Design, Fabrication Application and Advantages of Nanofiltration Unit

Gaurav R. Salbarde
Research Student, Department of Chemical Engineering, Priyadarshini Institute of Engineering & Technology, Nagpur – 440019, Maharashtra, India

Kiran D. Bhuyar
Assistant Professor, Department of Chemical Engineering, Priyadarshini Institute of Engineering & Technology, Nagpur – 440019, Maharashtra, India

Abstract- The term "membrane filtration" describes a family of separation methods.The basic principle is to use semi-permeable membranes to separate fluids, Gases, particles and solutes. Membranes are usually shaped as a thin film, which allows transport of some materials, but not all. For separations from the water phase the membrane is water-permeable, but less permeable to Solutes and other particles depending on their size and to some degree other Properties. All living organisms rely on natural membrane selective transport of solutes in to and out of biological cells. Membranes are the active barriers in organs like kidneys and the stomach. Although membrane filtration is a relatively new family of methods for technical filtration, the principles of most methods have been known for some time.

Semi-permeable membranes have pores in the range 0.5 nm to 5 µm.Most filter membranes are Produced with physical/chemical methods where the pores are formed byPhysical and chemical processes. An important property that characterizes theIndividual membrane methods is the driving force behind the separation.Some methods are summarizedshowing their driving force,membrane structure and the approximate time of introduction for technicalfiltration. It can be seen that the driving force is different, and so is the designof the technical filter equipment.*[C.J. Shirazi, S. Rao, P.Agarwal, Effects of operational parameters in nanofiltration. Water research (2006)]*

Membranes are usually made from synthetic organic polymers and the thickness is in the order of 0.2 mm for sheet membranes. The physical shapeof the membrane is designed to fit in suitable "modules". A number ofmembrane module types are made, using sheet as well as hollow fibers, capillary or tubular membranes. Capillary membranes have achieved acertain foothold for drinking water, mainly because they can be backflushedto remove deposits. Hollow fine fibers are common in desalination ofseawater. Spiral modules are popular for drinking water because of their lowcost and moderate fouling tendency.

A prefilter is an essential part in a membrane plant in order to prevent that particles larger than the size of the narrow channels between the membranes,commonly 0.7–2 mm, enter the modules. Still some accumulation of matter onthe membrane surface takes place and eventually reduces the flux and thecapacity of the plant. This phenomenon is referred to as fouling. Avoidingand controlling fouling is the most important challenge for successfulmembrane filtration. The nanofiltration separation mechanism can be identified as a sum of convection and diffusion transport mechanisms, *i.e.*, sieving effects, together with electromigration as a result of membranecharge.Desalination, by definition, refers to the process of removing salt from seawater or brackish water. In a broader sense of the definition, desalination can also beinferred as removal of various inorganic ions from solution with the final targetso as to produce clean and potable water. Nanofiltration as a subset of membrane processes has found wide application within this purview ofdesalination. Through the development of a good predictive modelling fornanofiltration membrane processes, it is possible to utilize the model for thepurpose of membrane characterization, process modelling, optimization,membrane design and applications. *[NidalHilal, Habis Al-Zoubi, Naif A. Darwish and Abdul Wahab Mohammad, Performance of Nanofiltration Membranes in the Treatment of Synthetic and Real Seawater, Separation Science and Technology (2007)]*

Keywords- NF= Nanofiltration; MWCO= Molecular weight cut off; MF= Microfiltration; UF= Ultrafiltration UV= Ultraviolet; TDS= Total Dissolved Solids; RO= Reverse Osmosis; ED= Electro dialysis; AFM= Atomic Force Microscope; SEM = Scanning Electron Microscope

I. INTRODUCTION

The nanofiltration (NF) membrane is a type of pressure-driven membrane with properties in between reverse osmosis (RO) and ultrafiltration (UF) membranes.NF offers several advantages such as low operation pressure, high flux, highretention of multivalent anion salts and an organic molecular above 300,relatively low investment and low operation and maintenance costs. Because ofthese advantages, the applications of NF worldwide have increased. [W.J., Conlon and S.A McClellan, Membrane softening: treatment process comes of age (2008)]
Desalination, by definition, refers to the process of removing salt from seawateror brackish water. In a broader sense of the definition, desalination can also beinferred as removal of various inorganic ions from solution with the final targetso as to produce clean and potable water. Nanofiltration (NF) as a subset ofmembrane processes has found wide application within this purview ofdesalination. NF for example has been used in a desalination plant as pretreatmentto both reverse osmosis (RO) and thermal processes, resulting inenhanced production of desalted seawater and reduced cost, yet remains anenvironmentally friendly process. Pre-treatment of seawater feed toRO using nanofiltration prevents scaling by removal of scaleforming hardness ions, prevents membrane fouling in RO processes by removalof turbidity and bacteria and is expected to lower the required pressure tooperate RO plant by reducing seawater feed TDS.
Taste and odour is a special case for membranes in that the chemical nature of such compounds is highly variable, from relatively large organic molecules tolow-molecular compounds. Often the source of taste and odour is volatilecompounds that are typically low- molecular, and in these cases RO may beneeded. In that case the use of activated carbon or ozone as a secondarytreatment may by the best solution.[M.M.VanPaassen, J.M.,Jong, Nanofiltration concentrate disposal experiences in the Netherlands. Desalination (2005)]

Membrane processes for liquid separation that use pressure difference as a driving force can be subdivided into four categories, i.e., microfiltration (MF), reverse osmosis (RO),nanofiltration (NF) and ultrafiltration (UF). Separation of fluids by size exclusion through these four processes is primarily dependent on the pore size and pore size distribution ofthe membrane. Pores can be classified according to their sizes ultrafiltration membranes, the pores on the surface are in the range of 1 ~ 100 nm. Theyare generally applied to micro-emulsion oil removal, biomolecule and virus separationfrom aqueous streams. The morphology and the separation performance of ultrafiltrationmembranes are mainly determined by the fabrication conditions. [L.F. Broens, B.W. Altena& C. A. Smolders, Asymmetric membrane structures as a result of phase separation phenomena, Desalination (2011)]

Membrane Process	**Separation Mechanism**	**Nominal pore size or Intermolecular Size**
Microfiltration	Size exclusion	500-50000
Ultrafiltration	Size exclusion	10-1000
Nanofiltration	Size exclusion Electrical exclusion	5-20
Reverse osmosis	Size exclusion Solution/diffusion	<5

Table 1.Membrane Separation Processes and Membrane Characteristics

II. PROCESS APPLICATIONS

Similarly the application of the models and membranes in areas such aswastewater treatment and seawater desalination has been successful andresulted in the development of inherent principles for the selection ofmembranes, process conditions and economic assessment for NF system. Theapplications studied include removal of divalent ions from seawater, heavy metals from leachate and electrolysis plating solutions. Anotherimportant work is in creating a value added product as a result of desalinationapplication in a palm oil mill effluent treatment. The retentate andpermeate of such processes were utilized successfully to produce enzymes anditaconic acids respectively through biotechnological means. This finding willaugur well in the effort to balance environmental concerns with cost-effectivetreatment and value-added usage of the resulting waste. [Petersen RJ (2006) Composite reverse osmosis and nanofiltration membranes.

III. MEMBRANE PROCESS

Membranes have the ability to differentiate and selectively separate salts and water. Usingthis ability but differently in each case, three membrane desalination processes have been developed for desalting water Electro dialysis (ED), reverse osmosis (RO) and nanofiltration(NF).The RO represents the fastest growing segment of the desalination market [(Blank et al., 2007)].

Membrane technologies can be used for desalination of both seawater and brackishwater, but they are more commonly used to desalinate brackish water because energyconsumption is proportional to the salt content in the source water.Although thermal technologies dominated from the 1950s until recently, membrane processesnow approximatively equal thermal processes in global desalination capacity.Compared to thermal distillation processes, membrane technologies generally have lowercapital costs and require less energy, contributing to lower operating costs. In fact, the mostimportant progress in the area of membrane systems is the reduction of membrane cost byfactor of approximatively 10 over the last 30 years making the pretreatment and the seawater intake as the most expensive items of a membrane system [(Khawaji et al., 2008)].However, the product water salinity tends to be higher for membrane desalination (< 500 ppmTDS) than that produced by thermal technologies (< 25 ppm), but when making use of asecond RO pass the same quality can be obtained.

IV. CHARACTERIZATION OF THE ULTRAFILTRATION OR NANOFILTRATION MEMBRANES

Most porous ultrafiltration or nanofiltration membranes, either polymeric or inorganic,have a complex porous structure, with a set of pores with various sizes ranging from afew nanometers to several tens of nanometers which determines mass transport throughmembrane. There are several well established techniques for the determination of poresize and pore size distribution. They include the bubble point technique, mercuryporosimetry, the microscopic approach, solute transport method, permporometry andthermoporometry[Cuperus, 2012].

AFM (atomic force microscope) can image the non-conducting sample without damagingthe membrane. While SEM (scanning electron microscope) requires heavy metal coatingfor non-conducting sample and high beam energy which may damage polymericmembranes. However, average pore sizes obtained from SEM were smaller than thoseobtained by AFM due to the sample preparation. In addition, AFM images are distortedby convolution between pore shape and cantilever tip shape. Moreover, from SEM andAFM, the images can only give structure information on the membrane outer layersurface without pore inside morphology. This can be verified from the experimentalresults in which the mean pore sizes measure by AFM were about 3.5 times larger thanthose calculated based on the data from solute transport technique [Singh et al. 1998].

V .DIFFERENT MEMBRANE OPERATIONS

A. Driving Forces-

Membrane processes can be divided according to their driving forces. As driving forces, gradients in pressure, concentration, temperature and electrical potential are used.

B. Electrically Driven Processes-

The electrically driven processes are electro dialysis and membrane electrolysis. The driving force for (ionic) transport in these processes is supplied by an electrical potential difference. Electrically driven processes can be employed only when charged molecules are present, using ionic or charged membranes.

C. *Concentration Driven Processes-*

Concentration driven membrane processes are dialysis and osmosis. In dialysis process, the transfer of the solute across the membrane occurs by diffusion and separation is obtained through differences in diffusion rates because of differences in molecular weight [Pontié, 2003].

Osmosis is the transport of water across a selectively permeable membrane from a compartment of higher water chemical potential to a compartment of lower water chemical potential until the osmotic pressures of both compartments are equal. It is driven by a difference in solute concentrations across the membrane that allows passage of water, but rejects most solute molecules or ions. Osmotic pressure (π) is the pressure which, if applied to the more concentrated solution, would prevent transport of water across the membrane [Cathet al. 2006].

D. Heat Driven Process-

Membrane distillation is a separation process for aqueous solutions, based on the use of hydrophobic micro porous membranes. The membranes are not wetted by the aqueous phase, until the operating pressure remains lower than the minimum penetration pressure of the membrane, so that the entrance of the pores acts as the physical support for a liquid vapour interface which can originate the separation of components of different volatility. The driving force for mass transfer across the membrane is a difference in the partial pressure between the two ends of the membrane pores. That can be maintained by acting on the temperature difference across the membrane, as in direct contact MD, by using a sweeping gas on the permeate side, by introducing an air gap or by applying vacuum in the permeate side [Cabassud et al. 2003].

E. Pressure Driven Processes-

Pressure driven membrane processes use the pressure difference between the feed and permeate side as the driving force to transport the solvent through the membrane. Particles and dissolved components are (partially) retained based on properties such as size, shape and charge. Four membrane processes can be distinguished when the driving force is a pressure difference across the membrane, separating two liquid solutions. These processes are Microfiltration (MF), Ultrafiltration (UF), nanofiltration (NF) and reverse osmosis. Going from MF through UF and NF to RO, the hydrodynamic resistance increases and consequently higher driving forces are needed. On the other hand the product flux through the membrane and the size of the molecules being retained decreases. The product flux obtained is determined by the applied pressure and the membrane resistance (Shih et al 2005).

METHOD	**DRIVING FORCE**	**MEMBRANE**	**PERMEATION**
Dialysis	Concentration	Porous	Solutes
Electro dialysis	Electrical	Porous	Ions
Cross flow filtration	Pressure/concentration	Porous	Water
Pervaporation	Partial pressure	Dense	Liquid
Membrane distillation	Partial pressure	Porous	Liquid

Table 2. Properties of various methods for membrane filtration

V. GROUNDWATER AND SOFTENING APPLICATIONS

Nanofiltration processes are capable of removing hardness, heavy metals,NOM, particles and a number of other organic and inorganic substances in one single treatment step. NF membranes have a reasonable high rejection of bivalent ions whereas the rejection of monovalent ions is moderate to low. Operating pressure is typically in the range of 5-30 bar. The process will be adequate for surface and ground waters with high concentrations of total dissolved solids (TDS), i.e. more than 500 mg/L, but with low NaClconcentrations.[Thorsen, T., Krogh, T. and Bergan. E.: "Removal of humic substances with Membranes. System, use and experiences", AWWA Proceedings, 2011 Membrane technology conference, Baltimore 2011]

Nanofiltration membranes have properties in between RO and UF Membranes. In Table the rejection of RO, loose RO, NF and UF membranes is compared for a number of substances. The most distinctive features of typical NF membranes are:

• The rejection of bivalent or higher charged anions, like sulphate (SO42-) and phosphate (PO43-) is practically total. Multivalent cations are retained to a higher extent than monovalent cations.

• The rejection of sodium chloride (NaCl) varies from about 70 % down to 0 %.

• The rejection of uncharged dissolved materials in solution depends mostly on the size and shape of the molecule.

SPECIES	RO (%)	LOOSE RO (%)	NF (%)	UF (%)
Sodium chloride	99	70-95	0-70	0
Sodium sulphate	99	80-95	99	0
Calcium sulphate	99	80-95	0-90	0
Magnesium sulphate	>99	95-98	>99	0
Sulphuric acid	98	80-90	0-5	0
Hydrochloric acid	90	70-85	0-5	0
Fructose	>99	>99	20-99	0
Sucrose	>99	>99	>99	0
Humic acid	>99	>99	>99	30
Virus	99.99	99.99	99.99	99
Protein	99.99	99.99	99.99	99
Bacteria	99.99	99.99	99.99	99

Table 3.Comparative rejection values for RO, loose RO, NF and UF.

VI. INDUSTRIAL DESALINATION PROCESSES

The choice of technology used for water desalination depends on a number of site specificfactors, including source water quality, the intended use of the water produced, plant size,capital costs, energy costs and the potential for energy reuse *[Al-Subaie et al. 2007]*.

Water desalination can be accomplished by different techniques that can be classified into twocategories: thermal and membrane processes. The thermal processes can be subdivided intothe following processes:(i) Multistage flash evaporation, (ii) Multiple effect distillation and(iii) Vapour compression. The membrane processes are subdivided into: (1) Reverse osmosis (2) Electrodialysis and (3) Nanofiltration. Some basic information on these processes

A. Thermal Processes-

This method mimics the hydrological cycle in that salty water is heated producing watervapor that in turn condensed to form fresh water free of salts. The fresh water is mineralizedto make it suitable for human consumption. The important factors to be considered for thismethod of desalination are the proper temperature relative to its ambient pressure and enoughenergy for vaporization for energy minimization and the control of scale formation. Theenergy needed for vaporization is reduced usually by the use of multiple boiling points insuccessive vessels, each operating at a lower temperature and pressure, where the scaleforming is controlled by controlling the top temperature of the process or by the addition ofanticipants to the seawater. The known thermal methods are the multi-stage flash process(MSF), multi effect distillation (MED) process and the vapor compression (VC) distillation process.

B. Multiple-Effect Distillation-

The multiple-effect distillation (MED) process is the oldest desalination method and is veryefficient thermodynamically. The MED process takes place in a series of evaporator's called effects, and uses the principle of reducing the ambient pressure in the various effects. Thisprocess permits the seawater feed to undergo multiple boiling without supplying additionalheat after the first effect. The seawater enters the first effect and is raised to the boiling pointafter being preheated in tubes. The seawater is sprayed onto the surface of evaporator tubes to promote rapid evaporation. The tubes are heated by externally supplied steam from anormally dual purpose power plant. The stream is condensed on the opposite side of the tubes, and the steam condensate is recycled to the power plant for its boiler feed water. The MEDplant's steam economy is proportional to the number of effects. The total number of effects islimited by the total temperature range available and the minimum allowable temperaturedifference between one effect and the next effect. Only a portion of the seawater applied tothe tubes in the first effect is evaporated. The remaining feed water is fed to the second effect, where it is again applied to a tube bundle. These tubes are in turn heated by the vapors created in the first effect. This vapor is condensed to fresh water product, while giving up heat toevaporate a portion of the remaining seawater feed in the next effect. The process ofevaporation and condensation is repeated from effect to affect each at a successively lowerpressure and temperature.

C. Multi-Stage Flash Distillation (MFS)-

In *flash* distillation, the water is heated under pressure, which prevents it from vaporizingwhile being heated. It then passes into a separate chamber held at lower pressure, whichallows it to vaporize, but well away from the heating pipes, thus preventing them frombecoming scaled. Like MED, practical flash-distillation systems have compartments and eachcompartment is called *stage*, hence the term *Multi-Stage Flash* (MSF). When first introducedin the 1960's, MSF offered slightly lower energy efficiency than MED, but this wasoutweighed by scaling considerations and MSF became the industry standard. The desalinatedwater produced by the MSF process contains typically 2-10 ppm dissolved solids. Therefore,it is remineralized through the potabilization (or post-treatment) process.

D. Vapour Compression-

Compressing water vapour raises its temperature, which allows it to be used at a heat sourcefor the *same* tank of water that produced it. This allows heat recycling in a single effectdistillation process. In Thermal Vapour Compression, the compressor is driven by steam, andsuch systems are popular for medium-scale desalination because they are simple, incomparison to MSF. In Mechanical Vapour Compression, the compressor is driven by a dieselengine or electric motor.

The water produced by the thermal process is very pure with almost no salts, where the feed water quality has almost negligible effect on energy consumption *[Nicos, 2001]*. Thermalprocesses are the primary desalination technologies used throughout the Middle East becausethese technologies can produce high purity water from seawater and because of lower fuelcosts in the region.

E. Membrane Processes-

Membranes have the ability to differentiate and selectively separate salts and water. Usingthis ability but differently in each case, three membrane desalination processes have beendeveloped for desalting water: Electrodialysis (ED), reverse osmosis (RO) and nanofiltration(NF).

The RO represents the fastest growing segment of the desalination market *[J.S. Blank et al. 2007]*. Membrane technologies can be used for desalination of both seawater and brackishwater, but they are more commonly used to desalinate brackish water because energyconsumption is proportional to the salt content in the source water. Although thermal technologies dominated from the 1950s until recently, membrane processes now approximatively equal thermal processes in global desalination capacity.

Compared to thermal distillation processes, membrane technologies generally have lower capital costs and require less energy, contributing to lower operating costs. In fact, the mostimportant progress in the area of membrane systems is the reduction of membrane cost byfactor of approximatively 10 over the last 30 years making the pretreatment and the seawaterintake as the most expensive items of a membrane system *[Khawaji et al., 2008]*.However, the product water salinity tends to be higher for membrane desalination (< 500 ppmTDS) than that produced by thermal technologies (< 25 ppm), but when making use of asecond RO pass the same quality can be obtained.

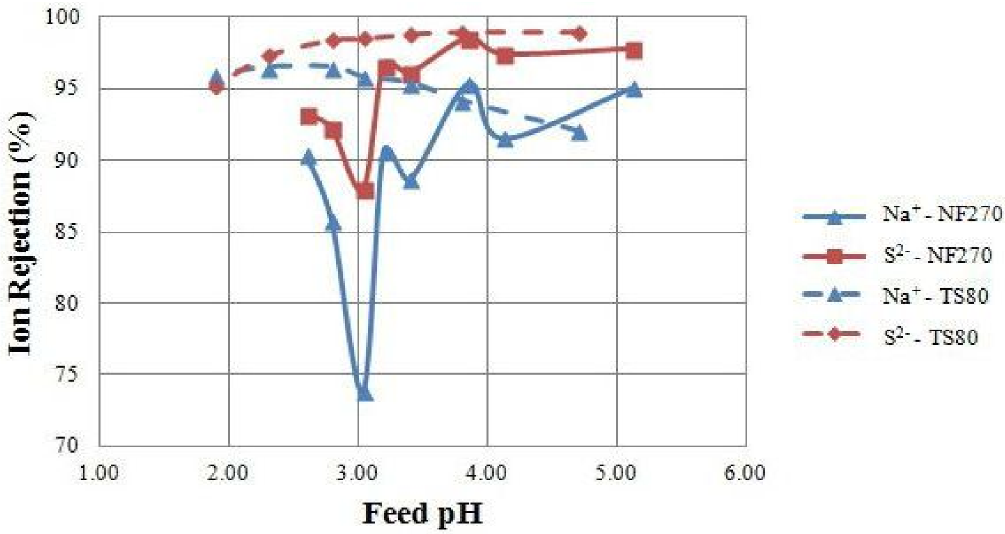
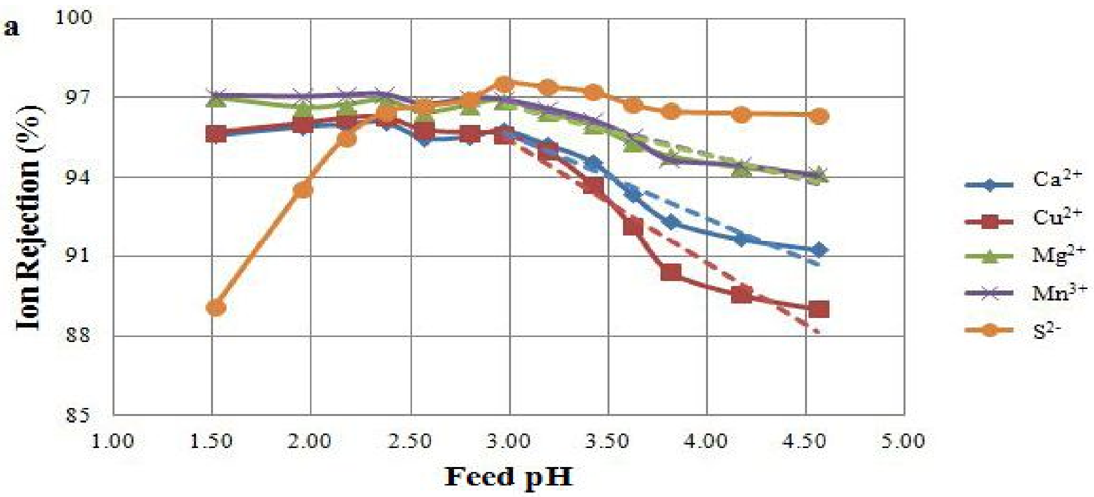


Figure 2. Ion rejection as a result of the IEP Tests. Tested feed solution: sodium chloride and sodium sulphate solutions. Tested membrane: NF 270 and TS 80.

Method of desalination	**Advantages**	**Disadvantages**
Multi-effect desalination (MED)	High production capacity Low capital cost High purity (< 30ppm) Energy input independent on salinity Minimal skilled operator	Dependence of output on local power availability Long construction period Difficult to control water quality Low conversion of feed water (30%-40%) Labor-intensive Large space and material requirements
Reverse osmosis (RO)	Suitable for both sea and brackish water Flexibility in water quantity and quality Low power requirement compared with MED and VC Flexibility in site location Flexibility in operation start-up and shut-off Simple operation	Low quality (250-500 ppm) Requires high quality feed water Relatively high capital and operating costs High pressure requirements Long construction time for large scale plants
Vapor compression (VC)	High water quality (20 ppm) High operational load Short construction period Operation and production flexibility	High operational costs High energy consumption Lack of water quality control

Electrodialysis (ED)	Low operating and capital costs Flexible energy source High conversion ratio (80%) Low energy consumption Low space and material requirements	Low to medium brackish water capability (3000ppm) Requires careful pretreatment of feed water Low production capacity Purity affected by quality of feed water
Multi-stage flash	Flexibility in salinity of feed water High purity production (< 30ppm) High production capacity Low skill requirement Production of both water and electricity High energy input	Labor intensive Low conversion ratio (30%-40%) High operating costs High construction requirements Limited potential for improvement

Table 4. Characteristics of desalination operations



VII. CONCLUSION

From this study the following conclusions can be drawn:

• Nanofiltration can be used for removal of a wide range of pollutantsfrom groundwater and surface water in view of drinking waterproduction. Softening and NOM-removal are major applications, butNF is frequently applied for the combined removal of NOM,micro pollutants, pesticides, arsenic, iron, heavy metals, sulphate,nitrate and bacteria and viruses. Reduced THM-formation potentialcan also be achieved. Full-scale installations have proven thereliability of NF in these areas.

• The main challenge in NF for water treatment is to control fouling of the membrane by scaling etc.
• Regardless of other conditions there will always be a maximum flux that can be applied in long term stable operation and therefore the fluxshould be limited and not exceed this value.
• This critical flux is almost always lower than the maximum fluxCapacity of the membrane and therefore there is a significant potential reduction in treatment costs to gain from better fouling control.
• There is a need for better understanding of the connection betweenSource water characterization and proper plant design and operation, in particular the value of the critical flux.
• There is a clear need for a better and cost-efficient prefilter that is effective in the particle range 0.1 to 3 µm.

• More knowledge of the rejection of typical and specific and importantWater pollutants and groups of pollutants for various types ofMembrane material would be useful.
• For softening and groundwater applications criteria for anticipant oracid dosing should be developed.
• There is a need for evaluation of waste disposal options and to assess the environmental impact of discharge.

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