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Membranes for water production and wastewater reuse

A.G. Fane

UNESCO Centre for Membrane Science and Technology, University of New South Wales, POB 1, Sydney 2052, Australia; Tel. +61 (2) 697-2222; Fax +61 (2) 662-1923

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Abstract

Membrane technology has a major role to play in the water industry, and there is a growing interest in this area. The membrane option is well established for desalination and is being actively evaluated for water treatment, secondary treatment, disinfection and water reuse. Hybrid processes based on MF and UF could be of special interest.

Keywords: Membranes; Wastewater reuse; Microfiltration; Ultrafiltration

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1. Introduction

The availability of good quality water is vital to mankind. Our requirements range from irrigation waters, process cooling waters, boiler feed water, drinking water to ultrapure water with minimal contaminants. In all but the case of irrigation water we have to purify a contaminated water resource before use. Membrane technology is finding increasing application in the water industry, and this paper attempts to briefly review where the membrane processes are applied. It also looks at some developments in membrane technology that are of potential interest to the water industry.

2. The membrane family

The membrane family is large and continues to grow. Tables 1a and 1b depict the range of processes in terms of typical contaminant removal. The processes can be categorized as follows:

1. *Pressure-driven* (MF, UF, NF, RO) — where the water passes through the membrane and contaminants are removed by various mechanisms depending on pore size.
2. *Solute-transfer* (ED, D, LM) — where the contaminant solute is removed through the membrane by electrochemical, diffusive or preferential solubility effects.
3. *Thermal* (MD, PV) — where liquid water undergoes phase change as it passes through the membrane and this requires a heated feed.
4. *Hybrid* — where one or more membrane process is coupled with another unit process such as adsorption, ion exchange, coagulation, bioconversion, catalysis, etc.

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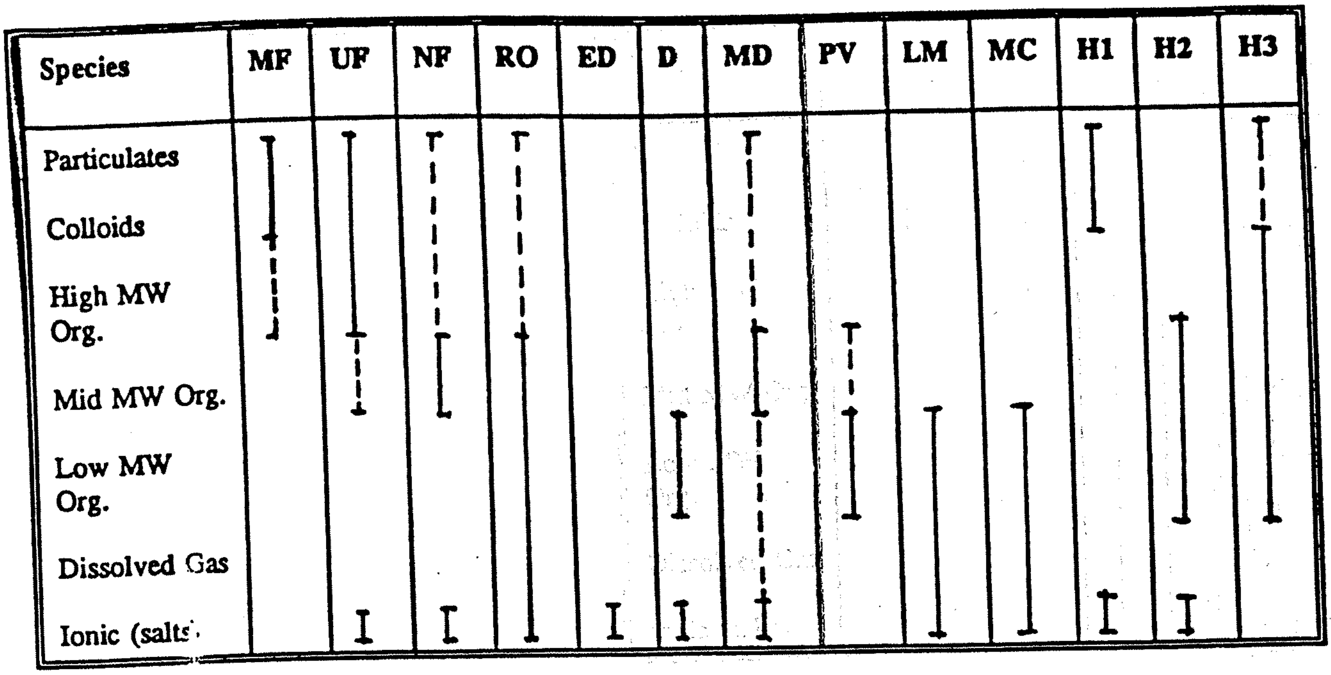
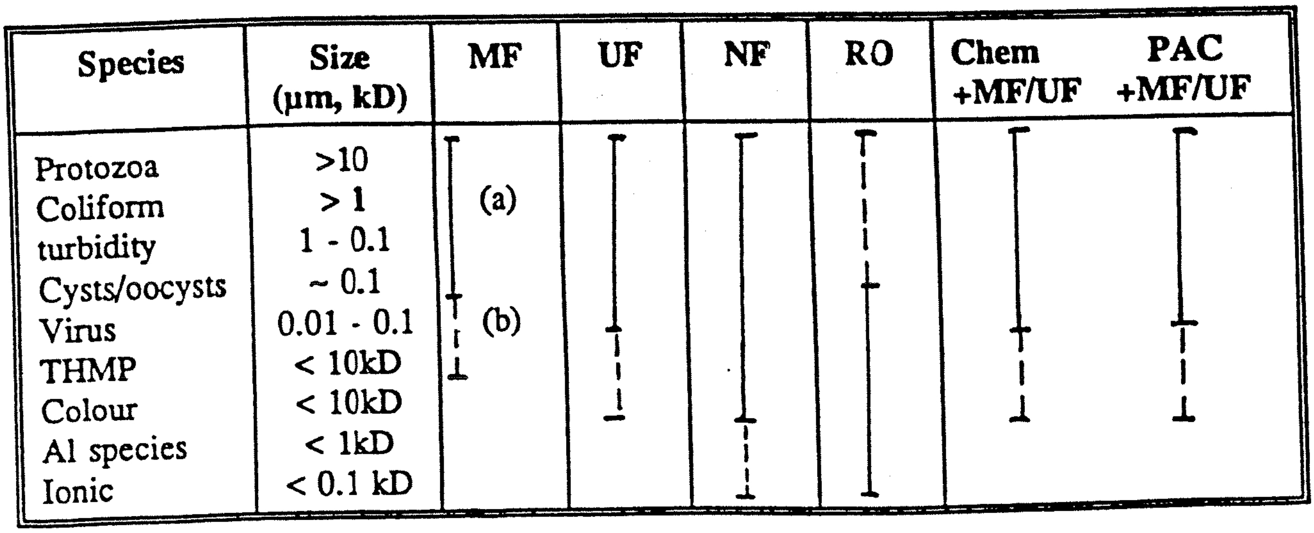
Table 1a
Membrane applications by contaminant type



D, dialysis; ED, electrodialysis, H1, Chem+MF/UF; H2, Ads+MF/UF; H3, Biol+MF/UF; LM, liquid membrane; MC, membrane contactcr; MD, membrane distillation; NF, nanofiltration; PV, pervaporation; RO, reverse osmosis; UF, ultrafiltration.

Table 1b
Membrane applications for water treatment by contaminant type



(a) near complete removal; (b) possible removal.

The growing interest in membrane technology in the water industry is based on the following:

- the potential for improved removal efficiencies compared with conventional technology,
- the suitability to small systems and distributed locations, the ease of system upgrading,
- the steady reduction in membrane processing costs (capital and operating).

Constraints to implementation include:

- uncertainties about economic performance,
- uncertainties about productivity (fouling) and product quality (species removal).

3. Strategies for water processing

Fig. 1 depicts in simple terms strategies in the production, use and recycle of water. In summary:

Strategy 1. Clean-up technology applied to a contaminated resource such as seawater, surface water or ground water. This includes desalination, water treatment and contaminated site remediation.

Strategy 2. End-of-pipe clean-up applied to process effluents. In these cases contaminants and water can be recovered for recycle or reuse if appropriate.

Strategy 3. Integrated treatment whereby separation techniques are used within the process to minimize waste or energy and improve yield.

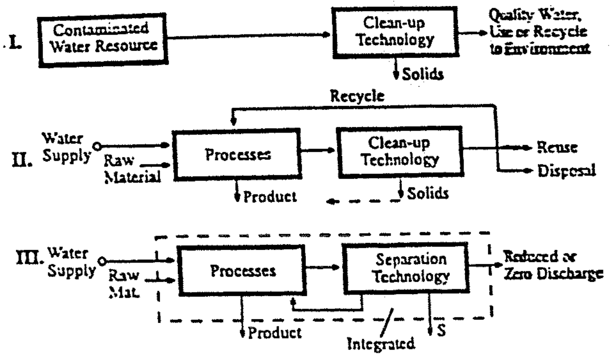


Fig. 1. Strategies for water processing.

This approach embraces the concept of cleaner production.

Membrane technologies are being applied to these water processing strategies as part of the clean-up technology or the separation process.

4. Applications to water processing

Developments in the use of membranes in desalination, water treatment, water reuse and effluent monitoring are discussed briefly below.

4.1. Desalination

Membrane processes, mainly RO (33%) with some ED (6%) now provide almost 40% of desalting capacity worldwide. RO appears to be steadily growing whereas thermal processes are declining [1]. Thus approximately 5 million m^3 of water pass through RO membranes every day to produce drinking water. Recent figures [1] suggest that desalination costs of about US $1/$m^3$ are feasible with seawater RO. In Australia it is estimated that there are 1000 RO desalination plants, although most of these are small. Trends in desalination suggest that areas of development may occur in

- improved membrane materials to give chemical robustness, particularly chlorine resistance,
- fouling resistance, particularly controlling biofouling,
- improved pretreatment, probably using MF or UF membranes, and
- further cost reductions via larger modules, reduced energy usage and energy recovery.

4.2. Water treatment

Table 2 presents several membrane options for the treatment of raw water through to treatment of sewage to a reusable standard. These applications provide huge opportunities for the membrane community with worldwide expenditure of >$10 billion/y projected over the next two decades [2].

Table 2
Conventional and membrane options for municipal water and wastewater treatment

RAW WATER						
REMOVAL	**CONVENTIONAL**	**MEMBRANE OPTION**				
	Filtration	**MF**	**UF**	**NF/RO**	**PV**	**HYBRID**
SS/Turbidity	x	x	x	-	-	MF + Chem
THMP	(x)	(x)	x	x	(x)	MF + Chem/AC
Colour	(x)	-	(x)	x	-	MF + Chem/AC
Metals	-	-	-	x	-	MF + UF + Chem
Nitrate	-	-	-	x	-	MF/UF + IX
Org-Micropollutant	-	-	(x)	x	x	MF/UF + AC
	Disinfection					
Bacteria	x	x	x	x	-	
Virus	x	(x)	x	x	-	MF + Chem
SEWAGE						
	Primary					
SS	(x)	(x)	-	-	-	-
BOD	(x)	(x)	-	-	-	-
	Secondary	-	-	-	-	
SS	(x)	-	-	-	-	Bio + MF/UF
BOD	x	-	-	-	-	
N	(x)					
	Tertiary					
SS	x	x	x	-	-	MF + Chem
N	x	-	-	(x)	-	
P	x	(x)	(x)	(x)	-	MF/UF + Chem
Inorganics	-	-	-	x	-	MF/UF + IX
Organics	-	-	-	x	-	MF/UF + AC
Bacteria	x	x	x	x	-	
Virus	x	(x)	x	x	-	MF + Chem
REUSE						

AC=Activated Carbon, Bio=Bioreactor, Chem=Chemical Addition, IX=Ion Exchange.

In water treatment conventional processes including screening, sand filtration and disinfection will give limited to zero removal of species such as THMP, colour, metals, nitrates or organic micropollutants. Membrane processes can be selected to remove any of these contaminants.

The choice of MF, UF, NF or low pressure RO is still a matter of debate, which revolves around the key issues of productivity, product quality and costs. Fig. 2 shows recent estimates [3] of water treatment costs (capital and operating) for MF, UF and MF/RO plotted against a

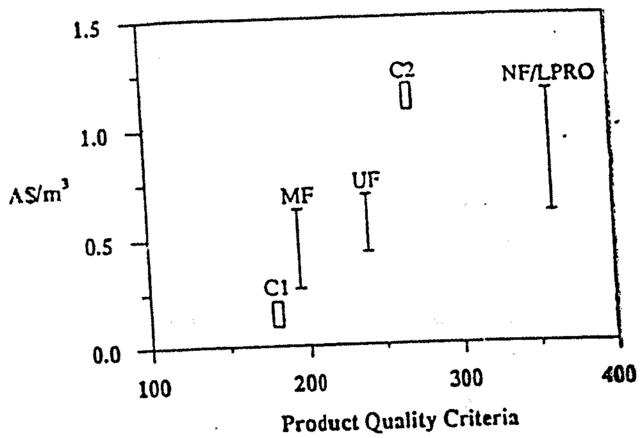


Fig. 2. Water treatment costs vs water quality for membranes and conventional. C1, sand filter+chlorination; C2, C1+ion exchange.

product quality criteria (=removals (%) for turbidity+ colour + pathogens + ions, i.e., maximum value is 400). Also included are costs of conventional treatment processes [4] adjusted to 1994 dollars. It is evident that the membrane options are becoming economically competitive, and across the spectrum they provide better quality than conventional technology.

4.3. *Secondary treatment*

Coupling biological wastewater treatment with a membrane has several attractions, i.e.:

- the process can be significantly more compact than conventional processes (the foot-print could be 1/10th the size),
- higher biomass (MLSS) concentrations can be achieved which results in reduced quantities of excess sludge,
- the effluent can be particulate free and partially disinfected.

Although the concept (of coupling UF and activated sludge) was commercialized by Dorr-Oliver in the 1960s, the application has only recently started to attract serious attention (Fig. 3).

The key to successful application is productivity (flux maintenance). What can be done to achieve this? Economically viable fluxes are probably in the range of 50–100 l/m²h at modest energy cost, and the challenge is to select the design and operating parameters that produce this. Fig. 4 shows some recent data for the membrane filtration of mixed liquor suspended solids, and indicates that economic performance is attainable.

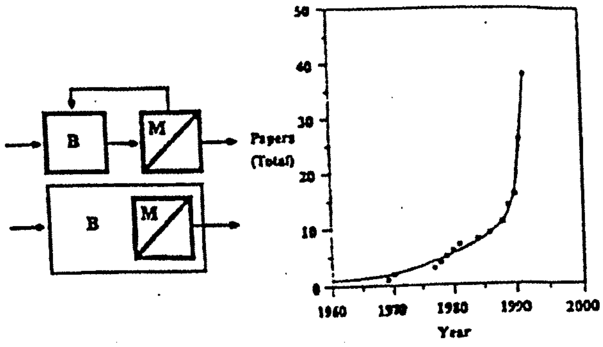


Fig. 3. Secondary treatment with membranes. B, bioreactor; M, MF,UF.

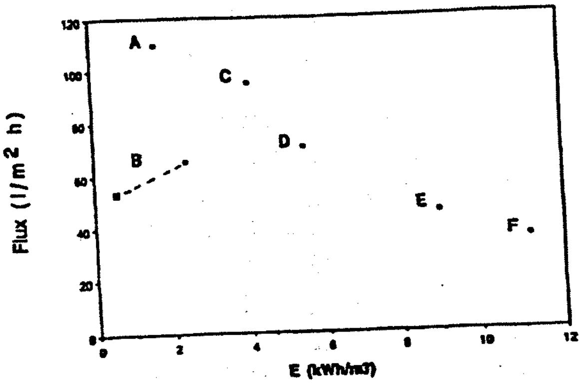


Fig. 4. Flux vs. energy. MF(UF) of activated sludge.

4.4. *Reuse*

The reuse of treated municipal (and other) effluents provides an alternative to building new water supply dams as well as encouraging reduced or zero discharge to sensitive environments. The application of RO to secondary effluent is being demonstrated on a large scale at Water Factory 21. Nevertheless, there are important issues to resolve to minimize biofouling of

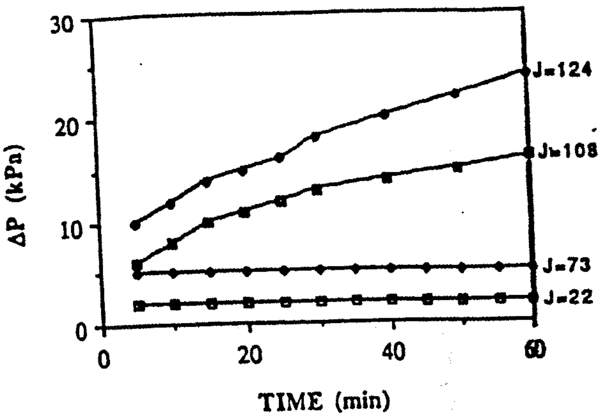


Fig. 7. ΔP history for various flux. Critical flux is >73 l/m^2 h.

- controlling the flux at a sub-critical level which avoids cake formation and allows very low transmembrane pressures to be used (Fig. 7) [8].
- formation of dynamic membranes whereby a porous support is precoated to provide MF capability. An interesting version of this is the Exxflow membrane process which uses flexible textile tubes as the support layer. The concept can also be used in the "dead-end" mode (no crossflow) to produce a high solid content "cake"; this process is known as Express [9]. These systems have relatively low costs but rely upon careful control in the formation of the dynamic layer. The "hybrid" process (see below) of MF plus chemical coagulation is a form of dynamic membrane operation since the chemical floc acts as "body feed" and forms a protective layer on the membrane. Significant flux improvements can be achieved [10].

The ability of MF to retain submicron species is surprising and depends on the nature of the feed and the operating conditions [11]. Retention mechanisms include (1) surface sieving (basis is size) and cakeforms, (2) surface collection (basis is charge) and cakeforms, (3) surface cake collection (fines collect in the cake) and (4) internal deposition, akin to depth filtration (basis is physical entrapment and adsorption due to surface interactions). Factors that increase retention include:

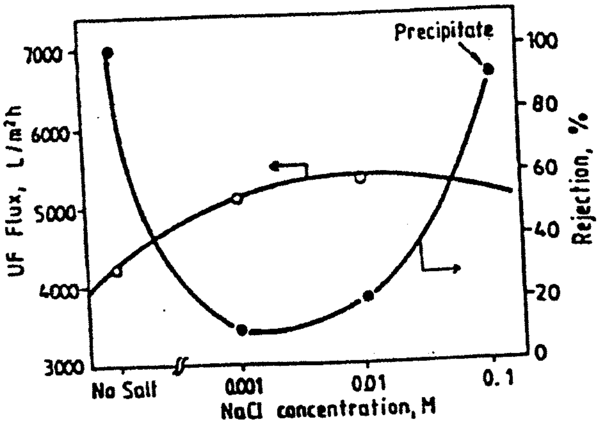


Fig. 8. UF flux and colloid rejection vs. salt concentration (Millipore PTMK, 3 mg/l Ag, pH 9.2, 100 kPa, stirred).

- ionic and pH environment (see Fig. 8 for effect of ionic content on retention of dilute silver colloids)
- effect of pressure (an increase tends to reduce retention of fine species) and hydrodynamics (surface shear tends to increase retention)
- nature of feed, including feed mixtures. We have observed for mixtures of non-biological solids that the presence of a larger particle can enhance the transmission of a smaller. For a mixture of virus and bacteria the effect is the opposite; the virus transmission is reduced by the presence of bacteria [12]. The retention of polio virus by 0.22 μm MF membranes is reported in Table 3 which shows that significant retentions are achievable.

Whilst the intrinsic ability of the membrane to retain species such as virus may be high, there is always the possibility of transmission through defects or damaged membranes. This problem applies to all membrane processes and also conventional filtration. Consequently the monitoring of membrane integrity is attractive. An interesting example is provided by hollow fibre test

Table 3
Removal of human virus by MF membranes under various conditions

Feed	Membrane, µm	Log removal value
Polio virus	0.2	1.3–1.7[a]
Polio virus + *E. coli*	0.2	1.2–2.0[a]
Secondary effluent (human enterovirus)	0.2	2–5[b]

[a]Stirred, 50–100 kPa.
[b]Range of feeds on commercial-scale plant.

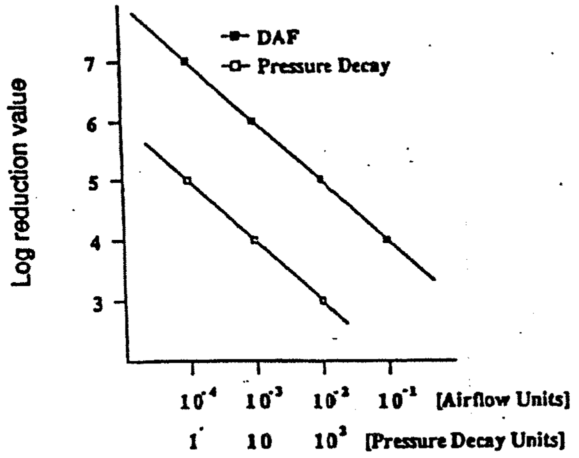


Fig. 9. Integrity test vs. pathogen removal.

procedures based on "diffusive airflow" and "pressure-hold testing". The former is more precise and can detect a single damaged fibre in 30,000. The results from these tests can be related to the log reduction value (LRV) for patho[illegible] in Fig. 9. This procedure can be [illegible] automatically and telemetrically and give rapid information of membrane performance.

5.2. Hybrid processes

There is growing interest in the coupling of MF (and UF) with other unit processes to give a hybrid process with better performance than either of the component parts. Most of these processes are being applied to water and wastewater treatment. An obvious example of hybrid process is the membrane coupled bioreactor described earlier (Fig. 3). Table 4 includes examples of MF and UF hybrid systems using chemical or physical additives to enhance the removal of micropollutants. The challenge here is to optimize the process by designing a continuous system with possible means of regeneration of additives. These hybrid processes should have an interesting future.

Table 4
MF and UF hybrid processes with chemicals and sorbents

Membrane type	Additive	Species removal
MF	Poly aluminium chloride	Turbidity
MF	Alum	Phosphorous
UF	Powdered activated carbon	Organics (pesticides)
UF	Micelles	Trichloroethylene
UF	Complexing agent	Metals
MF	Ion exchange resin	Nitrate
MF	Catalyst	Phenol

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