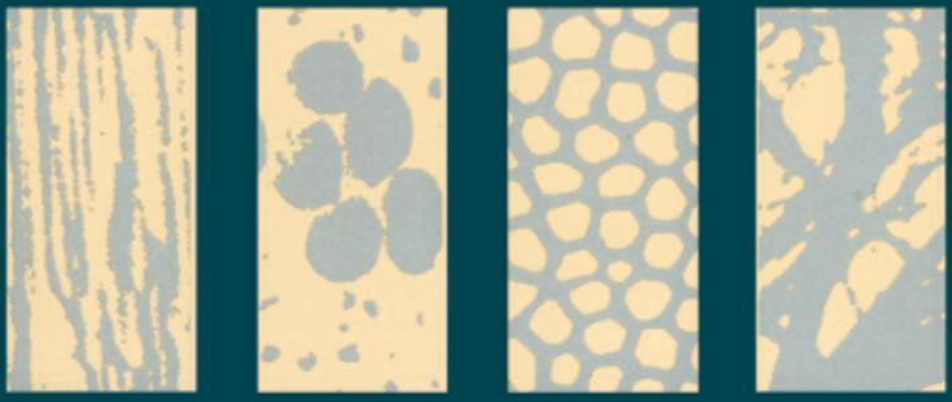
ULTRAFILTRATION and MICROFILTRATION HANDBOOK



Second Edition

Munir Cheryan

CRC PRESS

ULTRAFILTRATION
and
MICROFILTRATION
HANDBOOK
Second Edition

Taylor & Francis
Taylor & Francis Group
http://taylorandfrancis.com

ULTRAFILTRATION and MICROFILTRATION HANDBOOK

Second Edition

Munir Cheryan

CRC PRESS

Boca Raton London New York Washington, D.C.

Library of Congress Cataloging-in-Publication Data

Main entry under title:
Ultrafiltration and microfiltration handbook

Full catalog record is available from the Library of Congress

Direct all inquiries to CRC Press LLC, 2000 N.W. Corporate Blvd., Boca Raton, Florida 33431.

Visit the CRC Web site at www.crcpress.com

International Standard Book Number 1-56676-598-6
Library of Congress Card Number 97-62251
Printed in the United States of America 3 4 5 6 7 8 9 0
Printed on acid-free paper

TABLE OF CONTENTS

Taylor & Francis
Taylor & Francis Group
http://taylorandfrancis.com

PREFACE

Going back over the events in the membrane world since the first edition of *Ultrafiltration Handbook*, one cannot help being pleasantly surprised at the remarkable progress in many aspects of this ubiquitous technology. The development of the Sourirajan-Loeb synthetic membrane in 1960 provided a valuable separation tool to the process industries, but it faced considerable resistance in its early days. The situation is different today: membranes are more robust, modules and equipment are better designed (if the feedstream can be pumped, the chances are one or more of the modules available today will be able to handle it), and we have a better understanding of the fouling phenomenon and how to minimize its effects. Most important, costs have come down significantly, partly because of maturing of the technology and partly because of competition from an increasing number of membrane suppliers and original equipment manufacturers (OEM). Simultaneously, several company mergers and marketing alliances occurred that should provide a firmer footing from a business viewpoint. Developments in nanofiltration, gas separations, pervaporation, and bipolar membrane electrodialysis have widened the applicability of membranes, thus attracting even more attention. This revision of the *Ultrafiltration Handbook* is an attempt to catch up with these developments. The main themes remain the same and familiar to readers of the previous edition, but each chapter has been updated and revised while keeping the "handbook" flavor intact.

One major change in this edition starts with its title: *microfiltration* has been added to recognize it as an important member of the family of membrane technologies. Purists may argue that microfiltration (MF) is essentially the same as ultrafiltration (UF), with the difference being only in pore size. On the other hand, end users and membrane manufacturers tend to view them as distinct enough to justify separate treatment. I have tried to merge the two views since both are correct, but for different reasons. The scientific principles and much of the equipment may be the same, but these two sister technologies differ in operating strategies, mathematical modeling, and applications. A unified approach has been taken in earlier chapters, and distinctions are drawn in later chapters, especially when describing specific applications.

I have followed the same format as the first edition. Chapter 1 is a brief history of membranes, definitions, and basic thermodynamic principles. Chapter 2 reviews membrane chemistry and materials. The objective is not to teach membrane manufacture or design, but what membranes are designed to do. Unlike the early days when most membrane development was done by a few companies, there are numerous public and private institutions, universities, and independent research organizations involved today. This has lifted the veil of secrecy and improved manufacturing techniques to the extent that membranes are now considered to be a commodity. The trend today is towards specialization: many companies offer only membranes and/or modules of a certain type while relying on OEMs to provide system design and engineering. This is why Chapter 3 assumes even greater importance. Quality control and properties of membranes, inasmuch as they affect their potential use, are now the shared responsibility of the end user. Chapter 4 reviews mathematical models that will be useful in understanding the effect of process parameters on system performance. Here also, the emphasis is on factors the end user will need to consider when designing a membrane process.

Listing all the changes that have occurred over the past decade in equipment and module design (Chapter 5) has been a daunting task. Some of the companies that were major players a decade ago have ceased to exist or have been merged out of existence. This is part of the risk in a technology that is rapidly changing, not only to users of the equipment (where will they get replacement parts and support from?), but to authors of books targeted at the end user. Rather than attempt to describe each manufacturer's equipment in detail, the approach in this book has been to describe general operating principles of each type of equipment, with commercial examples being used to illustrate selected design features. Chapter 6 deals with an area of crucial importance: membrane fouling. A more general approach has been taken instead of the case study approach of the first edition. This is partly because of a better understanding of this vexing problem and also in order to be useful in as many applications as possible. Cleaning has been discussed in greater detail in this edition. Chapter 7 focuses on process design aspects, with expanded coverage of system design and cost calculations.

Like the previous edition, Chapter 8 forms the bulk of this book. At that time, I noted that the bias towards citing biologically oriented examples was probably because of the special interests of the author, rather than a reflection of actual usage of ultrafiltration. Although the range of applications of MF and UF has widened, it now appears that these bio-industries did indeed constitute the major market for UF and MF and will continue to be important for the foreseeable future. In contrast, chemical and petroleum industry applications are few. It is likely that water treatment and environmental applications will see the greatest growth in the next decade.

In order to serve readers with a variety of backgrounds and to keep this book as practical as possible, I have not delved too deeply into the theoretical aspects of the technology. Appendix C contains a list of books that provide greater depth in these areas. I have also minimized the use of jargon in order to be readily comprehensible to the novice, but sometimes it is unavoidable. A list of abbreviations at the beginning of the book and the glossary of terms at the end should be useful in this regard. Appendix A provides names and addresses of some membrane manufacturers (with the caveat that inclusion in this list should not be interpreted as an endorsement nor should omission be taken to mean otherwise). Appendix B contains conversion factors (to help translate English engineering units to the metric and vice versa).

Numerous individuals working for membrane manufacturers, engineering companies, and end users have continued to educate me in this exciting technology. Interacting with them has expanded my knowledge and appreciation of what it takes for this technology to succeed in the marketplace as much as scholarly papers from academic institutions helped elucidate the scientific principles. This subject has long ceased to be a "laboratory curiosity" or an "emerging technology." This, in turn, has generated vast numbers of papers and books over the past decade. I may have summarized, simplified, or omitted contributions of several distinguished workers in this area and perhaps not cited them individually. It should not be construed as ignoring or minimizing their contributions or those of the legions of scientists, engineers, and marketing people who may not publish papers but have done much to move this technology forward.

I am once again indebted to my graduate students and research associates for their enthusiasm and doing much of the experimental work while we were learning the art of membrane technology. Technomic Publishing Company did a magnificent job of converting essentially classroom notes into a widely used reference book with the first edition. They were extraordinarily patient waiting for this long-overdue revision. Needless to say, the most important element has been my family. This book is dedicated to them in appreciation for their support and for sharing the joys and tribulations that accompanied my professional life and the writing of this book.

MUNIR CHERYAN
Urbana, Illinois

Taylor & Francis
Taylor & Francis Group
http://taylorandfrancis.com

LIST OF ABBREVIATIONS

ACFF	affinity cross-flow filtration
AFM	atomic force microscopy
ATD	antitelescoping device
ATP	adenosine 5′-triphosphate
BOD	biochemical oxygen demand
BSA	bovine serum albumin
Btu	British thermal units
CA	cellulose acetate
CD	continuous diafilitration
cfu	colony forming units
CGM	corn gluten meal
CIP	clean-in-place
CMC	carboxylmethyl cellulose (Section 8.E)
CMC	critical micelle concentration (Section 8.D.7)
CMP	caseinomacropeptide
Co-A	coenzyme A
COD	chemical oxygen demand
CPF	co-current permeate flow
CR	cross-rotating
CSTR	continuous, stirred-tank reactor
CTA	cellulose triacetate
DAF	dissolved air flotation
d.b.	dry basis
DBP	disinfection by-product
DD	discontinuous diafiltration
DE	dextrose equivalent or diatomaceous earth
DESC	dead-end stirred cell
DF	diafiltration
DMF	dimethylformamide
DS	degree of substitution
E-coat	electrocoat
ED	electrodialysis

EDTA	ethylenediaminetetraacetic acid
FESEM	field emission scanning electron microscopy
FFA	free fatty acid
FIP	formed-in-place
FOG	fats, oils, and greases
FRP	fiberglass reinforced plastic
GFD	gallons per square foot per day
gpd	gallons per day
gpm	gallons per minute
HFF	hollow fiber fermenter
HFER	hollow fiber enzyme reactor
HIMA	Health Industry Manufacturers Association
IgG	immunoglobulin G
IPA	isopropyl alcohol
IPC	isophthaloyl chloride
JTU	Jackson Turbidity Units
LMH	liters per square meter per hour
LRV	log reduction value
LWC	low-weight cardboard
MEUF	micellar-enhanced ultrafiltration
MF	microfiltration
MJ	Megajoule
MPD	*m*-phenylene diamine
MRB	membrane recycle bioreactor
MW	molecular weight
MWCO	molecular weight cut-off
NAD	nicotinamide adenine dinucleotide
NADP	nicotinamide adenine dinucleotide phosphate
NF	nanofiltration
NMWCO	nominal molecular weight cut-off
NMWL	nominal molecular weight limit
NTU	nephelometric turbidity unit
OEM	original equipment manufacturer
ONPG	*o*-nitrophenyl-β-D-galactopyranoside
PA	polyamide
PAC	powdered activated carbon
PAN	polyacrylonitrile
PBW	periodic backwash
PEG	polyethylene glycol
PEI	polyethylenimine
PES	polyethersulfone
PI	polyimide
PLC	programmable logic controller

PP	polypropylene
PS	polysulfone
PTFE	polytetrafluoroethylene
PV	pervaporation
PVA	polyvinyl alcohol
PVC	polyvinyl chloride
PVDF	polyvinylidene fluoride
PVP	polyvinylpyrrolidone
QAC	quartenary ammonium compound
RBC	red blood cells
RC	regenerated cellulose
RO	reverse osmosis
RPM	revolutions per minute
RVPF	rotary vacuum precoat filter
SBR	styrene butadiene rubber
SCR	solute concentration ratio
SDS	sodium dodecylbenzene sulfonate
SEC	size exclusion chromatography
SEM	scanning electron microscope
SS	stainless steel
SS	suspended solids
SSL	spent sulfite liquor
TDI	toluene 2,4 diisocyanate
TDS	total dissolved solids
TEM	transmission electron microscope
TFC	thin-film composite
THM	trihalomethane
TMC	trimesoyl chloride
TMP	transmembrane pressure
TOC	total organic carbon
TPH	total petroleum hydrocarbon
TS	total solids
UF	ultrafiltration
UPW	ultra-pure water
UTP	uniform transmembrane pressure
VCR	volume concentration ratio
V-SEP	vibratory shear enhanced processing
WCR	weight concentration ratio
WPC	whey protein concentrate

Taylor & Francis
Taylor & Francis Group
http://taylorandfrancis.com

CHAPTER 1

Introduction

1.A.
DEFINITION AND CLASSIFICATION OF MEMBRANE SEPARATION PROCESSES

Filtration is defined as the separation of two or more components from a fluid stream based primarily on size differences. In conventional usage, it usually refers to the separation of solid immiscible particles from liquid or gaseous streams. Membrane filtration extends this application further to include the separation of dissolved solutes in liquid streams and for separation of gas mixtures.

The primary role of a membrane is to act as a selective barrier. It should permit passage of certain components and retain certain other components of a mixture. By implication, either the permeating stream or the retained phase should be enriched in one or more components. In its broadest sense a membrane could be defined as "a region of discontinuity interposed between two phases" (Hwang and Kammermeyer 1975), or as a "phase that acts as a barrier to prevent mass movement but allows restricted and/or regulated passage of one or more species through it" (Lakshminarayanaiah 1984). By these definitions, a membrane can be gaseous, liquid, or solid or combinations of these. Membranes can be further classified by (a) nature of the membrane—natural versus synthetic; (b) structure of the membrane—porous versus nonporous, its morphological characteristics, or as liquid membranes; (c) application of the membrane—gaseous phase separations, gas–liquid, liquid–liquid, etc.; (d) mechanism of membrane action—adsorptive versus diffusive, ion-exchange, osmotic, or nonselective (inert) membranes.

Membranes can also physically or chemically modify the permeating species (as with ion-exchange or biofunctional membranes), conduct electric current, prevent permeation (e.g., in packaging or coating applications), or regulate the rate of permeation (as in controlled release technology). Thus, membranes may be either passive or reactive, depending on the membrane's ability to alter the chemical nature of the permeating species (Lloyd 1985). Ionogenic groups and pores in the membrane confer properties such as *permselectivity* and *semipermeability*.

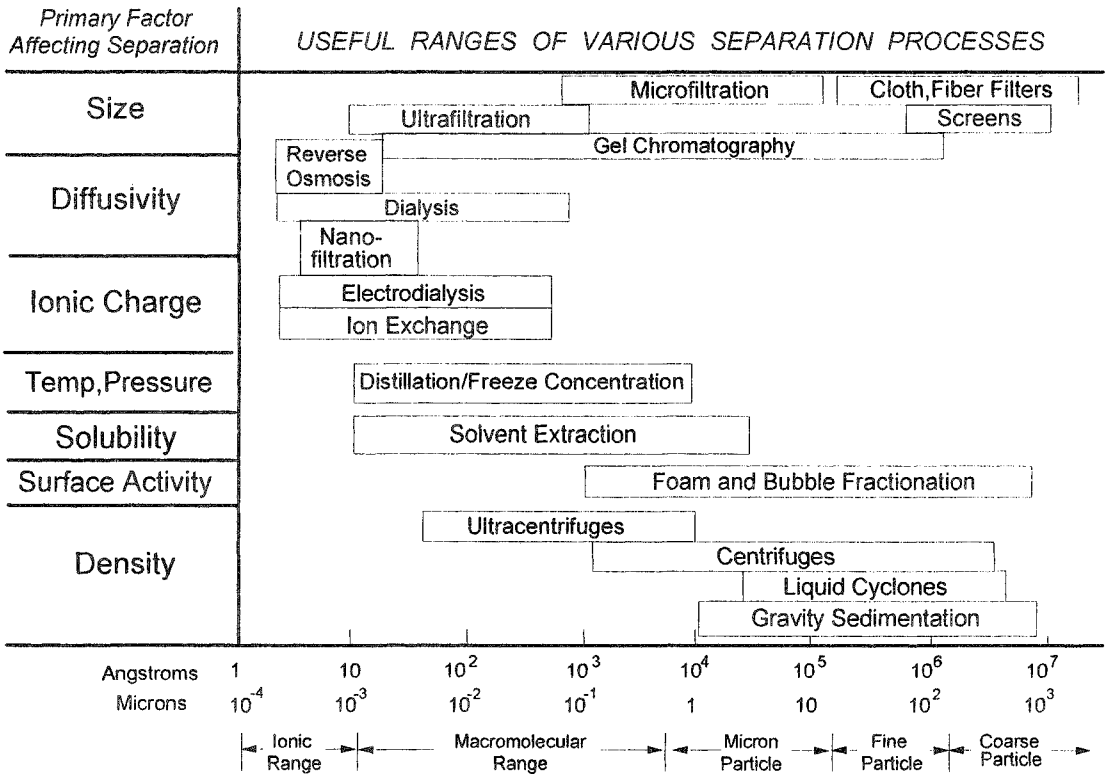


Figure 1.1. *Useful ranges of various separation processes.*

Table 1.1. Characteristics of membrane processes.

Process	Driving Force	Retentate	Permeate
Osmosis	Chemical potential	Solutes, water	Water
Dialysis	Concentration difference	Large molecules, water	Small molecules, water
Microfiltration	Pressure	Suspended particles, water	Dissolved solutes, water
Ultrafiltration	Pressure	Large molecules, water	Small molecules, water
Nanofiltration	Pressure	Small molecules, divalent salts, dissociated acids, water	Monovalent ions, undissociated acids, water
Reverse osmosis	Pressure	All solutes, water	Water
Electrodialysis	Voltage/current	Nonionic solutes, water	Ionized solutes, water
Pervaporation	Pressure	Nonvolatile molecules, water	Volatile small molecules, water

Figure 1.1 shows a classification of various separation processes based on particle or molecular size and the primary factor affecting the separation process. The major membrane separation processes—reverse osmosis (RO), nanofiltration (NF), ultrafiltration (UF), microfiltration (MF), dialysis, electrodialysis (ED), and pervaporation (PV)—cover a wide range of particle/molecular sizes and applications. Among membrane separation processes, the distinction between the various processes is somewhat arbitrary and has evolved with usage and convention. Table 1.1 shows the characteristics of various membrane processes. Osmosis (to be discussed in detail in Section 1.C.) is the transport of solvent through a semipermeable membrane from the dilute solution side to the concentrated solution side of the membrane. It is driven by chemical potential differences between the water on either side of the membrane. With an ideal semipermeable membrane, only water should permeate through the membrane. The common laboratory technique of dialysis, on the other hand, is primarily a technique for purifying macromolecules, such as desalting of proteins, and the primary driving force is the difference in concentration of the permeable species between the solution in the dialysis bag and outside the bag. Electrodialysis relies primarily on voltage or electromotive force and ion-selective membranes to effect a separation between charged ionic species.

What distinguishes the more common pressure-driven membrane processes—microfiltration, ultrafiltration, nanofiltration, and reverse osmosis—is the application of hydraulic pressure to speed up the transport process. However, the nature of the membrane itself controls which components permeate and which

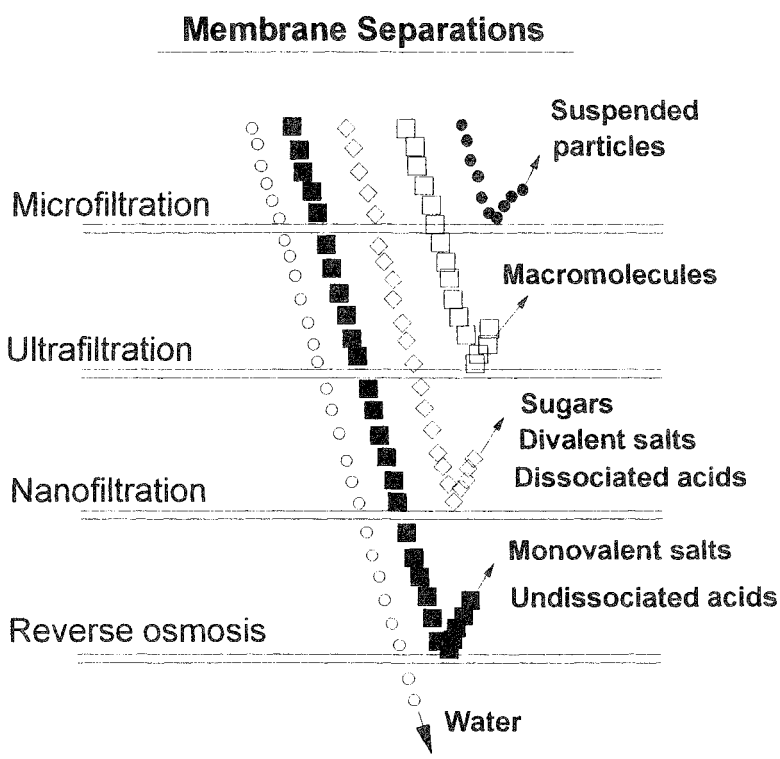


Figure 1.2. Pressure-driven membrane processes and their separation characteristics.

are retained, as shown in Figure 1.2. In its ideal definition, reverse osmosis retains *all* components other than the solvent (e.g., water) itself, while ultrafiltration retains only macromolecules or particles larger than about 10–200 Å (about 0.001–0.02 μm). Microfiltration, on the other hand, is designed to retain particles in the "micron" range, that is, suspended particles in the range of 0.10 μm to about 5 μm (particles larger than 5–10 μm are better separated using conventional cake filtration methods). Thus, in its broadest sense, reverse osmosis is essentially considered to be a dewatering technique, while ultrafiltration can be looked at as a method for simultaneously purifying, concentrating, and fractionating macromolecules or fine colloidal suspensions. Microfiltration is used mainly as a clarification technique, separating suspended particles from dissolved substances, provided the particles meet the size requirements for microfiltration membranes.

Nanofiltration is a relatively new process that uses charged membranes with pores that are larger than RO membranes, but too small to allow permeation of many organic compounds such as sugars. They also have a useful property in

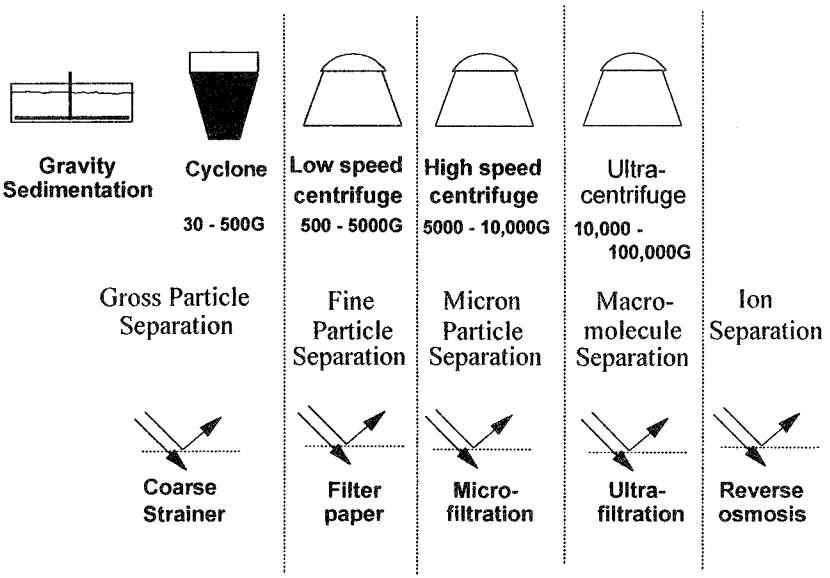


Figure 1.3. *Comparison of centrifugation and filtration processes.*

that they can separate dissociated forms of a compound from the undissociated form; e.g., organic acids such as lactic, citric, and acetic pass through easily at low pH but are rejected at higher pH when in their salt forms (Raman et al. 1994).

In terms of versatility, centrifugation is perhaps the only method to match membrane technology (Figure 1.3). However, an absolute requirement for centrifugal processes is the existence of a suitable density difference between the two phases that are to be separated, in addition to the two phases being immiscible. Membrane separation processes have no such requirement; indeed, the real value of membranes is that they permit separation of dissolved molecules down to the ionic range, provided the appropriate membrane is used.

Figure 1.4 shows some typical examples of components that fall under these four processes. Membranes are usually classified according to the size of the separated components, and thus particle sizes in MF applications are specified in microns (i.e., μm). However, with UF membranes, it is customary to refer to the "molecular weight cut-off" (MWCO) instead of particle size per se. In the early days of membrane technology, UF membranes were characterized by studying the relative permeabilities of proteins and polyethylene glycols, which were characterized in terms of their molecular weights. Even though it is known that molecular weight alone does not determine the size of a protein and, indeed, many manufacturers use dextrans rather than proteins to characterize UF membranes (as discussed in Chapter 3), this terminology is still used, sometimes prefixed with the word *nominal*, as in NMWCO. Thus, UF covers "particles"

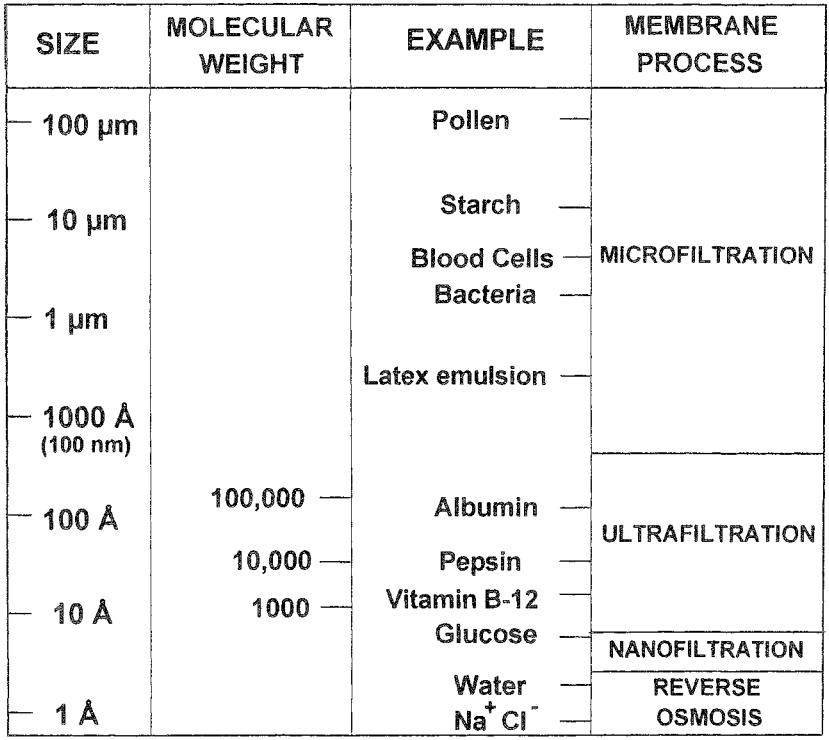


Figure 1.4. Typical examples of solutes separated by membrane processes.

and molecules that range from about 1000 in molecular weight to about 500,000 daltons.

When first developed in the 1960s, UF and RO—and later joined by their sister pressure-driven membrane processes, MF and NF—constituted the first continuous molecular separation processes that do not involve a phase change or interphase mass transfer. This is perhaps what is most exciting when considering applications in food, pharmaceutical, and biological processing. In its simplest form, as shown in Figure 1.5, membrane technology consists merely of pumping the feed solution under pressure over the surface of a membrane of the appropriate chemical nature and physical configuration. In MF and UF, the pressure gradient across the membrane would force solvent and smaller species through the pores of the membrane, while the larger molecules/particles would be retained. Thus, one feedstream is split into two product streams. The retained stream (referred to as "retentate" or "concentrate") will thus be enriched in the retained macromolecules, while the fraction going through the membrane (referred to as the "permeate") will be depleted of the macromolecules. The retentate will also contain some of the permeable solutes. In fact, the permeable

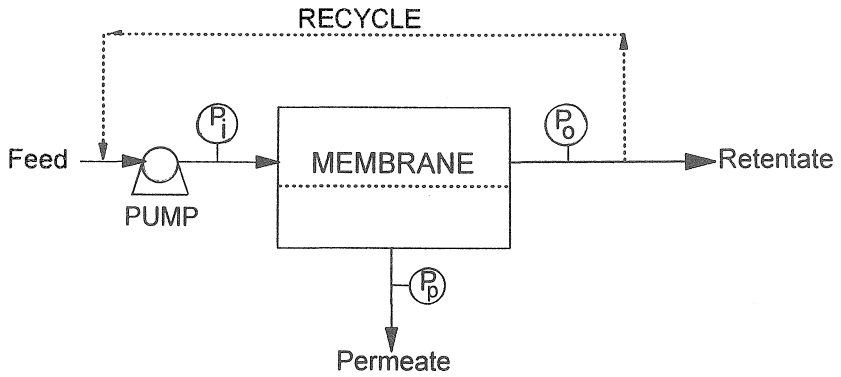


Figure 1.5. *Operating principle of membrane technology. Unlike a conventional filtration process, which operates in a "dead-end" mode, membranes are configured to be operated in the "cross-flow" mode, where the feed is pumped over the surface of the membrane, resulting in two product streams. Further details are provided in Chapter 4.*

solutes may be at the very same or higher concentration than in the permeate stream, depending on how the membrane separates or "rejects" that solute. However, since the retentate now forms a much smaller volume than the feed, there has, in effect, been a "purification" of the retained species. This will be explained in detail in Chapter 7.

Because ultrafiltration deals with the separation of fairly large molecules, such as natural polymers like proteins, starch and gums, and colloidally dispersed compounds such as clays, paints, pigments, latex particles, etc., the osmotic pressures involved in ultrafiltration processes are fairly low (see Section 1.C. for osmotic pressure calculations). In contrast, pressures involved in reverse osmosis would be fairly high, of the order of 500–1500 psi (35–100 bar), in order to overcome the high osmotic pressures of the small solutes. NF, used as it is for desalting and deacidification, has lower osmotic pressure to work against and thus will need lower operating pressures of 150–450 psi (10–30 bar). UF and MF, on the other hand, would thus need fairly low pressures for operation, which would lower equipment and operating (pumping) costs by a considerable margin.

A further advantage of membrane technology, as compared to conventional dewatering processes, is the absence of a change in phase or state of the solvent during the dewatering process. Evaporation and freeze concentration are common dewatering techniques used for liquid products. Evaporation requires the input of about 1000 Btu/lb of water evaporated (540 kcal/kg) while freezing requires about 144 Btu/lb water frozen, merely to effect the change in state of water from liquid to vapor and liquid to solid, respectively. Since membrane separations do not require a change in state of the solvent to effect a dewatering,

Table 1.2. Comparison of energy requirements and costs between evaporation and membrane processes.

Process	Evaporation	Membrane
Whole milk (2.2×)	136 kcal/kg (MVR)	17 kcal/kg (RO)
Cheese whey (3×) 18,000 lb/hour	$380,000/year (double effect)	$130,000/year (RO)
Corn steep liquor (6 to 50% TS) 300 gpm	$1.2 million/year (MVR)	$390,000/year (RO to 14% TS, then MVR)
Gelatin (2 to 18% TS) 20 tons/hour	$516,200/year (4-effect)	$186,750/year (UF)

Source: Data from Cheryan and Nichols (1992); Koch Membrane Systems (1987)

this should result in considerable savings in energy. Some examples of energy and cost savings are shown in Table 1.2.

It should be borne in mind, however, when comparing membrane processes to evaporation, that saving energy does not necessarily imply a savings in cost. Considerable economies in energy usage are possible in evaporation by the use of multiple effects and mechanical vapor recompression. Furthermore, the unit energy cost for steam can be much lower than electricity. For example, steam costs in the United States today are typically $5/1000 lb ($11/ton) and electricity costs $0.05 per kWh. The unit energy cost of steam is $0.515 per 1000 Btu ($0.488 per megajoule) and electricity is $1.46 per 1000 Btu ($1.382 per MJ). Thus, membranes must use 65% less energy in order to compete with a steam-based dewatering process. That is why it is more important to compare actual costs, as shown in Table 1.2 for the cheese whey, corn steep liquor, and gelatin examples, rather than just energy consumption.

A less obvious advantage is that no complicated heat transfer or heat-generating equipment is needed, and the membrane operation, which requires only electrical energy to drive the pump motor, can be situated far from the prime power-generating plant. No additional steam capacity need be installed to handle the UF/RO unit. A further advantage over evaporators is that no condensers (and the huge condenser cooling water supply needed for its operation) are needed, thus avoiding related problems like thermal pollution and overloading of sewage treatment systems. In fact, if a reverse osmosis system is used in tandem with an MF or UF plant to treat the UF permeate, the plant would get high-quality water as one of the by-products of the operation.

Another advantage of membrane processes is that they can be operated at ambient temperatures, even though there may be frequent occasions when it is necessary to operate at considerably lower temperatures (e.g., to prevent microbial growth problems or denaturation of heat-sensitive components) or higher temperatures (e.g., to minimize microbial growth problems; to lower viscosity of the retentate, which lowers pumping cost; to improve mass transfer and

flux). Thus, thermal or oxidative degradation problems common to evaporation processes can be avoided. Finally, since small molecules should normally freely pass through UF and MF membranes, their concentration on either side of the membrane should be the same during processing and about equal to that in the original feed solution. Thus, there should be minimal changes in the micro-environment during UF and MF, i.e., no changes in pH or ionic strength, a particular advantage when isolating and purifying proteins.

There are some limitations to membrane processes. None can take the solutes to dryness. In fact, membrane processes are quite limited in their upper solids limits. In RO, it is frequently the osmotic pressure of the concentrated solutes that limits the process. In the case of UF and MF, it is rarely the osmotic pressure of the retained macromolecules, but rather the low mass transfer rates obtained with concentrated macromolecules and the high viscosity that makes pumping of the retentate difficult. As an example, current technology permits skim milk to be concentrated economically by multiple effect evaporation to about 50% total solids, while the best obtained to date by RO is about 30% total solids and by UF about 42% total solids. Other problems that plagued early membrane applications—fouling of membranes, poor cleanability, and restricted operating conditions—have been overcome through the development of superior membrane materials and improved module design. This has vastly enlarged the applicability of MF and UF in the food, pharmaceutical, biological, and chemical processing industries.

1.B.
HISTORICAL DEVELOPMENTS

The phenomenon of osmosis, which is the transport of water or solvent through a semipermeable membrane (defined as a membrane that is permeable to solvent and impermeable to solutes), has been known about since 1748, when Abbe Nollet observed that water diffuses from a *dilute* solution to a more concentrated one when separated by a semipermeable membrane (Boddeker 1995; Lonsdale 1982). Dutorchet is credited with introducing the term *osmosis* to characterize spontaneous liquid flow across permeable partitions. Later, in 1845, Matteucci and Cima observed that these membranes tended to be anisotropic in nature; that is, their behavior was different, depending on which side of the membrane faced the feed solution. Schmidt also observed the same phenomenon in 1856.

In 1855, Fick developed the first synthetic membrane, made apparently of nitrocellulose. Two years later, Traube also prepared artificial membranes, while Pfeffer reported in 1877 the successful manufacture of membranes made by precipitating copper ferrocyanide in the pores of porcelain. The first quantitative measurements of diffusion phenomena and osmotic pressure were made using these early membranes. Interest also focused on membranes made of

"collodion," a term commonly used for cellulosic polymers. Basically, the procedure for making these membranes was as follows: nitrocellulose was dissolved in a suitable solvent, such as alcohol-ether or acetic acid, and the solution poured on a flat surface. The solvents were allowed to evaporate. Perhaps the first reference to the use of a membrane for separations is by Graham in 1854, who used it as a dialyser to separate a solution into its components.

Bechhold, around the year 1907, then developed methods for controlling the pore size of these collodion membranes, apparently by controlling the rate of evaporation of the solvents and by water washing of the film. He was the first to suggest using air pressure for improving permeation rates and also developed methods for measuring pore diameters using air pressure and surface tension measurements. He is generally credited with coining the term *ultrafiltration*.

The period of 1870–1920 saw the rapid development of theories of thermodynamics of solutions, most notably those of van't Hoff and his theory of dilute solutions and Gibbs, whose work led to the primary relationship between osmotic pressure and other thermodynamic properties. Membrane filters became commercially available in 1927 from the Sartorius Company in Germany, manufactured using the Zsigmondy process. In 1931, Elford developed methods for sterilizing membrane filters using ultraviolet radiation.

Up until 1945, membrane filters were used primarily for removal of microorganisms and particles from liquid and gaseous streams, for diffusion studies, and for sizing of macromolecules. German scientists also developed methods for culturing bacterial cells on membranes. In 1951, Goetz imprinted grid lines on filters to facilitate counting bacterial colonies. These gridded membranes are now used extensively for water analysis. In 1957, the U.S. Public Health Service officially adopted the membrane filtration procedure for drinking water analysis.

Simultaneously with these developments in microfiltration membranes, there was considerable interest in developing membranes for reverse osmosis applications, especially for desalination of seawater and purification of brackish water. Obviously, the semipermeable membranes used by the early investigators (linings of pig's bladders, onion skins, etc.) would be impractical for these purposes due to the high pressures necessary for practical desalination, which would be of the order of 500–1000 psi (35–70 bar). The MF membranes commercially available at that time were also obviously unsuitable because of their large pore sizes.

In the early 1950s, Samuel Yuster, of the University of California, Los Angeles, had predicted that, based on the Gibbs adsorption isotherm, it should be possible to produce fresh water from brine. Srinivasa Sourirajan, who also worked at the same university, reported some success with this concept (Yuster et al. 1958) using commercially available homogenous membranes (homogenous from an ultrastructural point of view). He used a hand-operated pump, and it is reported that it took a few days to produce a few milliliters of fresh water (Loeb 1981). Around the same time, Reid and Breton (1959) independently obtained promising results using a homogenous cellulose acetate membrane.

At this juncture, the general conclusions by most researchers in the reverse osmosis area were that, to obtain commercially feasible flux or dewatering rates, the most practical route would be to reduce the thickness of the membrane. From 1958 to 1960, Sourirajan, now joined by Sidney Loeb, attempted to modify commercial cellulose acetate membranes by heating them under water, in the apparent hope that this would expand the pores and that the pores would remain open when the membrane cooled, thus increasing flux. But exactly the opposite happened: heating contracted the pores. When the heat treatment was performed with commercially available ultrafiltration membranes, it caused the pores to shrink, which increased the rejection of salts but also resulted in much higher flux than before. This heating or annealing process created a phenomenon known as "anisotropy" or "asymmetry" in the ultrastructure of the membrane; i.e., the behavior of the membrane was different, depending on which side of the membrane faced the feed solution, an observation that had been made over 100 years ago with natural membranes.

Figures 1.6–1.9 show the ultrastructure of a typical asymmetric membrane. The anisotropic nature of the Loeb-Sourirajan membrane is characterized by a thin "skin" on one surface of the membrane, usually 0.1–0.2 μm thick, while the main body of the membrane is sponge-like in nature with extremely porous voids. Since the major resistance to mass transport through the membrane is the thickness of the membrane, and the effective thickness of the anisotropic membrane is now of the order of 0.1–0.2 μm, instead of the 100–200 μm of the old homogeneous membranes, this resulted in fairly high flux. The rejection of salt remained high, however, due to the decreased effective pore size, also a result of the annealing process. This single development of the asymmetric membrane by Loeb and Sourirajan is what converted a hitherto laboratory curiosity into a practical and viable unit operation that is unmatched in its versatility for the widest possible range of applications.

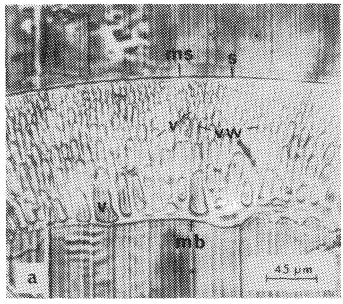


Figure 1.6. *Light microscope view of the cross section of an asymmetric membrane: ms = membrane surface, v = voids, vw = void wall (adapted from Cheryan and Merin 1980).*

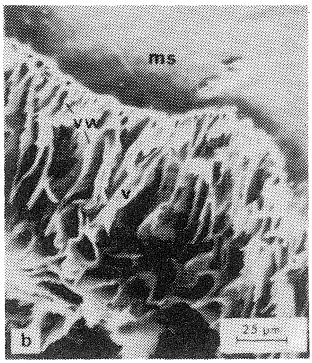


Figure 1.7. *Scanning electron micrograph of an asymmetric ultrafiltration membrane: ms = membrane surface, v = voids, vw = void wall (adapted from Cheryan and Merin 1980).*

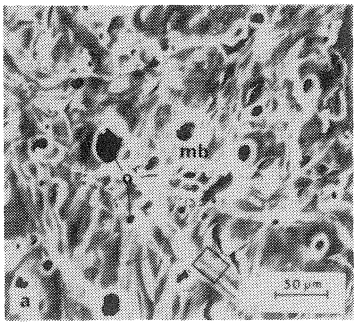


Figure 1.8. *Scanning electron micrograph of the bottom side of an asymmetric membrane. The "pores" or openings on this side of the membrane are much larger to minimize resistance of solvent transport (adapted from Merin 1979).*

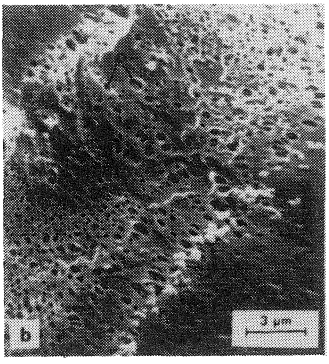


Figure 1.9. *Enlargement of the area shown in the box in Figure 1.8.*

Since that time, several major commercial developments in membrane science have taken place. The most notable include inorganic membranes, presently dominated by ceramic membranes, and which saw large-scale commercial applications in the early 1980s. Nanofiltration membranes found its own successful niche during this decade, as did large-scale gas separations. As we come to the end of the 20th century, new developments in pervaporation (so termed and observed by Kober as early as 1917) and bipolar membranes for electrodialysis will further widen the applicability of membrane technology in a wide variety of industries.

1.C.
PHYSICAL CHEMISTRY OF MEMBRANE SEPARATIONS

1.C.1.
CHEMICAL POTENTIAL AND OSMOSIS

All thermodynamic relationships used to correlate physicochemical properties of a system with thermodynamic parameters stem from the Gibbs free energy equation, which in its simplest form can be expressed as:

$$G = H - TS \tag{1.1}$$

$$H = E + PV \tag{1.2}$$

where

G = Gibbs free energy
H = enthalpy
T = absolute temperature
S = entropy
E = internal energy
P = pressure
V = volume

In differential form, these equations can be written as

$$\mathrm{d}G = \mathrm{d}H - T\,\mathrm{d}S - S\,\mathrm{d}T \tag{1.3}$$

$$\mathrm{d}H = \mathrm{d}E + P\,\mathrm{d}V + V\,\mathrm{d}P \tag{1.4}$$

or

$$\mathrm{d}G = \mathrm{d}E + P\,\mathrm{d}V + V\,\mathrm{d}P - T\,\mathrm{d}S - S\,\mathrm{d}T \tag{1.5}$$

From the first law of thermodynamics, we can write

$$dE = dq + dw \tag{1.6}$$

where q is the heat produced and w is the work done. Assuming the change in the system is reversible, by the second law,

$$dq - T\,dS = 0 \tag{1.7}$$

Assuming further that only "PV" work is allowed (i.e., no electric or magnetic fields present) and no change in composition of the system

$$dw + P\,dV = 0 \tag{1.8}$$

Combining Equations (1.5) through (1.8), we get the final result as

$$dG = V\,dP - S\,dT \tag{1.9}$$

For "open" systems, i.e., one in which matter and energy may leave and enter, the earlier equations must be modified by adding terms relating changes in the mass of a system. Equation (1.9) will then become

$$dG = -S\,dT + V\,dP + \mu_1\,dn_1 + \mu_2\,dn_2 + \mu_3\,dn_3 + \cdots \tag{1.10}$$

where

μ = chemical potential, by definition, of component 1, 2, 3 . . .

n = number of moles of component 1, 2, 3 . . .

$$dG = -S\,dT + V\,dP + \mu_i\,dn_i \tag{1.11}$$

Thus, by definition,

$$\mu_i = (\partial G/\partial n_i)_{T,P,n_j} \tag{1.12}$$

where i denotes the ith component of interest and j denotes all other components. Unlike other intensive thermodynamic properties such as pressure and temperature (i.e., those not dependent on the size of the system), chemical potential cannot be physically "felt" the way heat and force can, which results in some difficulty for the novice when trying to grasp its significance. In simple

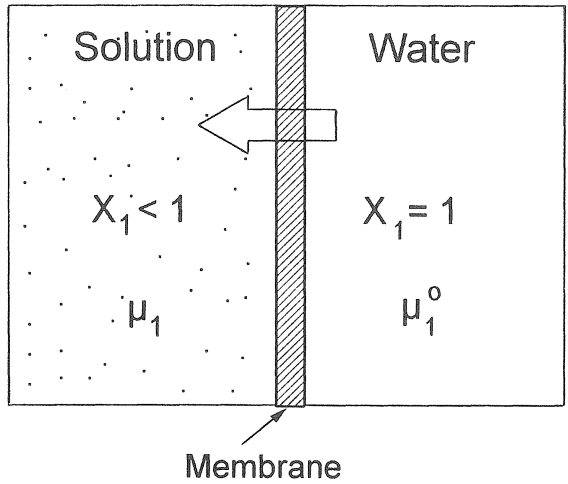


Figure 1.10. *The osmosis phenomenon. The two compartments are separated by an ideal semipermeable membrane. Arrow shows direction of water transport under the chemical potential gradient.*

terms, chemical potential μ can be looked at as being to chemical energy what temperature is to heat energy, pressure is to mechanical energy (e.g., flow of fluids), and voltage, or emf, is to electrical energy. Thus, chemical potential is essentially a driving force expressed as a change in the free energy of the system as a result of the change in the composition of the system.

The application of these concepts is shown in Figure 1.10, which shows two compartments separated by a semipermeable membrane. The right one contains a very dilute solution, or the pure solvent, and the other contains a solute dissolved in the solvent. The standard chemical potential is defined as the free energy change per mole of substance formed, consumed, or transferred from one phase to another in its standard state. The standard state is usually defined as being 1 atmosphere pressure at a particular temperature (e.g., 20°C) and in a certain reference form, usually the pure state of the component. For aqueous systems, this is pure water. Thus, in Figure 1.10, the pure solvent compartment, containing a mole fraction of water (X_1) of 1 would have a chemical potential designated by μ_1^0, while the solution compartment, with a mole fraction of water less than 1, would have a lower chemical potential of μ_1.

Physically speaking, the highest energy form of water is when it is in its pure state. Adding any material or impurity increases the entropy (since we create disorder in the system when a solute is added). The Gibbs energy Equation (1.1) states that this will result in a decrease in free energy. In other words, the chemical potential of water in a solution is always lower than when it is in a pure state. This means that the water in the right compartment has a greater chemical

potential than the water in the left compartment. Since the two compartments are separated by a semipermeable membrane, which in the ideal case is permeable only to the water and not to the solute, the natural tendency would be for the water to flow in the downward direction of the driving force. Thus, the water would be transported from the right compartment to the left. This is the phenomenon of *osmosis*, the movement of solvent from the dilute solution to the more concentrated solution. In the ideal case, with no pressure effects on either side of the membrane, the water would diffuse until the chemical potentials on both sides of the membrane were equal. In theory, this should never happen because of the presence of the solute in the solution compartment, resulting in X_1 always being less than 1. In practice, the increase in height of the liquid column in the left (solution) compartment would create a hydraulic pressure against the membrane, and the water would stop diffusing through the membrane when the pressure developed would just balance the chemical potential difference. This is shown schematically in Figure 1.11.

1.C.2. VAPOR PRESSURE

The two compartments depicted in Figure 1.10 will also have differences in vapor pressure as a result of differences in solvent concentration. The vapor pressure of a solution is always less than that of the pure solvent. This is best expressed according to Raoult's law as follows:

$$P = X_1 P^0 \tag{1.13}$$

where P is the vapor pressure of the solution and P^0 the vapor pressure of the pure solvent at that temperature. As mentioned earlier, to prevent passage of solvent from the pure solvent side to the solution side, we need to apply a pressure on the solution side equal to the osmotic pressure difference. However, this osmotic pressure is *not* the difference in the vapor pressures ($P^0 - P$). It is important to remember that, in osmosis (and reverse osmosis), we must overcome not only hydraulic and mechanical resistances, but also try to achieve chemical equilibrium. In other words, the criterion for osmotic equilibrium is that the *chemical potential of the solvent* should be the same on both sides of the membrane, rather than the "pressures" being the same.

1.C.3. OSMOTIC PRESSURE AND CHEMICAL POTENTIAL

In order to develop a relationship between osmotic pressure, chemical potential, and parameters that can be easily measured experimentally, we need to make two assumptions: (1) the solvent vapor behaves ideally and Raoult's law applies, and (2) the liquid is incompressible.

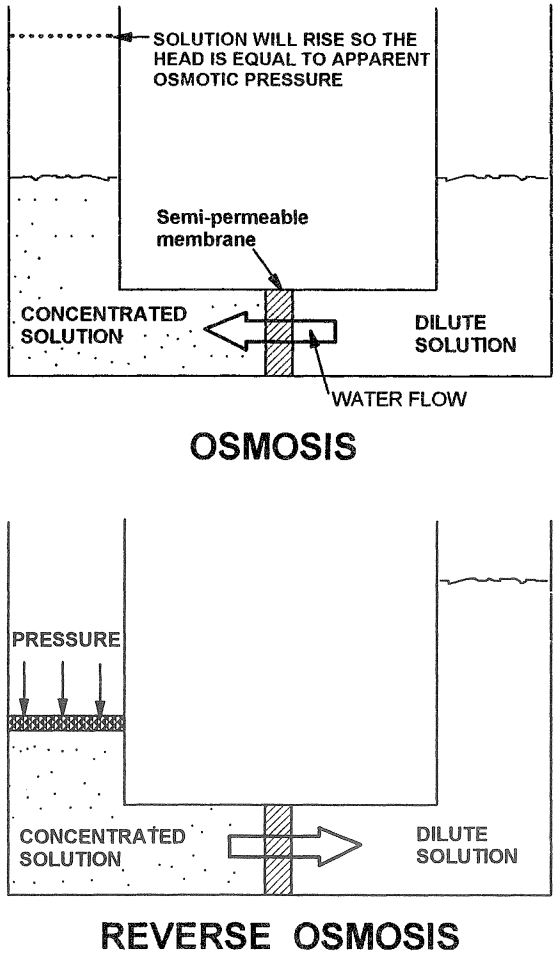


Figure 1.11. *The phenomena of osmosis and reverse osmosis.*

At constant temperature and composition, we can rewrite Equation (1.11) as

$$(\partial G/\partial P)_{T,n_i} = V \tag{1.14}$$

$$\left(\frac{\partial^2 G}{\partial n_i \partial P}\right)_{T,n_i} = \left(\frac{\partial V}{\partial n_i}\right)_{T,P,n_j} \tag{1.15}$$

By definition,

$$(\partial V/\partial n_i)_{T,P,n_j} = \bar{V}_i \tag{1.16}$$

where $\bar{V}_i$ is the partial molar volume of component i, which is the increase in volume per mole of component i when an infinitesimal amount of i is added. From Equations (1.12), (1.15), and (1.16),

$$\bar{V}_i = (\partial \mu_i / \partial P)_{T, n_i, n_j} \tag{1.17}$$

or

$$\mathrm{d}\mu_i = \bar{V}_i \, \mathrm{d}P \tag{1.18}$$

Equation (1.18) shows that the chemical potential of a system can be changed by changing the external applied pressure. Furthermore, since a solution and its vapor are in equilibrium, we can also substitute the ideal gas law into Equation (1.18) and obtain

$$\mathrm{d}\mu_i = RT \frac{\mathrm{d}P_i}{P_i} \tag{1.19}$$

Equation (1.19) states that a change in vapor pressure, due to a change in the concentration of solute or solvent, for example, will result in a change in chemical potential. Both Equations (1.18) and (1.19) relate changes in chemical potential μ for infinitesimally small changes in pressure for an ideal solution.

The following boundary conditions can be used when integrating Equation (1.19): for ideal solutions, $\mu = \mu_i^0$ when $P = P^0$, and $\mu = \mu_1$ when $P = P$. Thus, after integrating Equation (1.19):

$$\mu_i - \mu_i^0 = RT \ln P/P^0 \tag{1.20}$$

Or, for aqueous solutions, denoting $i = 1$ for water,

$$\mu_1^0 - \mu_1 = -RT \ln P/P^0 \tag{1.21}$$

Substituting Equation (1.13) into Equation (1.21),

$$\mu_1^0 - \mu_1 = -RT \ln X_1 \tag{1.22}$$

In physical terms, the above equation states that, since the mole fraction of water in a solution is always less than 1, the term ($\ln X_1$) is negative, which means the right-hand side of Equation (1.22) is always a positive quantity. Thus, $\mu_1^0 > \mu_1$ and the natural phenomenon will be for water to flow from the pure water side to the solution side. To overcome this natural tendency, the chemical potential difference has to be overcome by applying external pressure

to the solution side, in order to raise its chemical potential. Thus, the governing equation will now be a combination of Equations (1.22) and (1.18):

$$\mu_1 - \mu_1^0 = RT \ln X_1 + \int_{P_0}^{P^*} \bar{V}\, dP \tag{1.23}$$

where P^* is the external pressure and P_0 is a standard pressure. By definition, the pressure applied such that $\mu_1 - \mu_1^0 = 0$ is called osmotic pressure, i.e., $\pi = (P^* - P_0)$, and assuming further that the liquid is incompressible, so that V can be taken out from under the integral sign in Equation (1.23),

$$V_1 \pi = -RT \ln X_1 \tag{1.24}$$

or

$$\pi = \frac{RT}{\bar{V}_i} \ln X_1 \tag{1.25}$$

Equation (1.25) is the thermodynamic relationship for osmotic pressure, derived using only two assumptions: ideal solution behavior, which holds true only for very dilute solutions, and the liquid is incompressible, which is valid only at relatively low pressures.

Van't Hoff had independently developed a correlation for osmotic pressure

$$\pi = n_2 RT \tag{1.26}$$

where n_2 is the molar concentration of the solute in moles per liter of the solution. Van't Hoff's Equation (1.26) can be derived from the more rigorous Equation (1.25) by making some rather extreme approximations: since X_1 is mole fraction of water,

$$X_1 + X_2 = 1 \tag{1.27}$$

$$X_1 = 1 - X_2 \tag{1.28}$$

When X_2 is very small, i.e., when $X_2 \ll 1$,

$$\ln(1 - X_2) = -X_2 \tag{1.29}$$

$$\ln X_1 = -X_2 \tag{1.30}$$

By definition,

$$X_2 = \frac{N_2}{N_1 + N_2} \tag{1.31}$$

where N is the number of moles of component 1 or 2. Since $N_2 \ll 1$, Equation (1.31) can also be written to a first approximation as

$$X_2 = \frac{N_2}{N_1} \tag{1.32}$$

Substituting Equations (1.30) and (1.32) into Equation (1.25), we get

$$\pi = \frac{N_2}{V_1 N_1} RT \tag{1.33}$$

By definition, V_1 = molar volume of solvent = volume of solvent/moles of solvent = volume of solvent/N_1. Or

$$V_1 N_1 = \text{volume of solvent} \tag{1.34}$$

When the solution is an ideal, dilute, one, the volumes of the solvent and solution are essentially the same. Therefore, Equation (1.34) can be substituted into Equation (1.33) to get

$$\pi = \frac{N_2}{\text{Volume of solvent}} RT = n_2 RT = i \frac{C}{M} RT \tag{1.35}$$

which is the same as van't Hoff's Equation (1.26), where

C = concentration of solute in g/L of solution
M = molecular weight of solute
i = number of ions for ionized solutes (e.g., i = 1 for sugars, i = 2 for NaCl)
T = temperature of the solution in the absolute scale (e.g., °K or °R)
R = ideal gas constant (e.g., 0.08206 atm-L/gmole · °K, or 8315 N-m/kgmole · °K, or 1545 ft-lb_f/lbmole · °R)

Note that the van't Hoff equation has been modified for ionized solutes to include i.

Table 1.3 shows the relative accuracy of the two models in predicting osmotic pressure. The van't Hoff model deviates significantly even at low solute concentrations because of the several approximations made in its development. The Gibbs (thermodynamic) relationship, Equation (1.25), is more accurate over a wider range of solute concentrations. Higher concentration results in deviations from ideal solution behavior even with the Gibbs equation.

Since the van't Hoff equation resembles the ideal gas law, a common misconception has been to visualize osmotic pressure as being caused by the bombardment of solute molecules against the membrane. Higher concentrations

Table 1.3. Osmotic pressure of aqueous sucrose solutions at 30°C.

Concentration (% w/w)	Molality	Osmotic Pressure (atm)		
		van't Hoff Equation	Gibbs Model	Experimental Data
25.31	0.991	20.3	26.8	27.2
36.01	1.646	30.3	47.3	47.5
44.73	2.366	39.0	72.6	72.5
52.74	3.263	47.8	107.6	105.9
58.42	4.108	54.2	143.3	144.0
64.58	5.332	61.5	199.0	204.3

of solute would then logically result in higher osmotic pressure. This view is incorrect since the presence of the membrane per se is not necessary for the existence of an osmotic pressure.

The physical significance of osmotic pressure in biological and clinical situations is well known: the osmotic pressure difference is what causes germinating seeds to burst open their protective coat, causes the drawing of water from the soil into the root system of plants, and can burst open cells by immersing them in a solution of much lower osmotic pressure. As far as membrane processing is concerned, its major significance lies in the fact that the external pressure that must be applied for significant permeate flux must be higher than the osmotic pressure of the solution. As will be seen later, the basic relationship between applied pressure (e.g., by a pump), osmotic pressure, and flow of solvent through a membrane is, like many transport processes, expressed in terms of the flux (the rate of solvent transport per unit area per unit time) and the driving force and resistances. For an ideal semipermeable membrane:

$$J = A(P_T - \pi_F) \tag{1.36}$$

where J is the flux, A is a membrane permeability coefficient (the reciprocal of resistance to flow), P_T is the transmembrane pressure, and π_F is the osmotic pressure of the feed solution. Thus, there has to be a positive driving force for flux; i.e., P_T must be always greater than π_F.

Even relatively small concentrations of dissolved solutes can develop fairly large osmotic pressures. A concentration difference of 0.1 M across a membrane can result in an osmotic pressure of about 2.5 bar (about 37 psi). Table 1.4 shows some examples of osmotic pressure calculations using the van't Hoff equation. With sodium chloride, a 1% solution results in an osmotic pressure of about 125 psi (860 kPa). Thus, no flux will be obtained unless the pressure is above 860 kPa. On the other hand, a 1% solution of lactose (MW = 342) will have an osmotic pressure of 10 psi (69 kPa) and a 1% solution of casein, a milk protein (MW = 25,000) only 0.28 psi (1.8 kPa). Thus, much lower pressures have to

Table 1.4. Osmotic pressure of 1% solutions at 30° C, calculated using the van't Hoff equation.

Component	Molecular Weight (M)	Number of Ions (i)	Osmotic Pressure (psi)
NaCl	58.50	2	125
Lactose	342	1	10
Casein	25,000	1	0.28

be applied with the protein and sugar solutions than with the salt solution. This is why osmotic pressures are of little or no consequence in UF and MF, but important in RO and NF.

This is shown in Figure 1.12, which shows typical flux during RO of water ($\pi_F = 0$), solutions of 1% NaCl, 1% lactose, and a real liquid food (skim milk of 9.1% total solids with an osmotic pressure of 100 psi). As expected, no permeation was observed until the applied pressure was higher than the osmotic pressure. The slopes of the salt and sugar lines are almost the same as the water line. With milk, however, there is a deviation from linearity. As will be explained in Chapter 4, this is because of "concentration polarization" of

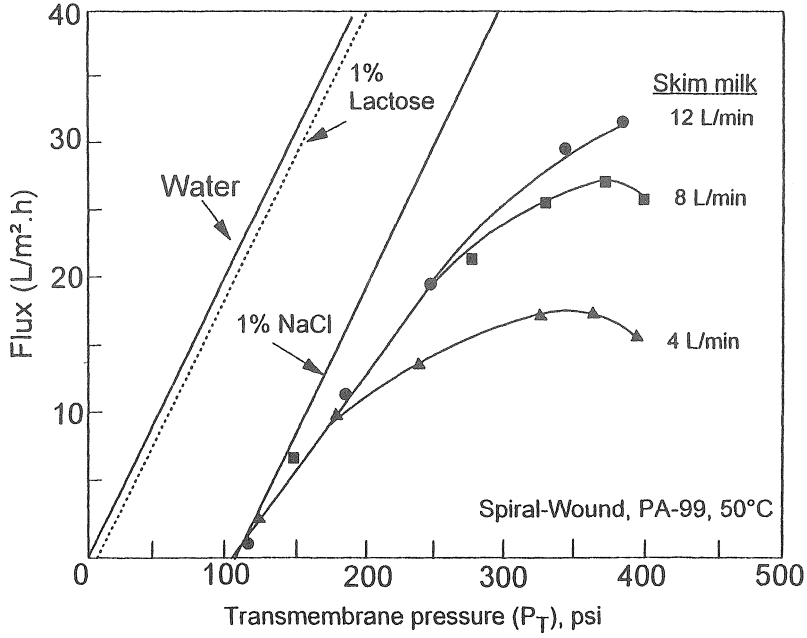


Figure 1.12. Reverse osmosis of a salt solution, sugar solution, and a complex protein suspension (adapted from Cheryan et al. 1990).

rejected particles. Flux becomes controlled by the mass transfer characteristics of the system. This explains why turbulence (in the form of higher velocities) has a beneficial effect with skim milk, but not so with salt or lactose where polarization is less important.

The significance of these calculations in MF and UF is that, at the normal concentrations of polymers and macromolecules (e.g., proteins), the osmotic pressure due to the presence of these macromolecules is usually low enough to be negligible. Since MF and UF are designed to retain only the larger dissolved solutes, such as proteins and other colloidal substances, it is assumed that the prevailing osmotic pressures in UF and MF are usually low enough to ignore, and thus the operating strategy will be to maximize mass transfer effects and control viscosity. In RO and NF, osmotic pressure effects are likely to be the dominant resistance.

Osmotic pressure data for macromolecular or colloidal solutes are few, especially as a function of concentration. This is unfortunate, since at sufficiently high concentrations, the osmotic pressure could become significant, especially at the membrane surface due to the polarization phenomenon (see Section 4.E. later). Table 1.5 lists osmotic pressures of food and biological products. Osmotic pressure data obtained from reverse osmosis experiments must be used with caution, since it is frequently obtained by extrapolation of flux data to zero flux.

If the van't Hoff model is used to calculate osmotic pressure, it should be remembered that it assumes that osmotic pressure will increase in a linear fashion with solute concentration. In fact, much of the actual experimental data and the Gibbs osmotic model indicate an exponential increase, as shown in Table 1.3 and also in Figures 1.13–1.15. Figure 1.13 compares the van't Hoff equation with experimental data. For charged molecules such as proteins, the

Table 1.5. Osmotic pressure of foods at room temperature.

Food	Concentration	Osmotic Pressure (psi)
Milk	9% solids-not-fat	100
Whey	6% total solids	100
Orange juice	11% total solids	230
Apple juice	15% total solids	300
Grape juice	16% total solids	300
Coffee extract	28% total solids	500
Lactose	5% w/v	55
Sodium chloride	1% w/v	125
Lactic acid	1% w/v	80
Sweet potato wastewater	22% total solids	870
Perilla anthocyanins	10.6% total solids	330

1 psi = 6.895 kPa = 0.0689 bar

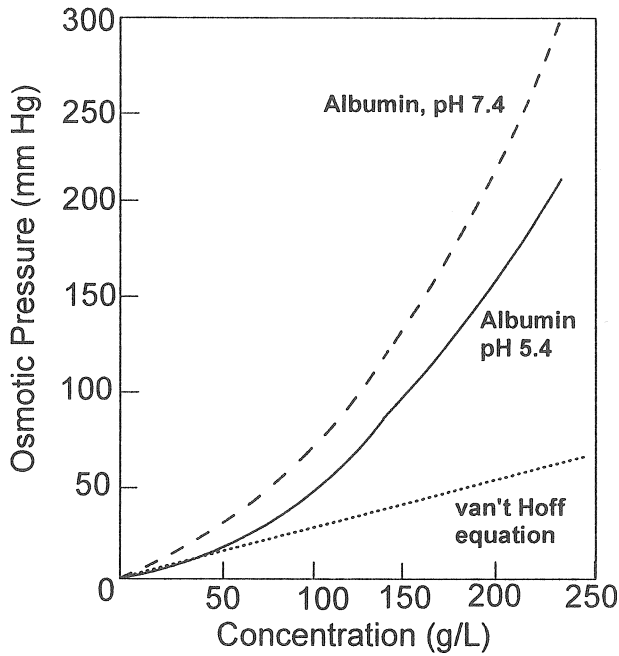


Figure 1.13. *Effect of protein concentration and pH on osmotic pressure of serum albumin. The bottom curve is the calculated curve based on the van't Hoff equation for a solute of 60,000 molecular weight. The other two curves are experimental data. Differences between the van't Hoff curve and the others are due to nonideality of the albumin solutions at higher concentrations. The difference between the two albumin curves is due to the net negative charge at pH 7.4 and the consequent Gibbs-Duheim effect (adapted from Scatchard et al. 1944).*

osmotic pressure also depends on pH and ionic strength of the solution. In general, osmotic pressure of protein solutions is minimum at the isoelectric point and tends to be higher away from the isoelectric point, especially if other charged species and salts are present. This phenomenon is shown in Figures 1.13 and 1.14. This pH effect is usually ascribed to the Gibbs-Donnan effect.

The dextran T10 and whey protein solutions (Figure 1.15) show surprisingly high osmotic pressures at concentrations where the viscosity is relatively low. For example, a 50% w/w dextran solution has a very high osmotic pressure of 25.5 atm, but the viscosity is only 270 cP (Jonsson 1984). Considering the magnitude of the osmotic pressures in Figures 1.13–1.15, it is quite possible that it is the osmotic pressure at the membrane surface that limits the flux, in addition to the resistance of any "gel-polarized" layer (see discussion in Chapter 4). The exponential increase in osmotic pressure with concentration also explains the maxima noticed at high pressures during RO (e.g., with skim milk in Figure 1.12).

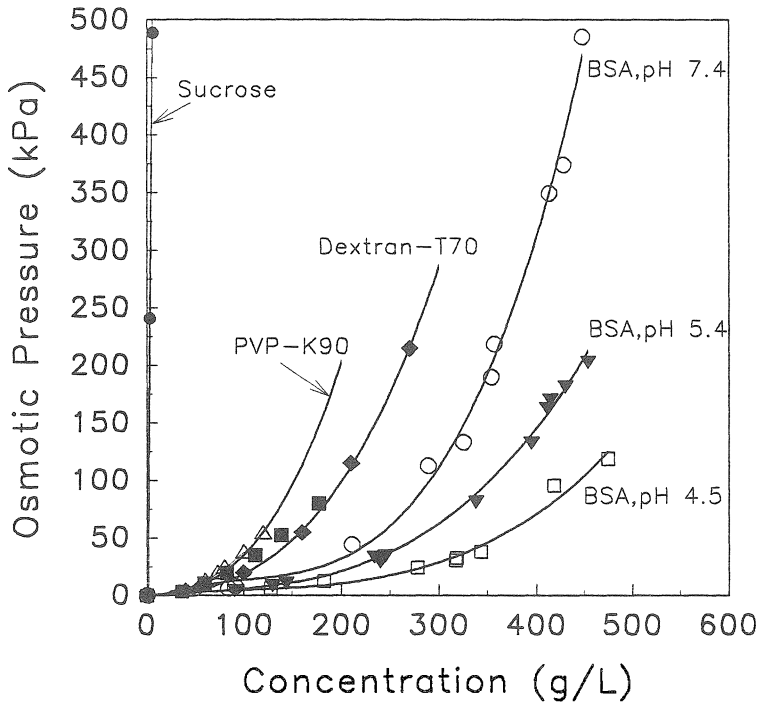


Figure 1.14. *Effect of concentration on osmotic pressure of selected macromolecules. Sucrose is shown for comparison. Lines are drawn according to the osmotic pressure model [Equation (1.37)] and virial coefficients in Table 1.6. Points are experimental data. The effect of pH on bovine serum albumin (BSA) is shown. Data sources are shown in Table 1.6.*

To account for the curvature in the osmotic pressure-concentration data, the van't Hoff model for osmotic pressure is expressed as

$$\pi = A_1 C + A_2 C^2 + A_3 C^3 + \cdots \tag{1.37}$$

where $A_1, A_2, \ldots$ are known as the "virial coefficients." Table 1.6 lists typical virial coefficients for several solutes. At high concentrations of macromolecules, the second and third virial coefficients may become sufficiently important that osmotic pressure effects may become significant in ultrafiltration.

In summary, the major resistances to be overcome in reverse osmosis are the resistance of the membrane, osmotic pressure of the retained solutes, and possibly mass transfer resistance in the boundary layer. In ultrafiltration and microfiltration, on the other hand, the major resistance is usually due to concentration polarization and the associated boundary layer and, to a lesser extent, the membrane resistance itself, depending on the feed properties and the operating conditions. Under certain conditions and with certain solutes, the osmotic

Table 1.6. Virial coefficients of selected compounds to calculate osmotic pressure (in kPa) with Equation (1.37).

Compound	Valid Range of Concentration	Units of C	A_1	A_2	A_3	Reference
Bovine serum albumin						Vilker et al. (1984)
pH 7.4	0–450 g/L	g/L	3.787×10^{-1}	-2.98×10^{-3}	1.000×10^{-5}	
pH 5.5	0–450 g/L	g/L	5.633×10^{-2}	-2.80×10^{-4}	2.604×10^{-6}	
pH 4.5	0–475 g/L	g/L	7.539×10^{-2}	-4.90×10^{-4}	1.852×10^{-6}	
Cetyl pyridinium chloride	0–200 g/L	g/L	0.39231	1.507×10^{-3}	1.605×10^{-5}	Markels et al. (1995)
Dextran D2	0–16.2%	% w/w	0.05102	0.1047	0.01055	Vink (1971)
Dextran T10	0–50% w/w	% w/w	11.31	−0.49752	0.03	Jonsson (1984)
Dextran T70	0–110 g/L	g/L	0.139	1.1×10^{-3}	3.16×10^{-6}	Nicolas et al. (1995)
MW = 70,400	0–270 g/L	g/L	3.75×10^{-3}	7.52×10^{-4}	7.64×10^{-6}	Wijmans et al. (1985)
MW = 66,300	0–500 g/L	% w/v	0.637	0.0625	7.62×10^{-3}	Clifton et al. (1984)
Dextran T500	0–200 g/L	g/L	8.67×10^{-3}	2.98×10^{-4}	8.98×10^{-6}	Wijmans et al. (1985)
Fibrinogen (bovine)	0–80 g/L	g/L	9.948×10^{-3}	-2.104×10^{-4}	2.833×10^{-6}	Vilker et al. (1984)
Fruit juices	0–0.12	X_c^*	2.675×10^{4}	1.287×10^{4}	1.2715×10^{6}	Sourirajan and Matsuura (1985)
Glycerol	0–35%	% w/w	262.06	2.669	0.0481	Sourirajan (1970)
Hydroxyethyl cellulose	0–8.4%	% w/w	1.232	0.3292	0.0125	Vink (1971)
β-Lactoglobulin	0–250 g/L	g/L	2.699×10^{-2}	1.311×10^{-3}	7.277×10^{-8}	van den Berg et al. (1987)
Low-density lipoprotein	0–300 g/L	g/L	1.001×10^{-3}	2.888×10^{-6}	3.269×10^{-8}	Vilker et al. (1984)
Mushroom blanch water	0–22% TS	% w/w	201.80	7.84	−0.2325	Chiang et al. (1986)
Ovalbumin	0–30% w/w	% w/w	3.55	0	8.34×10^{-3}	Nabetani et al. (1990)

(continued)

(continued)

Table 1.6. Virial coefficients of selected compounds to calculate osmotic pressure (in kPa) with Equation (1.37).

Compound	Valid Range of Concentration	Units of C	A_1	A_2	A_3	Reference
Polyethylene glycol						
PEG 6	14–40%	% w/w	15.72	−0.5738	0.0787	Prouty et al. (1985)
PEG 20	0–60%	% w/w	9.65	−0.177	0.04964	Prouty et al. (1985)
Polyethylene oxide						
MW = 43,500	0–7%	% w/w	3.32506	−0.9779	0.3352	Vink (1971)
MW = 278,000	0–130 g/L	g/L	4.439×10^{-2}	6.18×10^{-3}	3×10^{-5}	Nicolas et al. (1995)
MW = 600,000	0–60 g/L	g/L	1.097×10^{-2}	-9.72×10^{-5}	3.67×10^{-6}	Vilker et al. (1984)
Polystyrene 90 K	Up to 150 g/L	g/L	5.698×10^{-2}	8.3×10^{-4}	2×10^{-5}	Nicolas et al. (1995)
Polyvinylpyrrolidone						
PVP1 (MW = 27,900)	0–12.4%	% w/w	1.1816	0.0438	0.02549	Vink (1971)
PVP40 (MW = 40,000)	0–43%	% w/w	−5.7302	0.11496	0.0323	Prouty et al. (1985)
PVP K90	0–200 g/L	g/L	2.13×10^{-2}	1.626×10^{-3}	1.659×10^{-5}	Nicolas et al. (1995)
Sodium chloride solutions	0–25%	% w/w	869.50	−5.1105	1.0403	Sourirajan (1970)
Sucrose solutions	0–25%	% w/w	163.47	−5.882	0.1324	Sourirajan (1970)
Sweet potato waste water	6–22% TS	% w/w	−78.955	24.845	−0.5724	Chiang and Pan (1986)
Whey protein isolate	0–50%	% w/w	4.4585	-1.723×10^{-2}	8.0×10^{-3}	Jonsson (1984)

*Carbon weight fraction

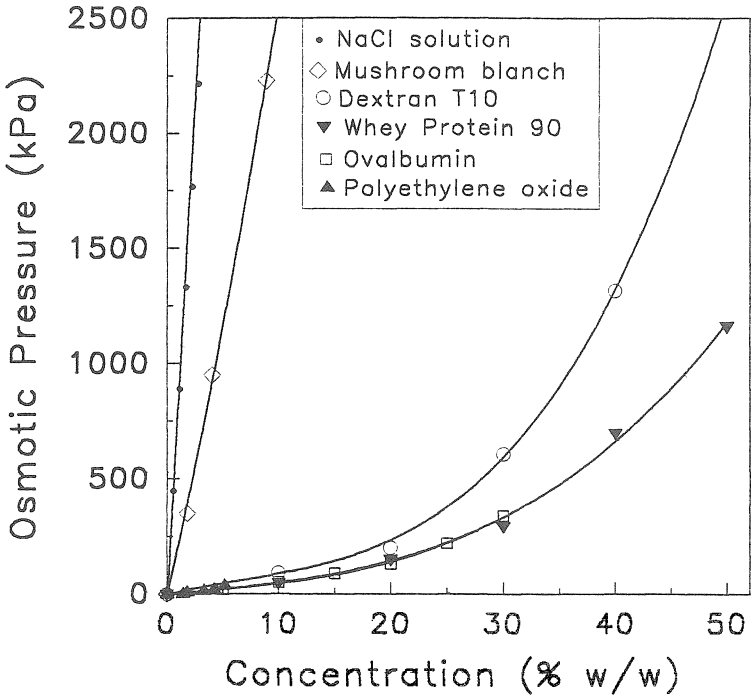


Figure 1.15. *Effect of concentration on osmotic pressure. Lines are drawn according to the osmotic pressure model [Equation (1.37)] and virial coefficients in Table 1.6. Points are experimental data. Data sources are shown in Table 1.6.*

pressure may become the limiting factor in ultrafiltration also. Thus, the operating strategy to maximize the flux will depend on the mechanism of the limiting flux.

REFERENCES

BODDEKER, K. W. 1995. *J. Membrane Science* 100: 65.

CHERYAN, M. and MERIN, U. 1980. *Polymer Sci. Technol.* 13: 619.

CHERYAN, M. and NICHOLS, D. J. 1992. In *Mathematical Modelling of Food Processes*, S. Thorne (ed.), Elsevier, London, p. 49.

CHERYAN, M., VEERANJANEYULU, B. and SCHLICHER, L. R. 1990. *J. Membrane Sci.* 48: 103.

CHIANG, B. H., CHU, C. L. and HWANG, L. S. 1986. *J. Food Sci.* 51: 608.

CHIANG, B. H. and PAN, W. D. 1986. *J. Food Sci.* 51: 971.

CLIFTON, M. J., ABIDINE, N., APTEL, P. and SANCHEZ, V. 1984. *J. Membrane Sci.* 21: 233.

DUTKA, B. J. 1981. *Membrane Filtration. Applications, Techniques, Problems.* Marcel Dekker, New York.

GELMAN, C. 1965. *Anal.Chem.* 87: 29.

GRAHAM, T. 1854. *Phil. Trans., Roy. Soc. (London)* 144: 177.

HWANG, S. T. and KAMMERMEYER, K. 1975. *Membranes in Separations*, Wiley-Interscience, New York.

JONSSON, G. 1984. *Desalination* 51: 61.

Koch Membrane Systems. 1987. Product literature. Wilmington, MA.

LAKSHMINARAYANAIAH, N. 1984. *Equations of Membrane Biophysics*. Academic Press, New York.

LLOYD, D. R. 1985. *Material Science of Synthetic Membranes*. American Chemical Society, Washington, DC.

LOEB, S. 1981. In *Synthetic Membranes. Vol. 1. Desalination*, A. F. Turbak (ed.), American Chemical Society, Washington, DC.

LONSDALE, H. 1982. *J. Membrane Sci.* 10: 81.

MARKELS, J. H., LYNN, S. and RADKE, C. J. 1995. *AIChE J.* 41: 2058.

MERIN, U. 1979. Ph.D. Thesis, University of Illinois, Urbana.

NABETANI, H., NAKAJIMA, M., WATANABE, A. NAKAO, S. and KIMURA, S. 1990. *AIChE J.* 36: 907.

NICOLAS, S., BOULANOUAR, I. and BARCOU, B. 1995. *J. Membrane Sci.* 103: 19.

PROUTY, M. S., SCHECHTER, A. N. and PARSEGIAN, V. A. 1985. *J. Mol. Biol.* 184: 517.

RAMAN, L. P., CHERYAN, M. and RAJAGOPALAN, N. 1994. *Chem. Engr. Progr.* 90 (3): 68.

REID, C. E. and BRETON, E. J. 1959. *J. Applied Polymer Sci.* 1: 133.

SCATCHARD, G., BATCHELDER, C. and BROWN, A. 1944. *J. Clin. Investigation* 23: 459.

SOURIRAJAN, S. 1970. *Reverse Osmosis*. Academic Press, New York.

SOURIRAJAN, S. and MATSUURA, T. 1985. *Reverse Osmosis/Ultrafiltration Process Principles*. National Research Council, Ottawa, Canada.

TOMBS, M. P. and PEACOCKE, A. R. 1974. *The Osmotic Pressure of Biological Macromolecules*. Clarendon Press, Oxford.

VAN DEN BERG, G. B., HANEMAAIJER, J. H. and SMOLDERS, C. A. 1987. *J. Membrane Sci.* 31: 307.

VILKER, V. L., COLTON, C. K., SMITH, K. A. and GREEN, D. L. 1984. *J. Membrane Sci.* 20: 63.

VINK, H. 1971. *Eur. Polym. J.* 7: 1411.

WIJMANS, J. G., NAKAO, S., VAN DEN BERG, J. W. A., TROELSTRA, F. R. and SMOLDERS, C. A. 1985. *J. Membrane Sci.* 22: 117.

YUSTER, S. T., SOURIRAJAN, S. and BERNSTEIN, K. 1958. Report 58-26, University of California-Los Angeles, Department of Engineering.

Taylor & Francis
Taylor & Francis Group
http://taylorandfrancis.com

References

1 1: INTRODUCTION

Boddeker, K. W. 1995. J. Membrane Science 100: 65.

Cheryan, M. and Merin, U. 1980. Polymer Sci. Technol. 13: 619.

Cheryan, M. and Nichols, D. J. 1992. In Mathematical Modelling of Food Processes, S. Thome (ed.), Elsevier, London, p. 49.

Cheryan, ML, Veeranjaneyulu, B. and Schlicher, L. R. 1990. J. Membrane Sci. 48: 103.

Chiang, B. H., Chu, C. L. and Hwang, L. S. 1986. J. Food Sci. 51: 608.

Chiang, B. H. and Pan, W. D. 1986. J. Food Sci. 51: 971. Clifton, M. J., Abidine, N., Aptel, P. and Sanchez, V. 1984. J. Membrane Sci. 21: 233. Dutka, B. I. 1981. Membrane Filtration. Applications, Techniques, Problems. Marcel Dekker, New York. Gelman, C. 1965. Anal.Chem. 87: 29. Graham, T. 1854. Phil Trans., Roy. Soc. (London) 144: 177. Hwang, S. T. and Kammermeyer, K. 1975. Membranes in Separations, Wiley- Interscience, New York. Jonsson, G. 1984. Desalination 51: 61. Koch Membrane Systems. 1987. Product literature. Wilmington, MA. Lakshminarayanaiah, N. 1984. Equations of Membrane Biophysics. Academic Press, New York. Lloyd, D. R. 1985. Material Science of Synthetic Membranes. American Chemical Society, Washington, DC. Loeb, S. 1981. In Synthetic Membranes. Vol. 1. Desalination, A. F. Turbak (ed.), Amer ican Chemical Society, Washington, DC. Lonsdale, H. 1982. J. Membrane Sci. 10: 81. Markels, J. H., Lynn, S. and Radke, C. J. 1995. AIChE J. 41: 2058. Merin, U. 1979. Ph.D. Thesis, University of Illinois, Urbana. Nabetani, H., Nakajima, M., Watanabe, A. Nakao, S. and Kimura, S. 1990. AIChE J. 36: 907. Nicolas, S., Boulanouar, I. and Barcou, B. 1995. J. Membrane Sci. 103: 19. Prouty, M. S., Schechter, A. N. and Parsegian, V. A. 1985. J. Mol. Biol. 184: 517. Raman, L. R, Cheryan, M. and Rajagopalan, N. 1994. Chem. Engr. Progr. 90 (3): 68. Reid, C. E. and Breton, E. J. 1959. J. Applied Polymer Sci. 1: 133. Scatchard, G., Batchelder, C. and Brown, A. 1944. J. Clin. Investigation 23: 459. Sourirajan, S. 1970. Reverse Osmosis. Academic Press, New York. Sourirajan, S. and Matsuura, T. 1985. Reverse Osmosis/Ultrafdtration Process Prin ciples. National Research Council, Ottawa, Canada. Tombs, M. P. and

Peacocke, A. R. 1974. The Osmotic Pressure of Biological Macro molecules. Clarendon Press, Oxford. van den Berg, G. B., Hanemaaijer, J. H. and Smolders, C. A. 1987. J. Membrane Sci. 31: 307. Vilker, V. L., Colton, C. K., Smith, K. A. and Green, D. L. 1984. J. Membrane Sci. 20: 63. Vink, H. 1971. Eur. Polym. J. 1: 1411. Wijmans, J. G., Nakao, S., van den Berg, J. W. A., Troelstra, F. R. and Smolders, C. A. 1985. J. Membrane Sci. 22: 117. Yuster, S. T., Sourirajan, S. and Bernstein, K. 1958. Report 58-26, University of California-Los Angeles, Department of Engineering.

Cadotte, J. E. 1985. In Materials Science o f Synthetic Membranes, D. R. Lloyd (ed.), American Chemical Society, Washington, DC.

Colomban, A., Roger, L. and Boyaval, P. 1993. Biotechnol Bioeng. 42: 1091.

Deanin, R. D. 1972. Polymer Structure, Properties and Applications. Chaners Books, Boston, MA. Resting, R. E. 1971. Synthetic Polymeric Membranes. McGraw-Hill, New York. Resting, R. E. 1985. Synthetic Polymeric Membranes. A Structural Perspective. 2nd edition. Wiley-Interscience, New York.

Rlein, E. 1991. Affinity Membranes. John Wiley, New York.

Leslie, V. L., Rose, J. B., Rudkin, G. O. and Feltzin, J. 1974. In New Industrial Polymers, R.D. Deanin (ed.), Symposium Series No. 4. American Chem. Society, Washington, DC.

Lloyd, D. R. 1985. Materials Science o f Synthetic Membranes. American Chemical Society, Washington, DC.

Lloyd, D. R., Barlow, J. and Rinzer, R. 1988. AIChE Symp. Series. 84 (No. 261): 28.

Matsuura, T. 1994. Synthetic Membranes and Membrane Separation Processes. CRC Press, Boca Raton, FL.

Merin, U. 1979. Ph.D. Thesis, University of Illinois, Urbana.

Mulder, M. 1991. Basic Principles o f Membrane Technology. Rluwer Academic Pub lishers, Dordrecht, The Netherlands and Norwell, MA.

PCI. 1994. Personal communication. PCI Membrane Systems, UR.

Petersen, R. J. 1993. J. Membrane Sci. 83: 81.

Porter, M. C. (Ed). 1990. Handbook o f Industrial Membrane Technology, Noyes Pub lications, Park Ridge, NJ.

Ridgway, H. F. 1988. In Reverse Osmosis Technology, B. S. Parekh (ed.), Marcel Dekker, New York.

Ripperger, S. and Schulz, G. 1986. Bioprocess Engr. 1: 43.

Rozelle, L. T., Cadotte, J. E., Cobian, R. E. and Ropp, C. V. 1977. In Reverse Osmosis and Synthetic Membranes. Theory—Technology—Engineering, S. Sourirajan (ed.), National Research Council Canada, Ottawa, Canada.

Sourirajan, S. 1970. Reverse Osmosis, Academic Press, New York.

Sourirajan, S. (Ed.). 1977. Reverse Osmosis and Synthetic Membranes. Theory— Technology—Engineering. National Research Council Canada, Ottawa, Canada.

Sourirajan, S. and Matsuura, T. (eds.). 1985. Reverse Osmosis and Ultrafiltration. American Chemical Society, Washington, DC.

Zeman, L. and Denault, L. 1992. J. Membrane Sci. 71: 233.

M i l l ip o r e C o rp o ra t io n . 1 9 9 0 . Tangents (3).

M u ld u r , M . 1 9 9 1 . B asic P rinciples o f M em brane Technology. K lu w e r A c a d e m ic P u b l is h e rs , D o rd re c h t, T h e N e th e r la n d s .

N a k a o , S. 1 9 9 4 . J. M em brane Sci. 9 6 : 131 1 6 5 .

P ersson , K . M . , G e k a s , V . a n d T r ag r a d h , G . 1 9 9 5 . J. M em brane Sci. 9 3 : 1 0 5 .

Porter , M . C . 1 9 7 9 . In H andbook o f Separation Techniques f o r Chem ical Engineers, P. A . S c h w e itz e r (e d .), M c G r a w H i l l , N e w Y o rk .

R och e , K . L . a n d L e v y , R . V . 1 9 9 2 . BioPharm . 5 (3): 2 2 .

R oche , K . L . , M e ie r , P. M . a n d L e f v y , R . V . 1 9 9 3 . Amer. Soc. Brewing Chem ists 51 (1): 4 .

Sa e e d , M . a n d C h e r y a n , M . 1 9 8 9 . J. Agric. Food Chem ., 3 7 : 1 2 7 0 .

Sh e ld o n , J. M . , R e e d , I . M . a n d H aw es , C . R . 1 9 9 1 . J. M em brane Sci. 6 2 : 8 7 .

So u r ir a ja n , S. a n d M a t s u u r a , T . 1 9 8 5 . R everse O sm osis/U ltrafiltration Principles. N a t io n a l R e s e a rc h C o u n c il C a n a d a , O tta w a , C a n a d a .

T k a c ik , G . an d M ic h a e ls , S. 1 9 9 1 . Bio/Technology. 9 : 9 4 1 .

V iv ie r , H ., P ons , M . N . a n d Po r t a l a , J. F. 1 9 8 9 . J. M em brane Sci. 4 6 : 8 1 .

W ater ho u s e , S. a n d H a l l , G . M . 1 9 9 5 . J. M em brane Sci. 1 0 4 : 19 .

W u , Q . a n d W u , B . 1 9 9 5 . J. M em brane Sci. 1 0 5 : 1 1 3 .

W o lb e r , P. a n d D o sm an , M . 1 9 8 7 . P harm

aceutical Technol. 1 1 (9): 2 6 .

Z e m a n , L . 1 9 9 2 . J. M em brane Sci. 7 1 : 2 3 3 2
4 6 .

Pradanos, P., de Abajo, J., de la Camp a, I. G. and Hernandez, A. 1995b. J. Membrane S c i 108: 129.

Pritchard, M., Howell, J. A. and Field, R. W. 1995. J. Membrane Set 102: 223.

Rajagopalan, N. and Cheryan, M. 1991. Chem. Engr. Comm. 106: 57.

Redkar, S. G. and Davis, R. H. 1993. Biotechnol Progr. 9: 625.

R iesmeier, B., Kroner, K. H. and K ula , M. R. 1989. J. Biotechnol 12: 153. Saglam, N. 1995. Ph.D. thesis, University of Illinois, Urbana. Segre, G. and Silberberg, A. 1961. Nature 189: 209. Shen, J. S. S. and Probstein, R. F. 1977. Ind. Eng. Chem. Fund. 16: 459. Sherwood, R. K., Pigford, R. L., and W ilke, C. R. 1975. Mass Transfer. McGraw-Hill, New York.

Shimuzu, Y., Shimodera, K. I. and Watanabe, A. 1993. J. Ferment. Bioeng. 76: 493.

Sims, K. A. and Cheryan, M. 1986. Biotechnol. Bioeng. Symp. 17: 495.

Smith, M. H. 1970. In Handbook o f Biochemistry, 2nd edition, edited by H. A. Sober. CRC Press, Cleveland, OH.

Tejayadi, S. and Cheryan, M. 1988. Appl. Biochem. Biotechnol. 19: 61.

Thomas, C. R., N ienow, A. W. and Dunnill, P. 1979. Biotechnol. Bioeng. 21: 2263.

Trettin, D. R. and Doshi, M. R. 1981. In Synthetic Membranes: Hyperfiltration and Ultrafiltration Uses, A. F. Turbak (ed.), American Chemical Society, Washington, DC.

Treybal, R. E. 1981. Mass Transfer Operations. McGraw-Hill, New York.

T yn, M. T. and Gusek, T. W. 1990. Biotechnol. Bioeng. 35: 327.

V ilker, V. L., Colton, C. K., Smith, K. A. and Green, D. L. 1984. J. Membrane Sci. 20: 63.

V irkar, P. D., Narendranath, T. J., Hoare, M. and Dunnill, P. 1981 .Biotechnol. Bioeng. 23: 425.

Walters, R. R., Graham, I. E , M oore, R. M. and Anderson, D. I. 1984. Anal. Biochem. 140: 190.

Warren, R. K., M acDonald, D. G. and Hill, G. A. 1991. Process Biochem. 26: 337.

W elsch, K., M cDonogh, R. M., Fane, A. G. and Fell, C. J. D. 1995. J. Membrane Sci. 99: 229.

W omans, I. G., Nakao, S. and Smolders, C. A. 1984. J. Membrane Sci. 10: 115.

W oerner, D. L. 1983. Ph.D. thesis, University of Washington.

W olf, W. I. and Briggs, D. R. 1959. Arch. Biochem. Biophys. 85: 186.

Yan, S. H., H ill, C. G. and Amundson, C. H. 1979. J. Dairy Sci. 62: 23.

Yeh, H. M. and Wu, H. H. 1997. J. Membrane Sci. 124: 93.

Young, M. E., Carroad, P. A. and Bell, R. L. 1980. Biotechnol. Bioeng. 22: 347.

Zahka, J. and M ir, L. 1977. Chem. Eng. Progr. 73 (12): 53.

Zydney, A. L. and Colton, C. C. 1986. Chem. Eng. Commun. 47: 1.

Brewster, M. E., Chung, K. Y. and Belfort, G. 1993. J. Membrane Sci 81: 127. Cheryan, M. 1986. Ultrafiltration Handbook, Technomic, Lancaster, PA.

Cheryan, M. and Chiang, B. H. 1984. In Engineering and Food; Vol 1, B. M. McKenna (ed.), Applied Science Pub., London U.K. p. 191. Cheryan, M. and Saeed, M. 1989. J. Food Biochem. 13: 289. Chung, K. Y., Edelstein, W. A. and Belfort, G. 1993. J. Membrane Sci. 81: 151. Jonsson, A. S. 1993. J. Membrane Sci. 79: 93. Levy, P. F. and Earle, R. S. 1994. J. Membrane Sci. 91: 135. Lopez-Levia, M. 1979. Master of Science Thesis, Lund University, Sweden. Porter, M. C. 1979. In Handbook of Separation Techniques for Chemical Engineers, P. A. Schweitzer (ed.), McGraw-Hill, New York. Porter, M. C. 1990. Handbook of Industrial Membrane Technology. Noyes, Park Ridge, NJ.

Robertson, G. H., Olieman, J. J. and Farkas, D. F. 1982. AlChE Symp. Ser. 78(218) 132.

Rolchigo, P. M. 1995. Product literature, Membrex Inc. Fairfield, NJ.

Shucosky, A. C. 1988. Chem. Engr 95(1): 72.

Swiezbin, J., Uberoi, T. and Janas, J. J. 1996. Chem. Engr. 103(1): 105.

Winzeler, H. B., and Belfort, G. 1993. J. Membrane Sci. 80: 35.

Akhtar, S., Hawes, C., Dudley, L., Reed, I. and Stratford, P. 1995. J. Membrane Sci 107: 209.

Armishaw, R. F. 1982. N.Z. J. Dairy Sci. Technol 17: 213-228.

Arroyo, G. and Fonade, C. 1993. J. Membrane Sci. 80: 117.

Baker, R. J., Fane, A. G., Fell, C. I. D. and Yoo, B. H. 1985. Desalination 53: 81.

Belfort, G., Davis, R. H. and Zydney, A. L. 1994. J. Membrane Sci. 96: 1.

Bertram, C. D., Hoogland, M. R., Li, H., Odell, R. A. and Fane, A. G. 1993. J. Membrane Sci. 84: 279.

Bhave, R. R. 1995. Personal communication. USFilter, Warrendale, PA.

Bowen, W. R. 1991. In Chromatographic and Membrane Processes in Biotechnology. C. A. Costa and I. S. Cabral (eds.), Kluwer Academic Publishers, The Netherlands, p. 207.

Bragulla, S. and Lintner, K. 1986. Sonderdruck aus Alimenta 5: 111-116.

Brors, A. and Kroner, K. H. 1992. In Proc., 9th International Biotechnology Symp. M. Ladisch and A. Bose (eds.) American Chemical Society, Washington, DC. p. 254.

Brink, L. E. S. and Romjin, D. J. 1990. Desalination 78: 209.

BSI. 1996. Company literature. Eden Praire, MN.

Busby, T. F. and Ingham, K. C. 1980. J. Biochem. Biophys. Methods. 2: 191.

Cabral, I. M. S., Casale, B. and Cooney, C. L. 1985. Biotechnol. Lett. 7: 749.

Chamchong, M. and Noomhorm, A. 1991. J. Food Process Engr. 14: 21.

Cheryan, M. 1986. Ultrafiltration Handbook. Technamic, Lancaster, PA.

Cheryan, M. and Chiang, B. H. 1984. In Engineering and Food, Volume 1. B. McKenna (ed.), Applied Science Publishers, London, p. 191.

Cheryan, M. and Merin, U. 1980. In Ultrafiltration Membranes and Applications. A. R. Cooper (ed.), Plenum, New York. p. 619. Daufin, G., Michel, F. and Merin, U. 1992. Aust. J. Dairy Technol. 47: 7. Defrise, D. and Gekas, V. 1988. Process Biochem. 23: 105. Dillman, W. I. and Miller, J. F. 1973. J. Colloid Interface Sci. 44: 221. Dornier, M., Petermann, R. and Decloux, M. 1995. J. Food Engineering 24: 213. Dychdala, G. 1993. The Chemistry of Membrane Cleaning. EcoLab-Klenzade technical bulletin. Fane, A. G., Fell, C. J. D. and Suki, A. 1982. Presented at the Symposium on Membranes and Membrane Processes, Perigia, Italy. Fane, A. G., Fell, C. J. D. and Suki, A. 1983. J. Membrane Sci. 16: 195. Field, R. 1996. In Industrial Membrane Separation Technology K. Scott and R. Hughes (eds.), Blackie Academic, London, U.K. p. 67. Field, R. W., Wu, D., Howell, J. A. and Gupta, B. B. 1995. J. Membrane Sci. 100: 259. Gekas, V. and Zhang, W. 1989. Process Biochem. 24: 159. Geppert, G. and Thielemann, H. 1983. Chem. Techn. (Germany) 35 (10): 517. Gesan, G., Daufin, G. and Merin, U. 1995. J. Membrane Sci. 104: 271. Gourley, L., Britten, M., Guthier, S. F. and Pouliot, Y. 1994. J. Membrane Sci. 91: 283. Gupta, B. B., Blanpain, P. and Jaffrin, M. Y. 1992. J. Membrane Sci. 70: 257. Gupta, B. B., Ding, L. H. and Jaffrin, M. Y. 1985. In Progress in Artificial Organs. Y. Nose, C. Kjellstrand and P. Ivanovich (eds.), ISAO Press, Cleveland, OH. p. 891. Gupta, B. B., Howell, J. A., Wu, D. and Field, R. W. 1995. J. Membrane Sci. 99: 31. Hanemaaijer, H. 1988.12-Procestechnolgie (Neth.) 4 (1): 15. Harris, T. A. J., Reuben, B. G., Cox, D. J., Vaid, A. K. and Carvell, J. 1988. J. Chem. Technol. Biotechnol. 42: 19. Hayes, J. F., Dunkerley, J. A., Muller, L. L. and Griffin, A. T. 1974. Aust. J. Dairy Technol. 29: 132. Henry, I. D. and Allred, R. C. 1972. Dev. Indust. Microbiol. 13: 177. Henry, J. D., Lawler, L. F. and Kuo, C. H. A. 1977. AIChEJ. 36: 907. Hermia, J. 1982. Trans. I Chem. E. 60: 183. Hiddink, J., DeBoer, R. and Nqoy, P. F. C. 1981. Milchwiss. 36: 11. Hildebrandt, J. R. 1991. In Chromatographic and Membrane Processes in Biotechnol ogy. C. A. Costa and J. S. Cabral (eds.), Kluwer Academic Publishers, The Nether lands. p. 363. Hodgins, L. T. and Samuelson, E. 1990. U.S. Patent 4,906,379. Jaffrin, M. Y., Ding, L. H., Couvreur, C. and Khari, P., 1997. J. Membrane Sci. 124: 233. Jagannadh, S. N. and Muralidhara, H. S. 1996. Ind. Eng. Chem. Res. 35: 1133. Jonsson, A. S. 1993. J. Membrane Sci. 19: 93. Jucker, C. and Clark, M. M. 1994.

J. Membrane Sci. 91: 37. Kai, M., Ishii, K., Honda, Z., Miyano, T. and Tam ad a, M. 1989. In Advances in Reverse Osmosis and Ultrafiltration. T. Matsuura and S. Sourirajan (eds.), National Research Council, Ottawa, p. 15. Kennedy, T. J., Merson, R. L. and McCoy, B. J. 1974. Chem. Eng. Sci. 29: 1927. Khorakiwala, K. H., Cheryan, M. and Mehaia, M. A. 1986. Biotechnol Bioeng. Symp. Ser. 15: 249. Kim, K. 1, Chen, V. and Fane, A. G. 1993. J. Colloid. Interface Sci. 155: 347. Kim, K. I., Fane, A. G. and Fell, C. J. D. 1988. Desalination. 70: 229. Kim, K. J., Fane, A. G. and Fell, C. J. D. 1989. J. Membrane Sci. 43: 187. Kim, K. J., Fane, A. G., Fell, C. J. D. and Joy, D. C. 1992. J. Membrane Sci. 68: 79. Kloosterman, J., Van Wassenaar, P. D., Slater, K. H. and Baksteen, H. 1988. Biopro cess Engr. 3: 181. Ko, M. K. and Pellegrino, J. J. 1992. J. Membrane Sci. 74: 141. Kuo, K. P. and Cheryan, M. 1983. J. Food Sci. 48: 1113. Kroner, K. H., Hummel, W., Volkel, J. and Kula, M.-R. 1986. In Membranes and Membrane Processes. E. Drioli and M. Nakagaki (eds.), Plenum Press, New York. p. 223. Kroner, K. H., Schutte, H., Hustedt, H. and Kula, M.-R. 1984. Process Biochem. 19 (April): 67.

Laine, J.-M., Hagstrom, J. P., Clark, M. M. and Mallevialle, J. 1989. J. Amer. Water Works Association 81 (November): 61.

Le, M. S., Spark, L. B. and Ward, P. S. 1984. J. Membrane Sci. 21: 219. Levy, P. F. and Sheehan, I. J. 1991. BioPharm. 4(4): 24.

Lockley, A. K., White, W. J. P. and Hall, G. M. 1988. Intern. J. Food Sci. Technol. 23: 11.

Mackley, M. R. and Sherman, N. E. 1992. Chem. Eng. Sci. 47: 3067.

Marshall, A. D., Munro, P. A. and Tragardh, G. 1993. Desalination 91: 65.

Matthiasson, E. and Sivik, B. 1980. Desalination 35: 59.

Matsumoto, K., Katsuyama, S. and Ohya, H. 1987. J. Ferment. Technol. 65: 77.

McDonogh, R. M., Welsh, K., Fane, A. G. and Fell, C. J. D. 1988. Desalination 70:251.

McGregor, W. C, Weaver, J. F. and Tansey, S. P. 1988. Biotechnol. Bioeng. 31: 385.

Merin, U. and Cheryan, M. 1980. J. Food Process. Preserv. 4: 183.

Merin, U., Gordin, S. and Tanny, G. B. 1983. N.Z. J. Dairy Sci. Technol. 18: 153.

Michaels, S. L. 1994. BioPharm. 7(8): 38.

Milisic, V. and Bersillon, J. L. 1986. Filtration & Separation 23 (Nov.): 347.

Miller, K. D., Wietzil, S. and Rodgers, V. G. J. 1993. J. Membrane Sci. 76: 77.

Nichols, D. J. and Cheryan, M. 1981. J. Food Sci. 46: 357.

Nilsson, J. L. 1990. J. Membrane Sci. 52: 121.

Oldani, M. and Schock, G. 1989. J. Membrane Sci. 43: 243.

Padilla, O. I. and McLellan, M. R. 1993. J. Food Sci. 58: 369.

Pall Filtron. 1995. Company literature. Northborough, MA.

Patel, P. N., Mehaia, M. A. and Cheryan, M. 1987. J. Biotechnol. 5: 1.

Persson, K. M., Capannelli, G., Bottino, A. and Tragardh, G. 1993. J. Membrane Sci. 76: 61.

Piot, M., Maubois, J.-L., Schaegis, P, Veyre, R. and Luccioni, L. 1988. Le Lait 64: 102.

Pitt, A. M. 1987. J. Parenteral Sci. Technol. 41: 110.
Porter, M. C. and Michaels, A. S. 1971. CHEMTECH 1: 440.

Radlett, P. J. 1972. J. Appl. Chem. Biotechnol. 22: 495.

Rane, K. D. and Cheryan, M. 1996. Stillage processing with ceramic membranes (un published data). University of Illinois, Urbana. Reed, I. M., Dudely, L. Y. and Gutman, R. G. 1987. Proc. 4th Eur Congr. Biotechnol. 2: 573. Reihanian, H., Robertson, C. R. and Michaels, A. S. 1983. J. Membrane Sci. 16: 237. Robinson, C. W., Siegel, M. H., Condemine, A., Fee, C., Fahidy, T. Z. and Glick, B. R. 1993. J. Membrane Sci 80: 209. Rodgers, V. G. J. and Sparks, H. E. 1993. J. Membrane Sci. 78: 163. Rogers, P. L., Lee, K. J. and Tribe, D. E. 1980. Process Biochem. 15 (Aug.-Sept.): 7. Rolchigo, P. 1995. Personal

communication. Membrex Inc., Fairfield, NJ. Saeed, M. and Cheryan, M. 1989. J. Agric. Food Chem. 37: 1270. Saglam, N. 1995. Ph.D. thesis, University of Illinois, Urbana. Sheldon, J. M., Reed, I. M. and Hawes, C. R. 1991. J. Membrane Sci. 62: 87. Spiazzi, E., Lenoir, J. and Grangeon, A. 1993. J. Membrane Sci. 80: 49. Suki, A., Fane, A. G. and Fell, C. J. D. 1984. J. Membrane Sci. 21: 269. Vradis, I. and Floros, J. D. 1995. In Food Process Design and Evaluation. R. K. Singh (ed.), Technomic, Lancaster, PA. p. 1. Wakeman, R. I. and Tarleton, E. S. 1987. Chem. Eng. Sci. 42: 829. Wakeman, R. J. and Tarleton, E. S. 1991. Desalination 83: 35. Wenten, I. G. 1995. Filtration & Separation 32(3): 253. Winzler, H. B. and Belfort, G. 1993. J. Membrane Sci. 80: 35. Yamagiwa, K., Kobayashi, H., Ohkawa, A. andOnodera, M. 1993. J. Chem. Eng. Japan. 26: 13.

Jaffrin, M. Y. 1990. Presented at 4th Symposium on Protein Purification Technologies, Clermont-Ferrand, France.

Knudsen, A. and Braun, H. 1985. Report No. 14, Danish Government Dairy Research Institute.

Kuo, W. H. and Chiang, B. H. 1987. J. Food Sci. 52: 1401.

Lin, S. S., Chiang, B. H. and Hwang, L. S. 1989. J. Food Engr. 9: 21.

Matthews, M. E., Doughty, R. K. and Hughes, I. R. 1978. N.Z. J. Dairy Sci. Technol 13: 37.

Merry, A. J. 1996. In Industrial Membrane Separation Technology, K. Scott and R. Hughes (eds.), Blackie Academic, London, U.K.

Ng, P., Lundblad, J. and Mitra, G. 1976. Separation Sci. 11: 499.

Nichols, D. I. and Cheryan, M. 1981. J. Food Process. Preservation. 5: 104.

Peri, C., Pompei, C. and Rossi, F. 1973. J. Food Sci. 38: 135.

Rajagopalan, N. and Cheryan, M. 1991. J. Dairy Sci. 74: 2435.

Sigdell, J. E. 1982. J. Art. Org. 5: 361.

Villarroel, E, Klein, E. and Holland, F. 1977. Trans. Am. Artif. Intern. Organs. 23: 225.

Eakin, D. E., Singh, R. P, Kohler, G. O. and Knuckles, B. 1978. J. Food Sci. 43: 544.

Elmaleh, S. and Ghaffor, N. 1996. J. Membrane Sci. 118: 111. Enzminger, I. D. and Asenjo, J. A. 1986. Biotechnol. Lett., 8: 7.

EPRI. 1992. Techapplication, Electric Power Research Institute, Walnut Creek, CA. Ericksson, G., Erriksson, P, Hallstrom, B. and Wimmerstedt, R. 1977. Desalination 27: 81.

Ericksson, G. and Sivik, B. 1976. Potato Res. 19: 279. Ericksson G. and von Bockelmann, I. 1975. Process Biochem. 10(Sept.): 11. Fauquant, J., Vieco, E., Brule, G. and Maubois, J. L. 1985. Lait. 65: 1. Fauquant, J., Maubois, J. L. and Pierre, A. 1988. Technique Laitiere & Marketing. 1028: 21-23. Fernando T. 1981. Biotechnol. Bioeng. 23: 19. FiltratioNews. 1984. Filtration Division, Alfa-Laval, Sweden. Fink, D. J. and Rodwell, V. W. 1975. Biotechnol. Bioeng. 16: 1029. Finnigan, T. I. A. and Lewis, M. J. 1989. Lebensm. Wiss. Technol. 22: 237. Flaschel, E., Raetz, E. and Renken, A. 1983. In Enzyme Technology, R. M. Lafferty and E. Maier (eds.), Springer-Verlag, Berlin, p. 285. Freund, P and Rios, G. M. 1992. Can. J. Chem. Eng. 70: 250. Froning, G. W., Wehling, R. L., Ball, H. R. and Hill, R. M. 1987. Poultry Sci. 66: 1168.

Garretson, R. 1983. Presented at 1MTEC ’83, Sydney, Australia.

Geckeler, K. E. and Volchek, K. 1996. Environmental Set Technol 30: 725.

Gesan, G., Daufin, G. and Merin, U. 1995. J. Membrane Sci. 104: 271.

Gesan, G., Daufin, G., Merin, U., Labbe, J. P. and Quemarais, A. 1993. J. Dairy Res. 62: 269.

Ghose, T. K. and Kostick, J. T. 1970. Biotechnol. Bio eng. 12: 921.

Goldberg, M. and Chevrier, D. 1979. Indust. Alim, et Agricoles 9/10: 951.

Goldsmith, R. L. 1981. Dairy Field. 16(3): 88.

Goldsmith, R. L. and Horton, B. S. 1972. EPA Project No. 12060 DXF, Office of Research and Monitoring, Environ. Protection Agency, Washington, DC.

Gould, R. M. and Nitsch, A. R. 1996. U.S. Patent 5,494,566.

Govind, R. and Itoh, N. 1989. Membrane Reactor Technology. AIChE Symp. Series Vol. 85, Number 268. American Inst. Chem. Engrs., NY.

Graver Separations. 1996. Lit. No. S-106, Glasgow, DE.

Groot, W. J., Sikkenk, C. M., Waldram, R. H., van der Lans, R. G. J. M. and Luyben, K. C. A. M. 1992. Bioprocess Engr. 8: 39.

Gueguen, J., Quemener, B. and Valdebouze, P. 1980. Lebensm. Wiss. Technol. 13: 72.

Hackert, R. and Swientek, R. J. 1986. Food Processing 47(1): 80.

Hamilton, K. M. and Howell, J. A. 1983. In Adv. Ferment. Proc. Conf, Wheatland, Rickmansworth, U.K. p. 171.

Hanemaaijer, J. H. 1985. Desalination 53: 143.

Hansen, C. 1983. Food Technol. 37(2): 77.

Hanssens, T. T., van Nispen, J. G. M., Koerts, K. and de Nie, L. H. 1984. International Sugar Journal 86: 227,240.

Hart, M. R., Huxsoll, C. C , Tsai, L. S., Ng, K. C , King, A. D., Jones, C. C., Halbrook, W. U. 1990. J. Food Process Engr. 12: 191.

Hart, M. R., Ng, K. C. and Huxsoll, C. C. 1989. ACS Symp. Ser. 405: 355-367.

Hayward, M. F. 1982. Proceedings of World Filtration Congress III, Uplands Press, U.K. p. 572.

Heinen, W., and Lauwers, A. M. 1975. Arch. Microbiol. 106: 201.

Henley, R. G., Yang, R. Y. K. and Greenfield, P. F. 1980. Enz. Microbial Technol. 2: 206.

Herve, D., Lancrenon, X. and Rousset, F. 1995. Sugar y Azucar 5: 40.

Hsu, J. C , Heatherbell, D. A., Flores, J. H. and Watson, B. T. 1987. Amer. J. Enol. Vitic. 38(1): 17.

Huang, Y. C. and Koseoglu, S. S. 1993. Waste Management 13: 481.

Hummel, W., Schutte, H. and Kula, M. R. 1981. Eur. J. Appl. Microbiol. Biotechnol. 12: 22.

Hydranautics. 1996. Hydrapaint bulletin. Oceanside, CA.

Iacobucci, G. A., Myers, M. J., Emi, S. and Myers, D. V. 1974. Proc. IVIntern. Congress Food Science Technol. 5: 83.

Inloes, D. S., Smith, W. J., Taylor, D. P., Cohen, S. N., Michaels, A. S. and Robertson, C. R. 1983. Appl. Environ. Microbiol. 46: 264.

Iwama, A. 1989. In Proceedings of World Conference on Edible Fats and Oils Process ing, American Oil Chemist's Society, Champaign, IL. pp. 244-250. Jacangelo, J. G., Laine, J. M., Carns, K. E., Cummings, E. W. and Mallevialle, J. 1991. J. AWWA 83(9): 97. Jacangelo, J. G., Adham, S. S. and Laine, J. M. 1995. J. AWWA 87(9): 107. Jameson, G. W. 1987. Food Technol. Australia. 39: 560. Jonsson, A. S., Jonsson, C , Teppler, M. and Wannstrom, S. 1996. Filtr. & Separation (Elsevier), 33(6): 453. Jonsson, A. S. and Jonsson, B. 1991. J. Membrane Sci. 56: 49. Juang, R. S. and Liang, J. F. 1993. J. Membrane Sci. 82: 175. Karrs, S. R. and McMonagle, M. 1993. Plating and Surface Finishing 80 (Sept.): 45. Kato. 1996. Product literature, Kato Brothers Honey Company, Japan. Katoaka, H., Saigusa, T., Mukutaka, S. and Takahashi, J. 1980. J. Ferment. Technol. 58:431. Kawakami, K., Hamada, T. and Kusunoki, K. 1980. Enz. Microbial Technol. 2: 295. Kawasaki, Y., Kawakami, H., Tanimoto, M., Dasako, S., Tomizawa, A., Kotake, M. and Makajima, I. 1993. Milchwiss. 48: 91. Keurentjes, J. T. F. 1991. Ph.D. Thesis, Agricultural University of Wageningen, The Netherlands. Keurentjes, J. T. F., Bosklopper, T. G. J., van Drop, L. J. and van't Riet, K. 1990. JAOCS 67: 28. Khorakiwala, K. H., Cheryan, M. and Mehaia, M. A. 1987. Biotechnol. Bioeng. Symp. Ser. 15: 249. Kim, S. H., Morr, C. V., Seo, A. and Surak, J. G. 1989. J. Food Sci. 54: 25. Kimura, S. 1991. Water Sci. Technol. 23: 1573. Kirjassoff, W. R., Pinto, S. and Hoffman, C. 1980. Chem. Engr. Progr. 76(2): 58. Kirk, D. E., Montgomery, M. W. and Kortekaas, M. G. 1983. J. Food Sci. 48: 1663. Kishihara, S., Tamaki, H., Fuji, S. and

Komoto, M. 1989. J. Membrane Sci. 41: 103. Klein, E. 1991. Affinity Membranes. John Wiley, New York. Klepac, J., Simmons, D. L., Taylor, R. W., Scamehorn, J. F. and Christian, S. D. 1991. Separation Sci. Technol. 26: 165. Koch. 1984. Product Literature. Koch Membrane Systems, Wilmington, MA. Koch. 1988. Case History 3. Koch Membrane Systems, Wilmington, MA. Koch. 1989. Product Literature. Koch Membrane Systems, Wilmington, MA. Koch. 1991. Case History 5: Sunkisfs Bitterfree Bounty. Koch Membrane Systems, Wilmington, MA. Koch. 1992. Industrial Wastewater Treatment. Koch Membrane Systems, Wilmington, MA. Koch. 1995. Abcor tubular ultrafiltration. Effluent-free paper coating. Koch Membrane Systems, Wilmington, MA. Koch. 1996. Konsolidator 252, Bulletin KPN0679191. Koch Membrane Systems, Wilm ington, MA. Kochergin, V. 1996. Personal communication, Amalgamated Research, Inc., Twin Falls, Idaho. Kohlwey, D. K. and Cheryan, M. 1981. Enz. Microbial Technol. 3: 64. Korus, R. A. and Olson, A. C. 1977a. Biotechnol. Bioeng. 19: 1. Korus, R. A. and Olson, A. C. 1977b. J. Food Sci. 42: 258. Koseoglu, S. S. 1991. INFORM (AOCS), 2: 334. Koseoglu, S. S. and Engelgau, D. E. 1990. JAOCS 67: 239. Koseoglu, S. S., Lawhon, J. T. and Lusas, E. W. 1990. Food Technology (IFT, USA), 44 (12): 90. Kosikowski, F. V. 1986. Food TechnoL 40(6): 71-77, 156. Kroll, J., Kujawa, M. and Schnaak, W. 1991. Fette Wissenschaft Technologie 93(2): 61. Kroner, K. H., Schutte, H., Hustedt, H. and Kula, M. R. 1984. Process Biochem. 19: 67-74. Kuo, K. P. and Cheryan, M. 1983. J. Food Sci. 48: 1113. Kunikane, S., Magara, Y., Itoh, M. and Tanaka, O. 1995. J. Membrane Sci 102: 149. Lah, C. L. and Cheryan, M. 1980a. J. Agric. Fd. Chem. 28: 911. Lah, C. L. and Cheryan, M. 1980b. Lebensm. Wiss. u. -TechnoL 13: 259. Lah, C. L., Cheryan, M. and DeVor, R. E. 1980. J. Food Sci. 45: 1720. LaMonica, D. A. 1994. U.S. Patent 5,310,487. Lancrenon, X., Theoleyre, M. A. and Kientz, G. 1994. Intern. Sugar Journal 96: 365. Lawhon, I. T. and Lusas, E. W. 1987. U.S. Patent 4,645,677. Lawhon, I. T., Mulsow, D., Cater, C. M. and Mattil, K. F. 1977. J. Food Sci. 42: 389. Le Berre, O. and Daufin, G. 1996. J. Membrane Sci. 117: 261. Lee, C. W. and Chang, H. N. 1987. Biotechnol. Bioeng. 29: 1105. Lee, I. H., Skotnicki, M. L. and Rogers, P. I. 1982. Biotechnol. Lett. 4: 615. Lee, S. H., Son, M. P, Kwon, Y. J. and Pyun, Y. R. 1991. Sanop Misaengmul Hakhoechi 19: 419 {Chemical Abstr. 119: 26778). Liu, F. K., Nie, Y. H. and Shen, B. Y. 1989. Proc. World Congress Vegetable Prot. Utiliz. Human Foods Anim. Feedstujfs, p. 84. Lopez, J. L. and Matson, S. L. 1997. J. Membrane Sci. 125: 189. Lowe, E., Durkee, E. L., Merson, R. L., Ijicki, K., and Cimino, S. L. 1969. Food TechnoL 23: 753. Luong, I. H. T., Nguyen, A. L. and Male, K. B. 1987. Trends in

Biotechnology, 5: 281. Luong, I. H. T., Male, K. B. and Nguyen, A. L. 1988. Biotechnol. Bioeng. 31: 516. Maartens, A., Swart, P. and Jacobs, E. P. 1996. J. Membrane Sci. 119: 9. Madaeni, S. S., Fane, A. G. and Grohmann, G. S. 1995. J. Membrane Sci. 102: 65. Madsen, R. F. 1973a. Intern. Sugar J. 75: 163. Madsen, R. F. 1973b. British Patent No. 1,330,037. Mak, F. K. 1991. Intern. Sugar J. 93: 263. Malmberg, R. and Holm, S. 1988. North European Food Dairy J. 1: 75. Mameri, N., Abdessemed, D., Belhocine, D., Lounici, H., Gavach, C , Sandeaux, J. and Sandeaux, R. 1996. J. Chem. TechnoL Biotechnol. 67: 169. Mannheim, A. and Cheryan, M. 1990. J. Food Science 55: 381. Mannheim, A. and Cheryan, M. 1993. Cereal Chem. 70: 115. Matson, S. L. and Quinn, J. A. 1986. Annals N. Y. Acad. Sci. 469: 152. Matsumoto, K., Katsuyama, S. and Ohya, H. 1987. J. Ferment. TechnoL (Japan). 65: 77. Mattiasson, B. and Ling, T. G. L 1986. In Membrane Separations in Biotechnology, W. C. McGregor (ed.), Marcel Dekker, New York. p. 99. Mattiasson, B. and Ramstorp, M. 1984. J. Chromatog. 283: 322. Maubois, J. L. 1989. North American Membane Society Annual Meeting, Austin, TX. Maubois, J. L. 1991. Australian J. Dairy Technol. 46: 91. Maubois, J. L., Mocquot, G. and Vassal, L. 1969. Brevet Frangais 2,052,121. Maubois, J. L., Pierre, A., Fauquant, I. and Piot, M. 1987. International Dairy Feder ation Bulletin. 212: 154-159. Mehaia, M. A. and Cheryan, M. 1983. Milchwissenschaft. 38: 708. Mehaia, M. A. and Cheryan, M. 1984a. Appl Microbiol Biotechnol 20: 100. Mehaia, M. A. and Cheryan, M. 1984b. Enz. Microbial Technol. 6: 117. Mehaia, M. A. and Cheryan, M. 1986. Enz. Microbial Technol 8: 289. Mehaia, M. A. and Cheryan, M. 1987. Process Biochem. 22(6): 185. Mehaia M. A. and Cheryan M. 1990a. In Biotechnology and Food Processing, H. G. Schwartzberg and M. A. Rao (eds.), Marcel Dekker, New York. p. 67. Mehaia, M. A. and Cheryan, M. 1990b. Bioprocess Engr. 5: 57. Mehaia, M. A. and Cheryan, M. 1991. Enz. Microbial Technol 13: 257. Mehaia, M. A., Alvarez, J. and Cheryan, M. 1993. International Dairy J. 3: 179. Meier, P. 1995. Personal communication. Cuno, Inc., Meriden, CT. Melling J. 1974. Process Biochem. 9 (Sept.): 7. Membre, J. M., Petiot, P., Rene, F. and Lalande, M. 1991. Recents Progr. Genie Pre cedes. 5: 91. Membrex. 1989. Taylor Applications. Technical Bulletins No. 1 and No. 2. Membrex, Inc., Garfield, NJ. Merin, U., Gordin, S. and Tanny, G. B. 1983. J. Dairy Res. 50: 503. Merry, A. 1995. PCI Membrane Systems, UK. Michaels, A. S. 1968. In Progress in Purification and Separation, E. S. Perry (ed.), Interscience, New York. p. 297. Michaels, S. L., Michaels, A. S., Antoniou, C , Pearl, S. R., Goel, V., de los Reyes, G., Keating, P., Rudolph, E., Kuriyel, R. and Siwak, M. 1995. In Separation Technology. Pharmaceutical and

Biotechnology Applications, W. P. Olson (ed.), Interpharm Press, Buffalo Grove, IL. Millipore Corp. 1983. Catalog No. AB822, Bedford, MA. Minier, M., Ferras, E., Goma, G. and Soucaille, P. 1984. Presented at the VIIInterna tional Biotechnology Symposium, New Delhi, India. Miyata, Y. 1984. Nippon Suisan Gakkaishi (Japan). 50(4): 659. Miyawaki, O., Nakamura, K. and Yano, T. 1982. J. Chem. Engr. Japan, 15: 224. Morgan, A. I., Lowe, E., Merson, R. L. and Durkee, E. L. 1965. Food Technol 19(12): 1790. Morikawa, Y., Karube, I. and Suzuki, S. 1978. Biochim. Biophys. Acta 523: 263. Mota, N., Lafforgue, C., Strehaianoi, P. and Goma, G. 1987. Bioprocess Engr. 2: 65. MSS. 1995. Micro-Steel Caustic Recovery System; Mem-Brine System, Membrane Sys tem Specialists, Wisconsin Rapids, WI. Muralidhara, H. S., Jirjis, B. F. and Seymour, G. F. 1996. U.S. Patent 5,482,633. Mutoh, Y., Matsuda, K., Ohshima, M. and Ohuchi, H. 1985. U.S. Patent 4,545,940. Nabetani, H., Abbott, T. P. and Kleiman, R. 1995. Ind. Engr. Chem. Res. 34: 1779. Nakajima, M., Iwasaki, K., Nabetani, H. and Watanabe, A. 1990. Agric. Biol Chem. 54: 2793. Nguyen, Q. T., Aptel, P. and Neel, J. 1980. J. Membrane Sci. 6: 71. Nichols, D. J. and Cheryan, M. 1981. J. Food Sci. 46: 357. Ninomiya, K., Ookawa, T., Tsuchiya, T. and Matsumoto, J. 1985. Nippon Suisan Gakkaishi (Japan). 51(7): 1133. Nipkow, A., Sonnleitner, B. and Fiechter, A. 1986. J. Biotechnol. 4: 49. Niro. 1994. Technical Report No. 40: Niro chemical recovery (NCR) systems with Mem- bralox ceramic membranes, Niro Hudson, Inc., Hudson, WI. Nitto-Denko. 1983. Product Bulletin, Shiga, Japan. Norman, S. I. 1994. Membrane and Adsorbent Applications for Enhancement of Citrus Juices. Dow Chemical Co., Midland, MI. Nuortila-Jokinen, J. and Nystrom, M. 1996. J. Membrane Sci. 119: 99. O'Connor, D. E. 1971. U.S. Patent 3,622,556. Ohleyer, E., Wilke, C. R. and Blanch, H. W. 1985. Appl. Biochem. Biotechnol. 11: 457. Ohlson, I., Traegardh, G. and Hahn-Haegerdal, B. 1984. Biotechnol. Bioeng. 26: 647. Okubo, K., Waldrop, A. B., Iacqbucci, G. A. and Meyers, D. V. 1975. Cereal Chem. 52: 263. Olsen, H. S. 1978. Lebensm. Wiss. u. -Technol. 11: 57. Olesen, N. and Jensen, F. 1988. Milchwissenschaft 44: 476. Omosaiye, O. and Cheryan, M. 1979a. J. Food. Sci. 44: 1027. Omosaiye, O. and Cheryan, M. 1979b. Cereal Chemistry 56: 58. Omosaiye, O., Cheryan, M. and Matthews, M. E. 1978. J. Food Sci. 43: 354. Oosten, B. 1976. Die Starke. 28: 135. Ostrowski, H. T. 1979. J. Food Proc. Preserv. 3: 59. Padilla, O. I. and McLellan, M. R. 1989. J. Food Sci. 54: 1250. Padilla, O. I. and McLellan, M. R. 1993. J. Food Sci. 58: 369. Pafylias, I., Cheryan, M., Mehaia, M. A. and Saglam, N. 1996. Food Research Intern. 29: 141. Pal, D. and Cheryan, M. 1987. Indian Dairyman. 39: 373. Pall. 1996. Bulletin PBB-DV50. Pall Ultrafine Filtration Company, East

Hills, NY. Parekh, B. S. 1991. Chem. Engr. 98(1): 70. Parekh, S. R. and Cheryan, M. 1994. Enz. Microbial Technol. 16: 104. Park, Y. S., Ohtake, H., Toda, K., Fukaya, M., Okumura, H. and Kawamura, Y. 1989. Biotechnol. Bioeng. 33: 918. Parrott, D. L. 1990. Third International Congress on Membranes and Membrane Pro cesses, Chicago, IL. Pasilac Company. 1982. Product Bulletin. Nakskov, Denmark. Patel, R. S., Reuter, H. and Prokopek, D. 1986. J. Soc. Dairy Technol. 39: 27. Patel, P. N., Mehaia, M. A. and Cheryan, M. 1987. J. Biotechnol. 5: 1. Patocka, J. and Jelen, P. 1987. J. Food Sci. 52: 1241. Paulson, D. J., Wilson, R. L. and Spatz, D. D. 1984. Food Technology 38 (12): 77.

Payne, R. E., Hill, C. G. and Amundson, C. H. 1973. J. Milk Food Technol. 36: 359.

Pedersen, P. J. 1992. International Dairy Federation Special Issue 9201: 33. Peri, C, Riva, N. and Decio, P. 1988. Amen J. Enol. Vitic. 39: 162. Permionics. 1995. Personal communication, Vadodara, India.

Pierrott, R, Fick, M. and Engasser, J. M. 1986. Biotechnol. Lett. 8: 253. Piot, P., Vachot, J. V., Veaux, M., Maubois, I. L. and Brinkman, G. E. 1987. Technique Laitiere & Marketing. 1016: 42-46. Plotka, A., Schmidt, J. and Zdziennicki, A. 1977. Prace Instytutow Lab. Bad. Przem. Spoz.t. 27, zeszyt 1, s. 29. Pompei, C. and Lucisano, M. 1978. Lebensm.-Wiss. u. -Technol. 9: 338. Porter, M. C. 1990. Handbook of Industrial Membrane Technology. Noyes, Park Ridge, NJ. Porter, M. C. and Michaels, A. S. 1971. CHEMTECH. 1: 440. Porter, J. J. and Zhuang, S. 1996. J. Membrane Sci. 110: 119. Pouliot, G. and Goulet, J. 1987. J. Food Sci. 52: 1394. Pungor, E., Afeyan, N. B., Gordon, N. F. and Cooney, C. L. 1987. Bio/Technology, 5: 604. Qureshi, N. and Cheryan, M. 1989. Process Biochem. 24(5): 172. Raaska, E. and Kelly, W. 1987. Kem.-Kemi. 14(3): 253-259. Rajagopalan, N. 1996. Personal communication. Hazardous Waste Research and Infor mation Center, Champaign, IL. Rajagopalan, N. and Cheryan, M. 1991. J. Dairy Sci. 74: 2435. Ramachandran, K. B. and Goma, G. 1988. J. Biotechnol. 9: 39. Raman, L. R, Cheryan, M. and Rajagopalan, N. 1994a. Chem. Engr. Progr. 90(3): 68. Raman, L. R, Rajagopalan, N. and Cheryan, M. 1994b. Oils Fats Intern. (UK). 6(10): 28. Raman, L. R, Cheryan, M. and Rajagopalan, N. 1996a. Fette Wiss. Technologie. 98(1): 10. Raman, L. R, Cheryan, M. and Rajagopalan, N. 1996b. JAOCS 73: 219. Rane, K. D. and Sims, K. A. 1995. Biotechnol. Bioeng. 20: 325. Rane, K. D. and Cheryan, M. 1996. Stillage processing with ceramic membranes (un published data). University of Illinois, Urbana. Rao, M. A., Agree, T. E.,

Cooley, H. J. and Ennis, R. W. 1987. J. Food Sci. 52: 375. Reed, W. M. and Bogdam, M. E. 1986. Biotechnol. Bioeng. Symp. 15: 641. Renner, E. and Abd El-Salam, M. H. 1991. Application of Ultrafiltration in the Dairy Industry. Elsevier, New York. Riesmeier, B., Kroner, K. H. and Kula, M. R. 1990. Desalination. 77: 219. Rinn, J. C., Morr, C. V., Seo, A. and Surak, I. G. 1990. J. Food Sci. 55: 510. Rolchigo, P. M. 1995. Personal communication, Membrex Inc., Fairfield, NJ. Rogers, P. L., Lee, K. J. and Skotnicki, M. L. 1982. Adv. Biochemical Engr. 23: 37. Romicon. 1988. Product and Process Bulletins. Woburn, MA. Rwabahizi, S. and Wrolstad, R. E. 1988. J. Food Sci. 53: 857. Ryder, D. S., Davis, C. R., Anderson, D., Glancy, F. M. and Power, J. N. 1988. Master Brew. Assoc. Am.—Tech. Quarterly 25: 67. Saglam, N. 1995. Ph.D. thesis, University of Illinois, Urbana. Schultz, J. S. and Gerhardt, P. 1969. Bacterial. Rev. 33: 1. Schwering, H., Gollisc, P. and Kemp, A. 1993. Plating and Surface Finishing 80 (April): 56. Sen Gupta, A. K. 1978. U.S. Patent 4,093,540. Sen Gupta, A. K. 1985. U.S. Patent 4,533,501. Seprotech. 1995. Environmental Improvements in Hide Processing, Ottawa, Canada. Shah, M. M. and Cheryan, M. 1995. Applied Biochem. Biotechnol. 51/52: 413. Shih, J. and Koznick, M. 1980. Poultry Sci. 59: 247. Shimizu, Y., Matsushita, K., Shimodera, K. and Watanabe, A. 1992. In Biochemical Engineering for 2001, S. Furasaki (ed.), T. Endo and R. Matsuno, Springr-Verlag, Tokyo, p. 578. Short, J. L. 1993. Membrane Industry News, Westford, MA. November issue. Short, J. L. 1994. Membrane Industry News, Westford, MA. 2(4): 4. Short, J. L. 1995a. Membrane Industry News, Westford, MA. 3(6): 5. Short, I. L. 1995b. Membrane Industry News, Westford, MA. 3(1): 4. Short, J. L. and Skelton, R. 1991. In Effective Industrial Membranes Processes: Benefits and Opportunities, M. K. Turner (ed.), Elsevier, New York. Sims, K. A. and Cheryan, M. 1986. Biotechnol. Bioeng. Symp. Ser. 17: 495. Sims, K. A. and Cheryan, M. 1992a. Biotechnol. Bioeng. 39: 960. Sims, K. A. and Cheryan, M. 1992b. StarchJStarke. 44: 345. Singh, N. 1997. Ph.D. Thesis, University of Illinois, Urbana. Singh, N. and Cheryan, M. 1997a. Cereal Foods World 42(7): 520. Singh, N. and Cheryan, M. 1997b. Cereal Foods World 42(1): 21. Snape, J. B. and Nakajima, M. 1996. J. Food Engr. 30: 1. Steiber, R. W. and Gerhardt, P. 1981. Biotechnol. Bioeng. 23: 535. Strathman, H. 1980. Sep. Sci. Technol. 15: 1135. Suzuki, S., Maebashi, N., Yamano, S., Nogaki, H., Tamaki, A. and Noguchi, A. 1992. U.S. Patent 5,166,376. Tabatabia, A., Scamehorn, J. F. and Christian, S. D. 1995. J. Membrane Sci. 100: 193. Tako, M. and Nakamura, S. 1986. Agric. Biol. Chem. 50: 833. Tanahashi, S. Nagano, K., Kasai, M., Tsubone, E, Iwama, A., Kazuse, Y., Tasaka, K. and Isooka, Y. 1988. U.S. Patent 4,787,981.

Tanaguchi, M., Kotani, N. and Kobayashi, T. 1987. Appl. Microbiol. Biotechnol. 25: 438, and J. Ferment. Technol. 65: 179. Tejayadi, S. and Cheryan, M. 1988. Appl. Biochem. Biotechnol. 19: 1. Tong, P. S., Barbano, D. M. and Jordan, W. K. 1988. J. Dairy Sci. 71: 2342. Tragardh, C. 1974. Lebensm.-Wiss. u.-Technol. 1: 199. Tran, T. V. 1985. Chem. Engr. Progr. 81(3): 29. Tsai, L. S., Ijichi, K. and Harris, M. W. 1977. J. Food Protection. 40: 449. Turpie, D. W. F, Steenkamp, C. J. and Townsend, R. B. 1992. Water Sci. Technol. 25: 127. Tzeng Y. M., Diosady, L. L. and Rubin, L. J. 1988. Canadian J. Food Sci. Technol. 21: 419.

Ulloa, J. A., Valencia, M. E. and Garcia, Z. J. 1988. J. Food Sci. 53: 1396.

USDA. 1978. Handbook No. 8, U.S. Department of Agriculture, Washington, DC.

US Filter. 1996. Ceramic Membrane News, Warrendale, PA. 2(6): 1.

Van der Horst, H. C. and Hanemaaijer, J. H. 1990. Desalination 77: 235.

Vavra, C. and Koseoglu, S. S. 1994. In Developments in Food Engineering, T. Yano, R. Matsuno and K. Nakamura (eds.). Blackie Academic, Glasgow, U.K. p. 683.

Verma, S. K., Srikanth, R., Das, S. K. and Venkidachalam, G. 1996. Indian J. Chem. Technology, 3: 136.

Vetier, C , Bennasar, M. and Tarodo de la Fuente, B. 1988. J. Dairy Res. 55: 381.

Vick Roy, T. B., Blanch, H. W. and Wilke, C. R. 1982. Biotechnol Lett. 4: 483.

Vick Roy, T. B., Mandel, D. K., Dea, D. K., Blanch, H. W. and Wilke, C. R. 1983. Biotechnol. Lett. 10: 665.

Wafilin, B. V. 1983. Product Bulletins, Hardenberg, The Netherlands.

Wajnowska, I., Bednarski, W. and Poznanski, S. 1979. Acta Aliment. Pol. 5(3): 327.

Wandrey, C. and Flaschel, E. 1979. Adv. Biochem. Engr. 12: 147.

Watanabe, A., Ohtani, T., Horikita, H., Ohya, Y. and

Kimura, A. 1984. In Engineering and Food. Volume 1, B. M. McKenna (ed.), Elsevier Applied Science Publishers, London, U.K. p. 225.

Welsh, F. W. and Zall, R. R. 1984. Can. Inst. Food Sci. Technol. 17: 92.

Wichmann, R., Wandrey, C., Buckmann, A. F. and Kula, M. R. 1981. Biotechnol. Bioeng. 23: 2789.

Wilson, E. L. and Burns, D. J. W. 1983. J. Food Sci. 48: 1101.

Wu, Y. V, Sexson, K. R. and Lagoda, A. A. 1985. Cereal Chem. 62: 470.

Yabushita, T. 1989. Nitto-Denko Technical Reports, 4: 47.

Yamazaki, Y., Maeda, H. and Suzuki, H. 1976. Biotechnol Bioeng. 18: 1761.

Yu, Z. R., Chiang, B. H. and Hwang, L. 1986. J. Food Sci. 51: 841.

Zahka, J. and Mir, L. 1977. Chem. Eng. Progr. 73(12): 53.
Zanto, L. T., Christiffer, L. M. and Birschel, S. E. 1970. J. Am. Soc. Sugar Beet Technologists. 16(1): 26.

Zhang, S. Q., Kutowy, O., Kumar, A. and Malcolm, I. 1997. Canadian Agricultural Engineering.

Zhang, D. X. and Cheryan, M. 1994. Process Biochem. 29: 145.

Index