (Egypt), and Central and Latin America (Puerto Rico, Mexico). The first ZenoGem® facility was built in 1991 in Mansfield, Ohio, to treat 60,000 gpm (9,462 L/h) of synthetic oils and greases produced by a metal fabrication industry. This facility is still successfully running today. The largest existing MBR facility, located in Ontario, Canada, has a 520,000 gpd (82,000 L/h) capacity, and was installed to treat municipal wastewater. Four major ZenoGem® facilities are currently under construction in Denver, Colorado, in British Columbia, Canada, and in two major cities of Egypt. Their capacities range from 0.66 to 2.0 MGD (0.029 to 0.087 m^3/s), and their application will be the treatment of municipal wastewater. Typical results include more than 98% reduction in BOD, COD, NH,, TSS, TKN, oil and grease and greater than 9-log removals of total and fecal bacteria.

Cycle-Let" installations have much smaller capacities than the ZenoGem® facilities. Capacities range from 388 to 20,000 gpd (61 to 3154 L/b), and their main purpose is the recycling of treated wastewater to reduce wastewater discharges in environmentally sensitive areas where sewers are not available or at capacities. Typical clients of the Cycle-Let" system include hotels, schools, hospitals, office buildings, shopping outlets, and recreational and residential developments. They are all found in the United States. Typical results include a 95% reduction in water use and wastewater discharge, and an effluent wastewater quality that meets the NJDEPS permit and the GWII discharge limitations.

CGE Anjou Research Center/Zenon

The CGE Anjou Research Center in Maisons-Laffitte (CRML), France has developed an immersed membrane activated sludge process (BIOSEP™), which incorporates modules of the hollow fiber ZW-150 Zenon ZeeWeed® membrane. One two-year pilot study was conducted, as well as full-scale evaluations of two waste water treatment plant upgrades of 237,780 gpd (37,500 L/h) capacity. The pilot study ran from 1995 to 1997. It showed total removal of particulate matter, with permeate values below detection level for suspended solids, and average turbidities of 0.24 NTU for CRML. Organic matter removal was very high, with total removal of BOD and COD values of 10 mg/L for CRML. A 99% ammonia removal was reached. Between 6 and 7 log removals of total coliform and more than a 3.8 log removal of bacteriophages were observed in the study.

Group Suez-Lyonnaise des Eaux I Degremont

Aerobic and anaerobic MBR processes (BRM") for industrial and municipal wastewater were first developed by the Centre International de Recherche sur l'Eau et l'Environnement (CIRSEE) in 1993. Nine BRM" installations currently exist in different parts of France, two of which have capacities greater than 100,000 gpd (15,770 L/h). Applications range from industrial to domestic wastewater treatment. The first BRM was installed at a cosmetic factory in northern France in 1993. It has a design capacity of 42,000 gpd (6,624 L/h) and 1,200 kg COD/day. Data from a preliminary 5-month pilot study demonstrated COD removal >98%, ammonia removal of 99%, and complete removal of TSS. Another pilot-scale study performed by Lyonnaise des Eaux was conducted at the municipal wastewater treatment plant of Aubergenville, France. At a SRT of 25 days and a HRT of 1 day, more than 95% of the influent COD, TKN, and BOD5 was removed.

Mitsubishi Rayon Co., Ltd

MBRs using STERAPORE were installed in Japan, China, the Philippines, and other areas across Asia. Applications of the process are found in domestic and industrial wastewaters. The pilot-study of Ueda, listed in Table 3-1, was performed using this technology.

A total of 185 MBRs are presently installed in Japan. These installations are found mainly in food, industrial, and domestic wastewater plants with the largest one having a capacity of 264,200 gpd (41,666 L/h). Typical results include more than 98% removals of BOD, and COD, and MLSS concentrations in the range of 5,000 to 15,000 mg/L.

Kubota Corporation

To date, eight domestic and municipal BIOREM" systems are installed and operating in Japan. Typical results include more than 95% BOD, COD and TSS removals. The first system was developed 10 years ago and is still running using the original ceramic membrane.

Table 5-1
Listing of Selected MBR Installations with Capacities< 50,000 GPD

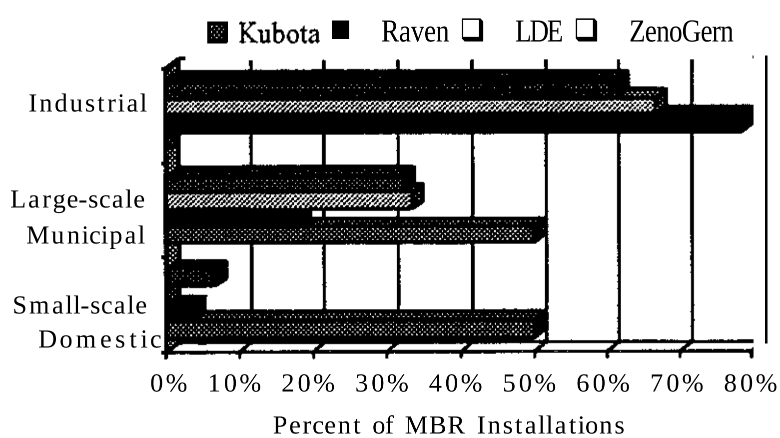
Location of Installation	Manufacturer	Application Field	Capacity (GPD)	Start-Up Year
France	Suez-LDE	Milk factory	211,260	02/97
France	Suez-LDE	Drinking Water	105,680	03/95
Pads, France	Suez-LDE	Municipal	486,129	100-day pilot
Chiba, Japan	Mitsubishi-Rayon	Industrial: needle plant wastewater	264,200	01/96
Ibaraki, Japan	Mitsubishi-Rayon	Industrial: food industry	52,840	1996
Xamaguchi, Japan	Mitsubishi-Rayon	Industrial: ice-cream factory	264,200	1996
Aichi, Japan	Mitsubishi-Rayon	Industrial: needle plant wastewater	198,150	1996
Ehime, Japan	Mitsubishi-Rayon	Industrial: confectionery factory	66,050	1996
Tokyo, Japan	Mitsubishi-Rayon	Hotel business: Regenerated water	19,260	1996
Chiba, Japan	Mitsubishi-Rayon	Office building: Regenerated water	121,532	1996
Gifu, Japan	Mitsubishi-Rayon	Industrial: beer brewery	92,470	1997
Kumamoto, Japan	Mitsubishi-Rayon	Industrial: beer brewery	92,470	1997
Shizuoka, Japan	Mitsubishi-Rayon	Industrial: beans paste plant	158,520	04/97
Aomori, Japan	Mitsubishi-Rayon	Industrial: seafood plant	52,840	03/97
Gifu, Japan	Mitsubishi-Rayon	Industrial: beer brewery	79,260	05/97
Kumamoto, Japan	Mitsubishi-Rayon	Industrial: beer brewery	79,260	05/97
Kagawa, Japan	Mitsubishi-Rayon	Industrial	79,260	03/97
Wakayama, Japan	Mitsubishi-Rayon	Industrial	221,929	03/98
Okinawa, Japan	Mitsubishi-Rayon	Industrial	118,890	06/98
France	CGE/Zenon	Municipal	237,780	1995-1996
B.C, Canada	Zenon	Recreational/domestic	200,000	11/96
B.C. Canada	Zenon	Municipal	134,000 200,000	1997:Phase II 1999:Phase III

Table 5-1
Listing of Selected MBR Installations with Capacities ≤ 50,000 GPD

Location of Installation	Manufacturer	Application Field.	Capacity (GPD)	Start-Up Year
Tecumseh, MI	Zenon	Industrial: ITT	60,000	n.a.
ON, Canada	Zenon	Municipal	260,000 to 520,000	06/97 One-year project
Denver, CO	Zenon	Municipal, WWTP	1,000,000 to 1,500,000	Currently under construction
Cairo, Egypt	Zenon	Municipal, WWTP	660,000 to 1,320,000	Currently under construction
Kaha, Egypt	Zenon	Municipal, WWTP	1,000,000 to 2,000,000	Currently under construction
Orascum, Egypt	Zenon	Municipal, WWTP Irrigation	265,000	Currently under construction
B.C, Canada	Zenon	Municipal, WWTP	1,000,000 to 2,000,000	Currently under construction
Mansfield, OH	Zenon	Industrial : GM	60,000	1991
ON, Canada	Zenon	Industrial: GM	230,000	end of 1994
Columbia, WA	Zenon	Industrial:beverage	120,000	n.a.
Puerto Rico	Zenon	Industrial:cosmetic	60,000	n.a.

n.a.: not available

Currently, the majority of the installed MBR systems are being used for the treatment of wastewater from the automotive, cosmetic, metal fabrication, food and beverage processing, landfill leachate, and other industries. Figure 5-l illustrates the distribution of MBR installations by treatment category.



Distribution of MBR Installations by Wastewater Type
Figure 5-l

SECTION 6

CONCLUSIONS AND RECOMMENDATIONS

The MBR process shows tremendous promise as a pre-treatment to RO for water reuse applications. While many bench-scale and pilot-scale studies have demonstrated the effectiveness of this process for a wide variety of applications (landfill leachate, drinking water, industrial wastewater, high rise building recycling, domestic wastewater) there have been no parallel studies of a submerged MBR, an in-line MBR, and conventional treatment prior to RO treatment for water reuse applications. Most of the existing water reuse installations are very small-scale and municipal wastewater MBR plants of 1 to 2 MGD (0.0435 to 0.087 m^3/s) capacity are currently under construction in Canada, the United States, and the Middle East.

This demonstrates the need for a pilot-scale study to fully investigate the performance characteristics and robustness of the MBR processes under real-world working conditions. In the early 1990's microfiltration and ultrafiltration were emerging technologies which showed tremendous potential for water reuse and water treatment applications. Our experience with the implementation of MF and UF demonstrated that emerging technologies tend to remain tied to small-scale applications until an initial pilot demonstration and subsequent large-scale implementation enable the technology to gain widespread acceptance. The MBR process is today, where MF and UF were in 1990. It has been tested and proven in small-scale studies and installations. Wide-scale acceptance and use of the process still awaits the performance of a definitive study which demonstrates the effectiveness of the treatment to the satisfaction of regulators and constituents.

REFERENCES

Beaubien, Andre, Trouve, Emmanuel, Urbain, Vincent, Aman, Didier, and Manem, Jacques. 1994. Membrane Bioreactors Offer New Solution to Old Wastewater Treatment Problems. Environmental Solutions, December.

Behmann, H., Mourato D. and Wingfield, H., T. 1996. Upgrade of Municipal Wastewater Treatment Plants. Literature provided by Zenon Environmental Inc. on November 4, 1996.

Bodzek, Michal, Debkowska, Zuzanna, Lobos, Ewa and Konieczny, Krystyna. 1996. Biomembrane Wastewater Treatment by Activated Sludge Method. Desalination, 107:83-95.

Chaize, S., and Huyard, A. 1991. Membrane Bioreactor On Domestic Wastewater Treatment Sludge Production and Modeling Approach. Wat. Sci. Tech., 23:1591-1600.

Chiemchaisri, C., Yamamoto, K. and Vigneswaran S. 1993. Household Membrane Bioreactor in Domestic Wastewater Treatment. Wat. Sci. Tech. 27:1:171-178.

Choo, K-H. And Lee, C-H. 1996. Membrane Fouling Mechanisms in the Membrane-Coupled Anaerobic Bioreactor. Wat. Res. 30:8:1771-1780.

Çiçek, N., Franco, J., and Suidan, M. 1997. Characterization and Comparison of a Membrane Bioreactor and a Conventional Sludge System in the Treatment of Wastewater Containing High Molecular Weight Compounds. Obtained directly from Nazim Çiçek.

Côte, P., Buisson, H., Pound, C., and Arakaki, G. 1997. Immersed Membrane Activated Sludge for the Reuse of Municipal Wastewater. Desalination 113: 189-196.

Fan, Xiao-Jun, Urbain, Vincent, Yi Qian, and Manem, Jacques. 1996. Nitrification and Mass Balance with a Membrane Bioreactor For Municipal Wastewater Treatment. Wat. Sci. Tech. 34:1-2:129-136.

Fane, A.G. 1996. Membranes for Water Production and Water Reuse. Desalination 106 :l-9.

Husain, H. and Mourato, Diana. 1996. Application of Membrane Bioreactor Technology For Industrial and Municipal Wastewater Treatment. Presented at the 1996 Air and Waste Management Association Conference, Nashville, TN.

Huyard, A., Trouve, E., and Manem, J. 1992. Recent Advances on Membrane Bioreactors Applications to Water and Wastewater Treatment. Proc. Euromembrane Interfiltra. Conf., Paris 6(21):189-193.

Ishiguro, K., Imai, K. and Sawada, S. 1994. Effects Of Biological Treatment Conditions On Permeate Flux of UF Membrane in a Membrane/Activated-Sludge Wastewater Treatment System. Desalination, 98:119-126.

Kimura, S. 1991. Japan's Aqua Renaissance '90 Project. Wat. Sci. Tech., 23: 1573-1582.

Kishino, H., Ishida, H., Iwabu, H. and Nakano, I. 1996. Domestic Wastewater Reuse Using a Submerged Membrane Bioreactor. Desalination, 106: 115-l 19.

Manem, J., Trouve, E., Huyard, A., Urbain, V., and Beaubien, A. 1997. Membrane Bioreactor For Urban and Industrial Waste-Water Treatment: Recent Advances. Obtained directly from Jacques Manem.

Roncken, G.C.G. and Dijk, L. van 1995. Application of the Membrane-Bioreactor for the Treatment of Highly Concentrated Wastewaters. IAWQ Yearbook 1995-96:46-48.

Shimizu, Yasutoshi, Okuno, Yu-Ichi, Uryu, Katsushi, Ohtsubo, Sadami and Watanabe, Atsuo. 1996. Filtration Characteristics of Hollow Fiber Microfiltration Membranes Used In Membrane Bioreactor For Domestic Wastewater Treatment. Wat. Res., 30:10:2385-2392.

Smith, Clifford V. Jr., Gregorio, David Di., Talcott, Robert M. and Oliver, Dorr. The Use of Ultrafiltration Membranes for Activated Sludge Separation.

Trouve, E., Urbain, V., and Manem, J. 1994. Treatment of Municipal Wastewater by a Membrane Bioreactor: Results of a Semi-Industrial Pilot-Scale Study. Wat. Sci. Tech., 30:4:151-157.

Ueda, Tatsuki, Hata, Kenji, Kikuoka, Yasuto and Seino, Osamu. 1997. Effects of Aeration on Suction Pressure In a Submerged Membrane Bioreactor. Wat. Res., 31:3:489-494.

Ueda, T., Hata, K., and Kikuoka, Y. 1996. Wat. Sci. Tech., 34:9:189-196.

Urbain, Vincent, Benoit, Raymond, and Manem, Jacques. 1996. Membrane Bioreactor: A New Treatment Tool, Journal AWWA, 88:5:75-86.

Vera, L., Villarroel-López, R., Delgado, S., and Elmaleh, S. 1997. Cross-flow Microfiltration of Biologically Treated Wastewater. Desalination 114:65-75.

Appendix B

BUREAU OF RECLAMATION / CITY OF SAN DIEGO
Membrane Bioreactor (MBR) Plant Survey Questionnaire

Please complete this questionnaire in its entirety. If certain information and/or data are not available, indicate by writing "No Data". If a question does not apply to your treatment facility, please mark "N/A" for not applicable in the space provided. For questions that may require more space than is provided, please use a separate sheet of paper. Handwritten responses are preferred to avoid transcription errors during typing. Please include units of measurement where requested. Please return the questionnaire by April 10, 1998, by mail or fax (626-568-6323) to:

Dr. Samer Adham
Montgomery Watson
250 North Madison Avenue
Pasadena, California 91101-7009
United States of America

Should you have any questions regarding this questionnaire, please contact Dr. Adham at 626-568-6751 (voice), 626-568-6323 (fax), or by email at Samer.Adham@us.mw.com.

I. BACKGROUND INFORMATION

Name of Utility: ....

Address of Utility:

....

....

....

Contact person:

Name ....

Title ....

Telephone .... voice .... fax

E-Mail ....

Average daily MBR plant flow (specify units): ....

Wastewater type (percent each type): ...... domestic ...... industrial

Name and address of the MBR plant (if different than utility name and address):

....

....

....

II MEMBRANE BIOREACTOR PLANT INFORMATION

1. Plant startup date: (month and year)
2. Design hydraulic capacity of plant: (specify wits)
3. MBR used as pretreatment to reverse osmosis (check one): yes no
4. Membrane information:

   Membrane module (check one): submerged non-submerged

Membrane manufacturer: ....

Membrane configuration (check one): ...... hollow fiber tubular spiral wound other

Number of elements: ....

Effective surface area per element: (specify units)

Membrane material (if known):

Nominal molecular weight cutoff and/or pore size: (specify units)

Fiber diameter (where appropriate): (specify units)

Flow direction (where appropriate, check one) inside/out outside/in

5. Bioreactor information:

Bioreactor hydraulics (check one): completely mired plug flow

Bioreactor volume: (specie units)

Bioreactor shape and dimension:

Please draw or attach schematic representation of bioreactor shape and dimensions (including units)

Bioreactor aeration (check one): .... porous diffuser .... jet aerator

other (specify) ....

III MEMBRANE OPERATIONAL INFORMATION (Typical values, over last 12 months of operation)

SUBMERGED AND NON-SUBMERGED MEMBRANES

Average transmembrane flux rate: .... (specify units) at (reference temperature & units)

2. Backwash parameters:

Backwash conducted using (check one): liquid air

Backwash duration: .... (specify units)

Backwash frequency: (specify units)

Backwash volume : .... (specify units)

Backwash chlorinated: yes no

if yes, backwash free chlorine (mg/L), and combined chlorine (mg/L)

SUBMERGED AND NON-SUBMERGED MEMBRANES (continued)

3. Chemical cleaning of membranes:

Cleaning frequency: number per year

Chemicals employed Typical dosage

Example: Sodium Hydroxide .. *10 mg/L*

.... (specify units)

(specify units)

.... (specify units)

SUBMERGED MEMBRANES ONLY		
Average suction vacuum:	(specify units)	
Average suction cycle frequency:	time on (units)	time off (specify units)

NON-SUBMERGED MEMBRANES ONLY		
1. Average cross-flow velocity (where applicable):	(specify	units)
2. Average transmembrane pressure:	(specify units)	

IV BIOREACTOR OPERATIONAL INFORMATION

Parameter	Unit (please specify)	Monthly Average Value	Monthly Minimum Value	Monthly Maximum Value
Influent flow				
Loading rate (F/M)				
Hydraulic retention time				
Sludge age				
Sludge production (dry)				
Aeration rate (when operating)				

Aeration mode (check one): .... continuous .... intermittent

if intermittent, percentage of time aeration is on: .... percent

Oxygen source: .... air .... pure oxygen

Mechanical mixing (check one: .... yes .... no

Additional nutrient addition: .... yes .... no

if yes, nutrient type ....

if yes, nutrient dose .... (specify units, i.e. mg/L)

V. WATER QUALITY INFORMATION

Use average monthly values where available, for most recent 12 month period

1. BIOREACTOR INFLUENT WATER QUALITY

BIOREACTOR INFLUENT WATER QUALITY				
Parameter	**Unit (please specify)**	**Monthly Average Value**	**Monthly Minimum Value**	**Monthly Maximum Value**
Biological oxygen demand (BOD)				
Chemical oxygen demand (COD)				
Total organic carbon				
Total nitrogen				
Ammonia nitrogen				
Total phosphorus				
pH				

BIOREACTOR INFLUENT WATER QUALITY (continued)				
Parameter	**Unit (please specify)**	**Monthly Average Value**	**Monthly Minimum Value**	**Monthy Maximum Value**
Temperature				
Total suspended solids (TSS)				
Total dissolved solids (TDS)				
Turbidity				
Alkalinity				
Total coliform bacteria				

2. BIOREACTOR WATER QUALITY

BIOREACTOR WATER QUALITY				
Parameter	**Unit (please specify)**	**Monthly Average Value**	**Monthly Minimum Value**	**Monthly Maximum Value**
Mixed liquor suspended solids (MLSS)				
Mixed liquor volatile suspended solids (MLVSS)				
Dissolved oxygen (DO)				

3 MEMBRANE EFFLUENT WATER QUALTIY

MEMBRANE EFFLUENT WATER QUALITY				
Parameter	**Unit (please specify)**	**Monthly Average Value**	**Monthly Minimum Value**	**Monthly Maximum Value**
Biological oxygen demand (BOD)				
Chemical oxygen demand (COD)				
Total organic carbon				
Total nitrogen				
Ammonia nitrogen				
Total phosphorus				
pH				
Temperature				
Total suspended solids (TSS)				
Total dissolved solids				
Turbidity				
Alkalinity				
Total coliform bacteria *				

* before disinfectant addition

VI. COSTS

1 Is this a new plant or retrofit of an existing plant? (check one) . . . . . . new plant . . . .
retrofit of existing plant

2 Capital costs (please specify currency):

Membrane system cost . . . . (specify currency)

Total plant cost . . . . (specify currency)

(Do not include land acquisition, engineering, site development, or source water development)

3 Membrane module replacement cost (cost per module): . . . . (specify currency)

4 Operation and maintenance (O&M) costs (please specify currency and membrane effluent volume unit):

Example: *$ 100 U.S. / 1000 U.S. gallons*

O&M costs:	labor	(specify units) and, ...	man-hr/unit vol
(last 12 months)	energy-aeration	(specify units) and, ...	kw-hr/unit vol
	energy-pump	(specify units) and, ...	kw-hr/unit vol
	replacement parts	. . . .	(specify units)
	sludge disposal	. . . .	(specify units)
	miscellaneous	. . . .	(specify units)
	chemical	. . . .	(specify units)

VII. SATISFACTION

Please indicate your level of satisfaction with the MBR process with respect to:

1. Membrane system reliability (check one):

. . . . very satisfied . . . . satisfied . . . . somewhat dissatisfied d i s s a t i s f i e d

2. Ease of operations of membrane system (check one):

very satisfied s a t i s f i e d somewhat dissatisfied d i s s a t i s f i e d

VIII. DATE QUESTIONAIRE COMPLETED:

Appendix C

APPENDIX C

DETAILED COST ANALYSIS

Table C-l
Capital Costs for MBR, Oxidation Ditch and Conventional Activated Sludge Based on 1 MGD plant Design: *Wastewater treated to pre-RO qualify*

Zenon MBR		Oxidation Ditch		Conventional Activated Sludge	
Process/ Equipment	Capital Costs	Process/ Equipment	Capital Costs	Process/ Equipment	Capital Costs
Headworks: mech. bar screen; grit chamber; pumps	$650,000	Headworks: mech. bar screen: grit chamber; pumps	$650.000	Headworks: mech. bar screen; grit chamber; pumps	$650,000
Headworks: rotating screen- 3 mm: channel to aeration tanks	$500,000	Oxidation Ditch; Secondary clarifiers; RAS/WAS P.S.	$1,750,000	Primary clarification	$625,000
MBR: MF modules; pumps; blowers: CIP tanks; Elec controls & panels; misc. valves	$1,575,600	Chemical addition	$15,000	Secondary treatment: aeration basin; clarifiers: RAS/WAS P.S.	$1,340,000
Bioreactor tank (49' x 49' x 17.5')	$250,000	Flash Mix Pump	$60,000	Chemical addition	$15,000
Concrete slab	$30.000	MF Modular Units	$1,000,000	Flash Mix Pump	$60,000
				MF Modular Units	$1,000,000
Subtotal	**$3,005,600**		**$3,475,000**		**$3,690,000**
Site Work (8 - 10%)	$240,400		$347,500		$369,000
Yard Piping (7 - 10 %)	$210,400		$347,500		$369,000
Electrical/Instrumentation (10 – 14%)	$420,800		$486,500		$5 16,600
Installation (22%)	$346,600				
Subtotal	**$4,223,900**		**$4,656,500**		**$4,944,600**
Contingency (20%)	$844,800		$931,300		$988,920
Total **Construction**	**$5,068,600**		**$5,587,800**		**$5,933,520**

Table C-2
O&M Costs for MBR, Oxidation Ditch and Conventional Activated Sludge
Based on 1 MGD plant Design: *Wastewater treated to pre-RO qualify*

Zenon MBR		Oxidation Ditch		Conventional Activated Sludge	
O&M Item	**O&M costs**	**O&M Item**	**O&M Costs**	**O&M Rem**	**O&M costs**
Personnel [1a]	$58,000	Personnel [2a]	$58,000	Personnel [3a]	$54,000
Supervision-administration [1a]	$21,000	Supervision-administration [2a]	$21,000	Supervision-administration [3a]	$21,000
Power [1b]	$95,000	Power [2a]	$78,000	Power””	$35,000
spare parts-replacement (includes MBR membranes) [1c]	$90,000	Spare parts-replacement [2a]	$44,000	spare parts-replacement [3a]	$46,000
chemicals”“’	$3,000	Chemicals’“’	$3,000	Chemicals [3a]	$3,000
		MF Modules		*MF Modules*	
		O&M (incl power) [2b]	$73,000	O&M (incl power) [3b]	$73,000
		Replacement parts [2c]	$30,000	Replacement parts [3c]	$30,000
Total per yr	$267,000		$307,000		$262,000

la From *The Cost* **of** *Wastewater Reclamation* in *California,* Nov 1992, D. Richard, T. Asano, G. Tchobnglous

lb Per Zenon, power @ for 0.06/kw hr for MBR = $76,000. Power for other equipment

lc Membrane replacement costs are $500,000/10 yr. $1,000,000/20 = $50,000/yr plus $40,000 for other spare parts

2a From *The Cost* **of** *Wastewater Reclamation in California,* Nov 1992, D. Richard, T. Asano, G. Tchobnglous

2b Per Memcor, O&M costs are $0.20/1000 gal treated

2c Memcor membranes require replacement every 5 yrs. $150,000/5yrs = $30,000/ yr over 20 yrs

3a From The Cost *of Wastewater Reclamation in California,* Nov 1992, D. Richard, T. Asano, G. Tchobnglous

3b Per Memcor, O&M costs are $0.20/1000 gal treated

3c Memcor membranes require replacement every 5 yrs. $150,000/5yrs = $30,000/ yr over 20 yrs

Appendix D

APPENDIX D

FACILITIES AND EQUIPMENT INFORMATION

The proposed site for the MBR pilot evaluation (Phase II) is at the Aqua 2000 Research Center located at the San Pasqual Aquatic Treatment Facility in Escondido, California. This pilot site provides an excellent location for the pilot study since it is already connected to a wastewater source typical for the City of San Diego and is equipped with many auxiliary systems that would be necessary for the study. The main pilot equipment that would be required for the proposed pilot testing is MBR pilot units. Below is a list of the facilities and equipment that are currently available at the proposed pilot site.

D.l STRUCTURAL

- 5000 square foot concrete pad.
- Semi-permanent shading to protect from sunlight.
- Wastewater connections after primary treatment.
- Potable water connections.
- Drainage system.
- Chemical containment area.
- Sufficient lighting for 24-hour operation.
- Full electrical supply.
- Chemical safety shower and eyewash.
- An operations trailer with conference room, offices, and computers
- A laboratory trailer for on-site water quality analyses.

D.2 INSTRUMENTATION/EQUIPMENT

Laboratory

- DR 4000 Spectrophotometer by Hach
- Ratio/non-ratio 2100N Turbidimeter by Hach
- pH/Temperature meter by Fisher (No. 13-635-BAA)
- Portable conductivity meter by Fisher (No. 09-327-f)
- Two TOC Analyzers (Sievers Model No. 800)
- SDI Filter Plugging Analyzer by Chemetek (No. FPR-3300)

Concrete Pad

- Package Plate Settler System
- Monomedia Tertiary Filter (125 gpm)
- Reverse Osmosis Skid with 6 pressure vessels, instrumentation, conductivity probes, high pressure boost pumps, and low pressure transfer pumps.
- Feed, permeate, backwash, and waste storage tanks.

- Chemical Cleaning Skid with hot water supply.
- Chemical Feed Systems.
- Micro 2000 On-line Chlorine Analyzer.
- Three 172OC On-line Hach Turbidimeters.
- Transfer pump (100 gpm) to provide secondary water to tertiary system.
- Transfer pump (100 gpm) to provide tertiary water to concrete pad.

Appendix E

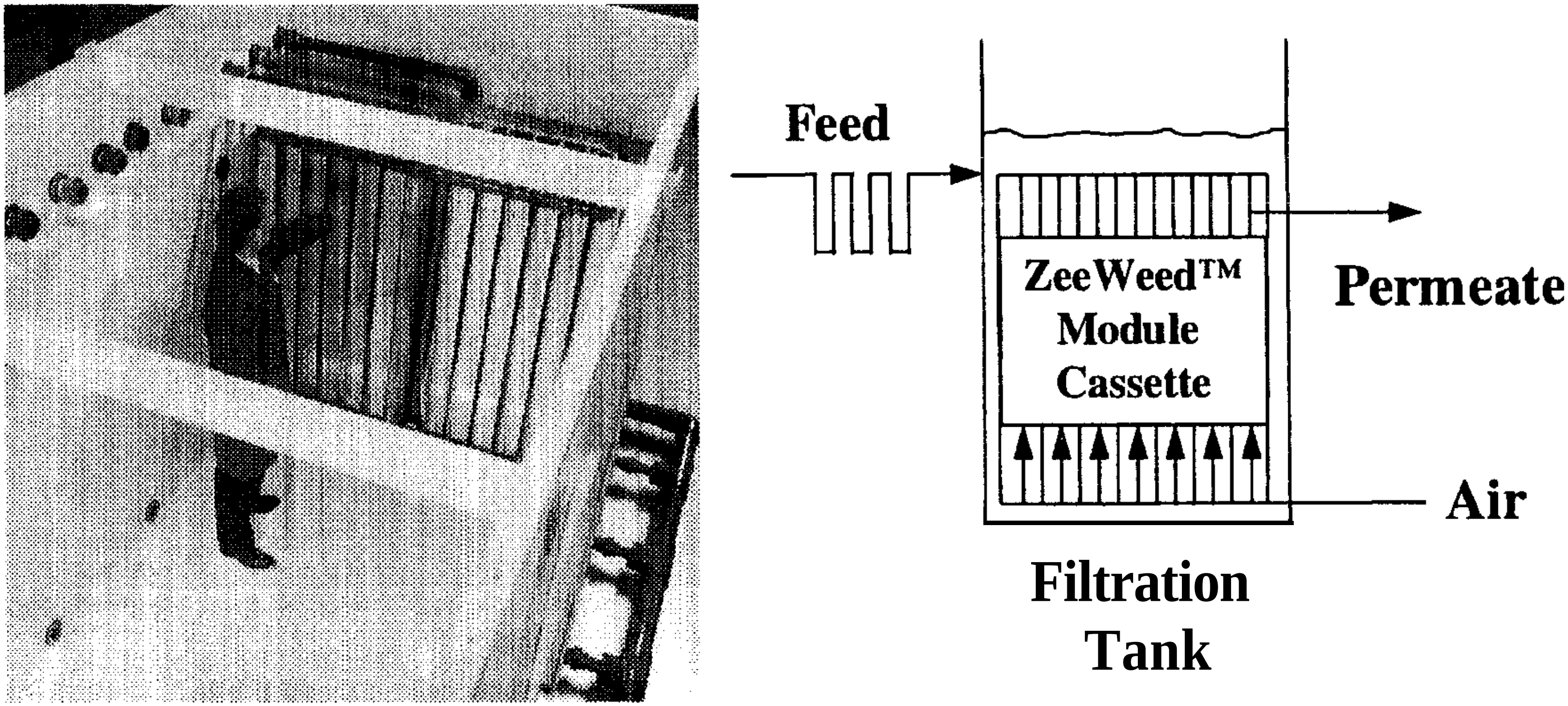
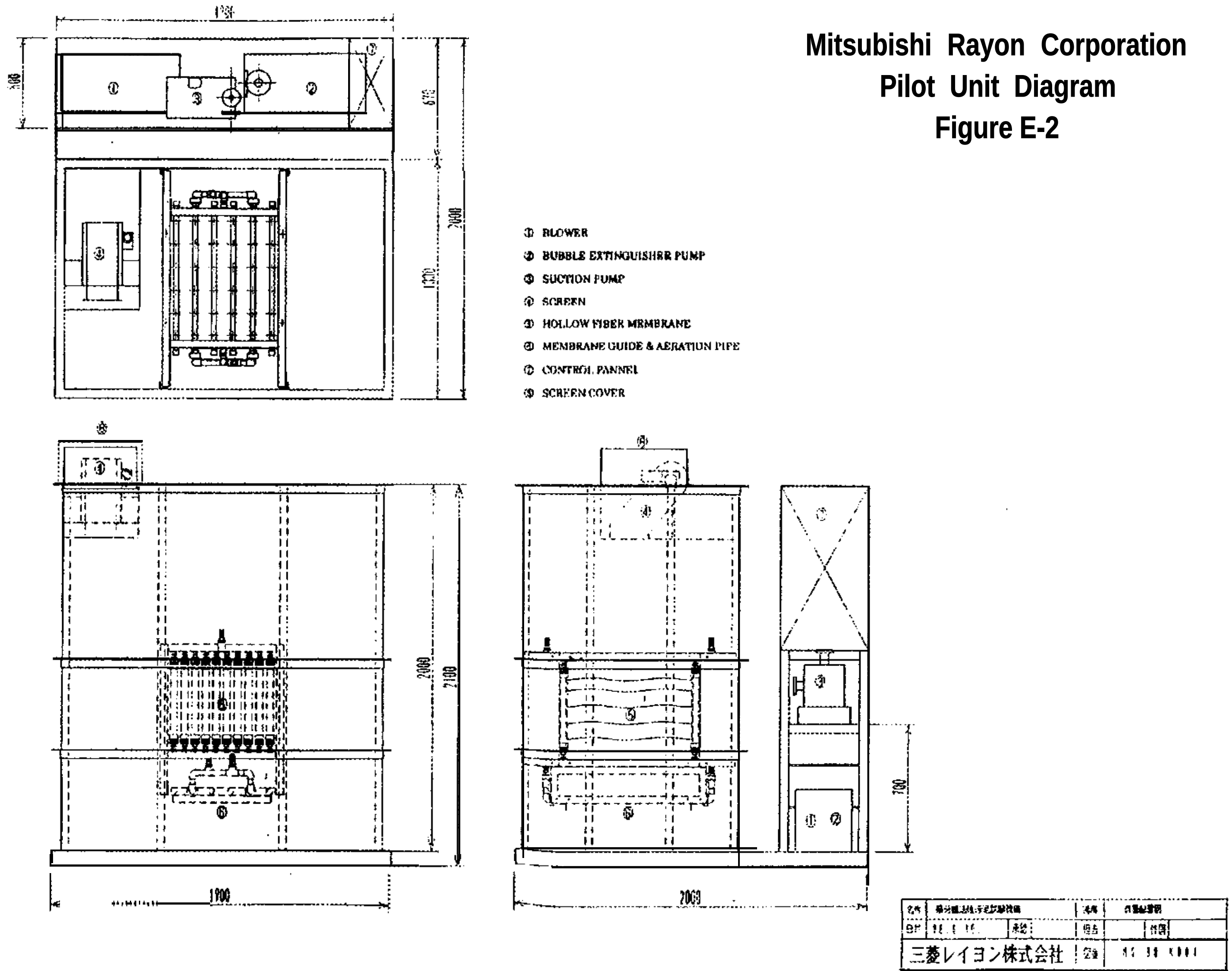
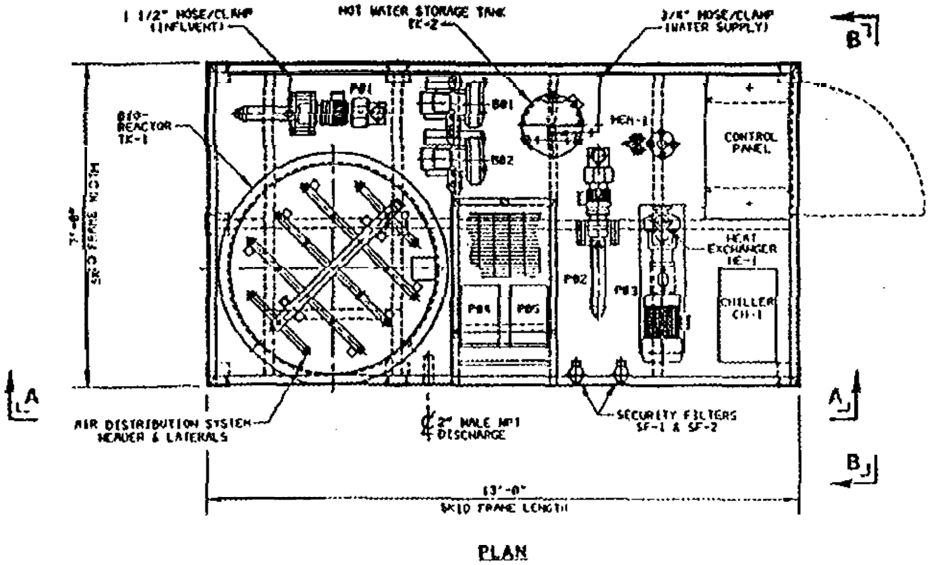


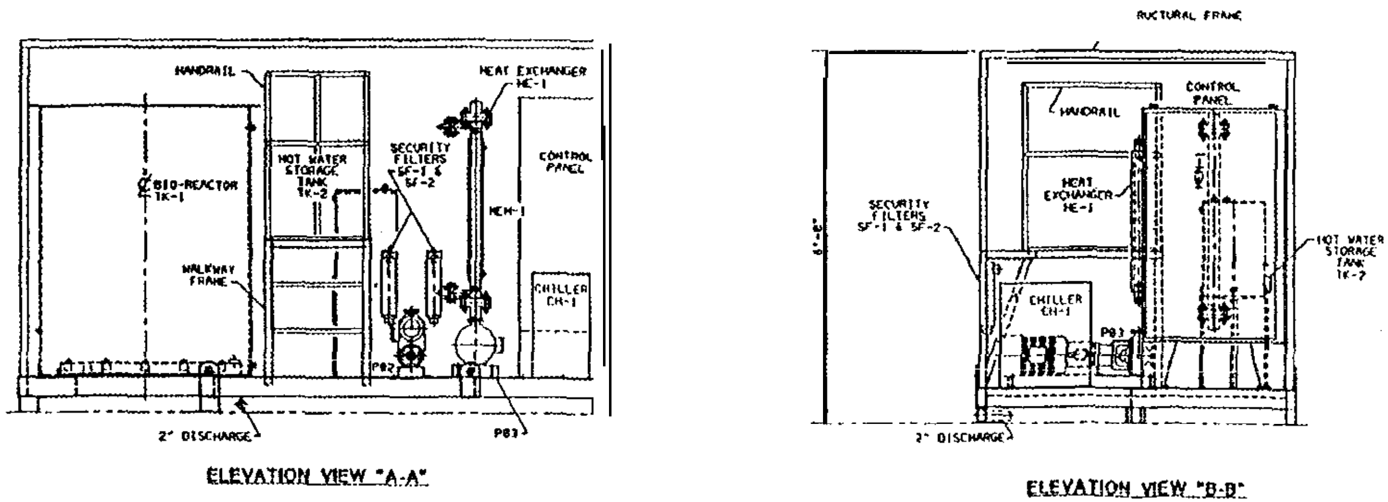
Figure E-l
Zenon Pilot Unit Diagram

Mitsubishi Rayon Corporation
Pilot Unit Diagram
Figure E-2



Infilco Degremont, Inc.
Pilot Unit Diagram
Figure E-3A





Infilco Degremont, Inc.
Plumbing Details
Figure E-3B