

Ultrafiltration of Salt Solutions by Ion-Excluding and Ion-Selective Membranes*

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INTRODUCTION

Ultrafiltration of salt solutions has been demonstrated for several membranes.¹⁻³ Membranes which are effective salt filters can be classified as ion-excluding and ion-selective. Ion-selective membranes are composed of polyelectrolytes and block the passage of either anions or cations, thus filtering the salt unless a short circuit occurs across the membrane. Ion-excluding membranes, of which cellulose acetate has been a singular example, contain hydrophilic groups and block the passage of both the anions and cations of the salt. The high salt rejection by cellulose acetate appears to be the result of bound water in the membrane; this prohibits the passage of ions which do not fit into the quasicrystalline bound-water network.

This paper presents ultrafiltration and ohmic resistance data for several membranes not previously investigated and attempts to relate their salt-filtering ability to structural characteristics.

EXPERIMENTAL

Preparation of Membranes

The membranes were prepared by spreading a solution of the polymer on a level glass sheet with a doctor blade and then evaporating the solvent in a dry box. The thickness of the membranes was determined with a dial indicator to an accuracy within ± 3 microns. Some membranes were also prepared by casting the polymer solutions on cellophane taped to the glass sheet. (Films supported by cellophane are indicated in this paper by an asterisk, e.g., PVM/MA*.) In order to obtain a flat surface upon which to cast the film, it was necessary to wet the cellophane with the solvent to

be used in the casting solution while taping it to the glass. In several cases a modified procedure was used, in which cellophane was soaked in water for three weeks and then taped to the glass while wet in order to obtain a more porous supporting membrane.

The preparation and conditioning of specific membranes was as follows.

Polyvinyl Alcohol (PVA). PVA membranes were cast from aqueous solutions of du Pont Elvanol, 72-60, which is specified as better than 99% hydrolyzed. These membranes were conditioned by baking at temperatures higher than 100°C.

Mixtures of PVM/MA and PVA. PVM/MA is a 1:1 copolymer of methyl vinyl ether and maleic anhydride, provided by the General Aniline and Film Corp. It is water-soluble and compatible with PVA, thus permitting the casting of aqueous solutions of the mixtures. Flexible, insoluble membranes were prepared by moderate baking (above 100°C.) of membranes containing small fractions of PVM/MA. Extended baking produced membranes too brittle for handling when dry, which were easily torn when wet. Membranes containing a carboxyl fraction X_f (where X_f denotes the ratio of carboxyl groups to the total of carboxyl plus hydroxyl groups) greater than 0.09 were usually also very brittle, even with mild baking. However, thin films containing high concentrations of PVM/MA could be made flexible and strong by casting on cellophane.

Formaldehyde-Cellophane. The cellophane was du Pont's PT-300, 22 microns thick. A modification of the procedure suggested by Kärholm⁴ was followed for the reaction of formaldehyde with cellophane: After removing the plasticizer by soaking in water, the cellophane was soaked for 1 hr. in a 15% solution of formaldehyde containing a trace of NH_4Cl and then baked at 110-120°C. for 30 min.

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Polyvinyl Methyl Ketone (PVMK). PVMK was prepared by bulk polymerization of distilled methyl vinyl ketone (Chas. Pfizer & Co., Inc.). The method was outlined by Marvel and Levesque.⁵ Membranes were cast from either acetone or acetic anhydride solutions.

Polyvinyl Acetate (PVAc). Vinyl acetate was polymerized by an emulsion method. Membranes were cast from acetone solutions.

Others. Cellulose isobutyrate and cellulose acetate butyrate membranes were cast from acetone solutions of samples provided by the Tennessee Eastman Co. Nylon 6 membranes were cast from commercial formic acid solutions of samples provided by the Chemstrand Corp. Cellulose acetate was du Pont's CA-43, 22 microns thick. Mylar C, 6 microns thick, was also tested.

Experimental Measurements

Ultrafiltration. The apparatus used to determine the ultrafiltration properties of the membranes is similar to the one described previously.¹ It consists of six membrane-supporting units in parallel, in which the membranes were clamped over porous supporting disks, connected to the solution reservoir, to which pressure was applied by means of compressed air. The solution was circulated across the membranes by convection.

Salt rejection (per cent reduction in concentration) and flow rates (microliters per hour per square centimeter) were determined at room temperature at an applied pressure of 40 atm. The influent was a 0.1M NaCl solution. Salt rejection was determined by comparing the conductivity of the effluent and the reservoir solutions.

An apparatus with a single membrane-supporting unit was used when runs were made to determine the effects of temperature and pressure on the ultrafiltration properties. The temperature was controlled by enclosing the unit in a can of water through which was circulated water of the desired temperature. The water was also passed through the cooling jacket to preheat the salt solution prior to its contact with the membrane. The temperatures recorded were those of the water surrounding the unit and were constant to within $\pm 1^\circ\text{C}$.

Ohmic Resistance. The apparatus for determining the ohmic resistance of the membranes was similar to the one previously described.¹ The contact area of the whetstone compressing blocks had an area of 1.0 cm.², and both electrodes were silver/silver chloride.

Runs were made at room temperature with a direct current of less than 0.5 μamp . The whetstone blocks were soaked in a 0.018M NaCl or HCl solution prior to each run. The membranes were conditioned by soaking them in water and then blotting several times with filter paper. The resistance of the cell without the membrane was first determined over the pressure range, then the membrane was inserted and the resistance measured again. Membrane resistance was calculated as the difference between the two measurements. Readings were made after 2 min. at the desired pressure.

The membrane resistance to NaCl was determined as the pressure was raised to a maximum and then reduced. The results varied widely unless the membranes were inserted between filter papers which had also been soaked in the electrolyte solution. Apparently the whetstone blocks punctured the membranes unless they were protected by the filter paper.

The membrane resistances to H^+ , Na^+ , and Cl^- were determined by sandwiching the membranes between either Amberplex cation or anion exchange membranes in the desired form. The resistance of the exchange membranes was first determined and was found to be nearly constant over the pressure range. Then the membrane was inserted, the pressure raised to about 250 atm. and the resistance determined as the pressure was reduced.

Elongation. Elongation of the PVM/MA-PVA membranes was determined after immersing them in water at $30 \pm 1^\circ\text{C}$. for 48 hr. This was sufficient time for elongation to become constant. Successive measurements did not vary more than $\pm 1\%$ in elongation.

PROPERTIES OF MEMBRANES

Ultrafiltration and Ohmic Resistance

The results of the ultrafiltration and ohmic resistance measurements made on the membranes are presented in Table I. The membranes are classified as ion-selective or ion-excluding by their resistance properties. Membranes with high resistance to NaCl, Na^+ , and Cl^- , but not to H^+ are classified as ion-excluding. Cellulose acetate, cellulose isobutyrate, PVMK* and PVAc* are in this category. Membranes that reject salt and have low resistance except to Cl^- are regarded as ion-selective. This type includes the PVM/MA—PVA and formaldehyde-cellophane membranes.

The salt rejection for the ion-selective membranes increased in the order of the resistance to Cl^- .

TABLE I
Results of Ultrafiltration and Ohmic Resistance Measurements

Membrane	Flow rate, $\lambda/\text{hr.}/\text{cm.}^2$	Salt rejection, %	Resistance at 40 atm., kohms		
			NaCl	Na^+	Cl^-
PVA	380	15	0.2	0.3	0.2
PVM/MA-PVA $X_f = 0.09$	25	60	0.2	0.3	1.8
PVM/MA-PVA* $X_f = 0.50$	9	98	0.1	0.1	3.0
Cellophane ^a	500	8	0.1	0.2	0.1
Formaldehyde-cellophane	20	45	0.2	0.1	0.5
Cellulose isobutyrate	40	87	130	100	85
Cellulose acetate butyrate ^a	10	8	~1000		
Cellulose acetate ^a	30	92	90	130	140
PVMK	35	3	(variable with time)		
PVMK*	40	60	8	10	10
PVAc	65	0			
PVAc*	4	70	50	75	60
Nylon 6	52	15			
Mylar C	10	0	>1000		

^a Also investigated previously.¹

These results expand the number of membranes known to have at least a moderate salt rejection. It is significant that PVMK* has a moderately high salt rejection. It was later improved to high salt rejection. It is the first ion-excluding membrane with high salt rejection investigated thus far which has groups other than ester linkages.

Durability of Membranes

The ultrafiltration properties of four typical membranes were investigated for several weeks. Results are summarized in Table II. None of the membranes failed abruptly. The durability of the PVM/MA-PVA* membrane was good despite the presence of ester linkages. It was much more durable than membranes of cellulosic esters. Perhaps the explanation is that the crosslinking prevents swelling, which precedes hydrolysis in cellulose acetate.¹ In addition, the ester group may be less susceptible to hydrolysis because of steric factors, since it is a link between two large multi-linked polymer molecules.

It was thought possible that the addition of a small amount of PVM/MA to cellulose acetate might crosslink with the residual hydroxyl groups when baked, which would prevent swelling and subsequent hydrolysis. This did not occur. The inclusion of 10% PVM/MA in cellulose acetate of 39.4% acetyl content produced membranes which exhibited lower initial salt rejection and failed more rapidly than the untreated membranes.

PVM/MA-PVA Membranes

Structural Variables. Flow rate, salt rejection, and elongation in water were investigated for a group of PVM/MA-PVA membranes varying both PVM/MA content and baking time. Table III summarizes the results. Salt rejection generally increased with baking time for membranes of like PVM/MA content and increased with X_f for membranes baked for the same period of time. Flow rate decreased as the salt rejection increased. The addition of a small amount of PVM/MA to PVA greatly decreased the elongation when baked. Figure 1, a graph of the points of Table III, shows the relationships of both flow rate and salt rejection to elongation. Apparently, the more swelling

TABLE II
Ultrafiltration Properties of Membranes as a Function of Time

Membrane	Duration of test, weeks	Initial		Change	
		Flow rate, $\lambda/\text{hr.}/\text{cm.}^2$	Salt rejection, %	Δ Flow rate, $\lambda/\text{hr.}/\text{cm.}^2$	Δ Salt rejection, %
PVM/MA-PVA* $X_f = 0.50$	25	23	92.5	0	-1.3
PVM/MA-PVA $X_f = 0.18$	13	127	44	41	-7
PVMK*	8	50	90.0	35	2.5
Cellulose isobutyrate	3 days	40	87	148	-40

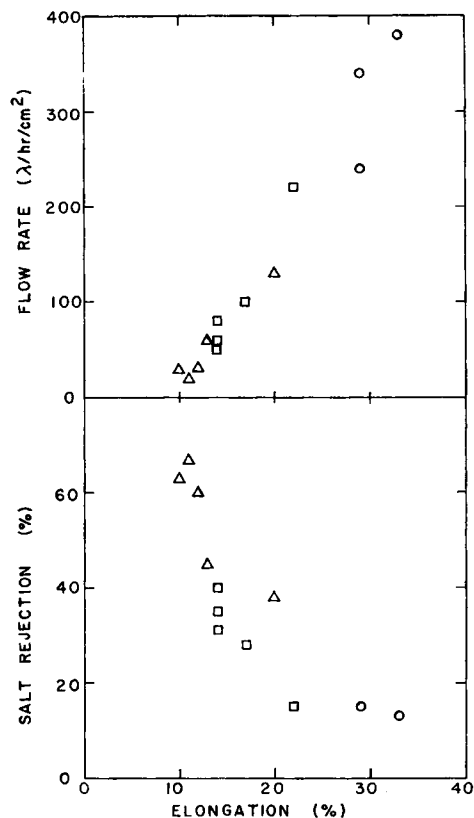


Fig. 1. Relationships of flow rate and salt rejection to elongation for PVM/MA-PVA membranes: (O) $X_f = 0$; (□) $X_f = 0.04$; (Δ) $X_f = 0.09$.

is restricted, the lower the flow rate, and the greater the salt rejection.

TABLE III
Ultrafiltration Properties and Elongation of PVM/MA-PVA Membranes

Membrane, X_f	Baking time, hr.	Flow rate, $\lambda/\text{hr.}/\text{cm.}^2$	Salt rejection, %	Elongation, %
0	0.5	380	13	33
	2.0	240	15	29
	5.0	340	15	29
	10.0	—	—	28
	20.0	—	—	29
0.04	0.5	220	15	22
	2.0	100	28	17
	5.0	80	31	14
	10.0	60	35	14
	20.0	50	40	14
0.09	0.5	130	38	20
	2.0	60	45	13
	5.0	30	60	12
	10.0	20	67	11
	20.0	30	63	10

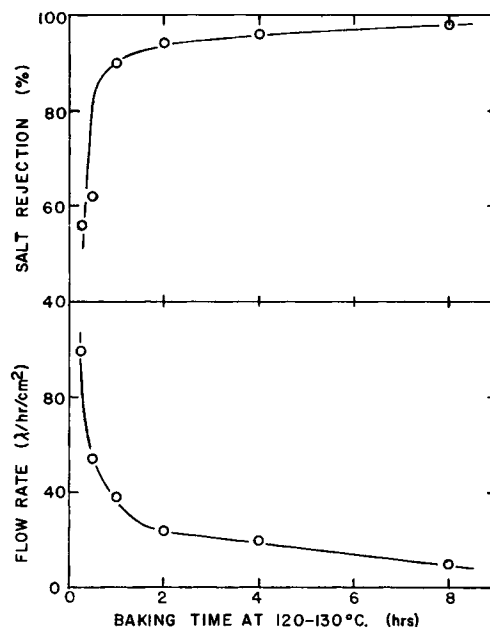


Fig. 2. Effect of baking time on the ultrafiltration properties of PVM/MA-PVA* membranes, $X_f = 0.50$.

High salt rejection was obtained for thin PVM/MA-PVA films cast on cellophane. For short baking times, 2 hr. at 100–110°C., the films separated from the cellophane, resulting in high flow rates and low salt rejection (comparable to cellophane alone). A longer baking time, 19 hr. at 100–110°C., bonded the films to the cellophane, and high rejection with reduced flow rates resulted. Salt rejection increased with baking for a very thin film, about 4 microns, until it reached 98% after 8 hr. at 120–130°C. (Fig. 2). The salt rejection was inversely related to the flow rate.

The low flow rates of high-rejection films of PVM/MA-PVA* were increased substantially, with some reduction in salt rejection, by casting them on swollen cellophane. For example, when cast on cellophane, a 4-micron film with X_f of 0.50, baked 8 hr. at 120–130°C., had a flow rate of 9 $\lambda/\text{hr.}/\text{cm.}^2$ and a salt rejection of 98%. Similar treatment of a like film cast on swollen cellophane resulted in flow rates of about 88 $\lambda/\text{hr.}/\text{cm.}^2$ and salt rejection of about 88%. Results are the average of two runs.

The thickness of the membranes affects flow rate to a much greater degree than salt rejection. Table IV shows that the salt rejection of PVM/MA-PVA was essentially the same for a membrane 28 microns thick as for one half as thick, while the flow rate was nearly 6 times as great in the thinner membrane. Salt rejection was lower for a very thin membrane

in which defects are much more likely. The relation of the ultrafiltration properties of PVM/MA-PVA* films to thickness is complicated by the requirement that they must bond to the cellophane to produce high salt rejection. Thick films tend to swell and separate from the cellophane in the presence of water, while thin films are more susceptible to defects. Thus, films of intermediate thickness gave higher salt rejection and lower flow rates than very thin or very thick films (Table IV).

TABLE IV
Effect of Membrane Thickness on the Ultrafiltration Properties of PVM/MA-PVA Membranes

Thickness, microns	Flow rate, λ /hr./cm. ²	Salt rejection, %
PVM/MA-PVA membranes, $X_f = 0.09$		
8	41	52
15	29	63
23	7	68
28	5	66
PVM/MA-PVA* films, $X_f = 0.50$		
1	17	78
4	10	94
8	14	71
20*	190	15

* The thickest film was cast from a solution calculated to produce a membrane approximately 20 microns thick. The remaining membranes were prepared from diluted solutions of the original casting solution.

Process Variables. The effect of temperature on the ultrafiltration properties of PVM/MA-PVA membranes is presented in Table V. The results indicate that flow rate is much more sensitive to temperature than is salt rejection. It should be noted that rapid deterioration of the ultrafiltration properties occurred at 91°C.; however, no significant deterioration was observed when the temperature was maintained at 60–70°C. for two weeks. Perhaps the difference in behavior at the two temperatures is related to the requirement that the PVA must be heated to about 85°C before it will form an aqueous solution.

The influent NaCl concentration was varied over the range 0.11–0.57M at an applied pressure of 30 atm. in excess of the osmotic pressure of the solution. The results given in Table VI show that the ultrafiltration properties of the high-rejection membrane are constant over the concentration

TABLE V
Effect of Temperature on the Ultrafiltration Properties of PVM/MA-PVA Membranes

Temperature, °C.	Flow rate, λ /hr./cm. ²	Salt rejection, %
PVM/MA-PVA membrane, $X_f = 0.09$		
9	28	60
30	52	52
PVM/MA-PVA* film, $X_f = 0.50$		
30	11	98
53	25	97
73	57	95
91*	91–130	92–82

* Rapid deterioration occurred at this temperature. The values reported are those at the beginning and end of 24 hr. of testing.

range. For other membranes, the salt rejection decreased and the flow rate increased as the concentration was increased. The results demonstrate that PVM/MA-PVA membranes are effective salt filters at concentrations comparable to that of sea water, and that their behavior at the usual testing concentration of 0.1M NaCl is indicative of their behavior at higher concentrations. Sea water contains lesser concentrations of ions other than Na⁺ and Cl⁻; their effects on durability and ultrafiltration properties were not investigated. Gregor³ indicates that complexing ions, such as copper, should decrease the selectivity of membranes containing carboxyl groups. However, the ultrafiltration properties of a PVM/MA-PVA

TABLE VI
Effect of Solution Concentration on the Ultrafiltration Properties of PVM/MA-PVA Membranes

	Solution concn.			
	0.11M	0.24M	0.54M	0.57M
PVM/MA-PVA membrane, $X_f = 0.09$				
Flow rate, λ /hr./cm. ²	21	25	28	—
Salt rejection, %	49	45	40	—
PVM/MA-PVA* film, $X_f = 0.50$				
Flow rate, λ /hr./cm. ²	24	26	26	24
Salt rejection, %	91	90	87	87
PVM/MA-PVA* film, $X_f = 0.50$				
Flow rate, λ /hr./cm. ²	12	13	13	12
Salt rejection, %	95	96	95	95

* The chronological order of the concentrations was 0.57, 0.24, 0.11 and 0.54.

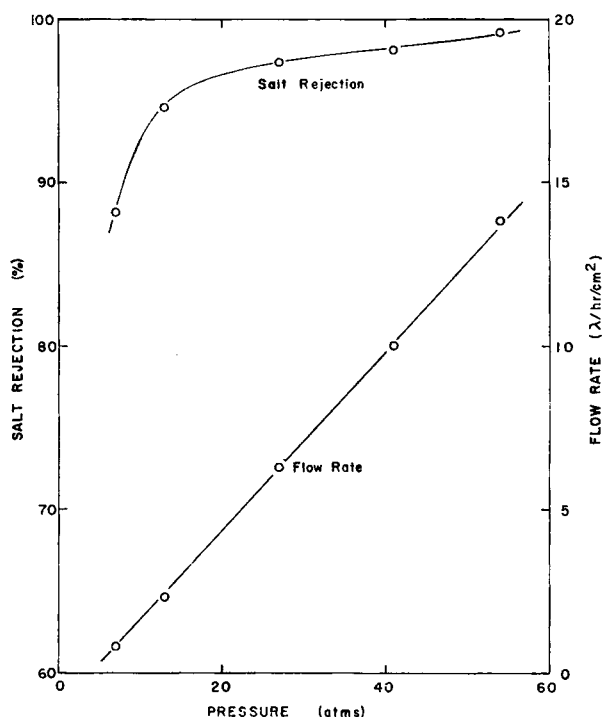


Fig. 3. Effect of pressure on the ultrafiltration properties of a PVM/MA-PVA* membrane, $X_f = 0.50$.

membrane soaked overnight in a 0.1M CuSO_4 solution were not altered.

The ultrafiltration properties of a PVA/MA-PVA* film were determined over the applied pressure range of 7–55 atm. Figure 3 shows that the flow rate increased linearly with pressure over this range, while high salt rejection was obtained at the low pressures and increased slightly with pressure. The increase of flow rate with pressure is contrary to results of investigations of other ion-selective membranes. McKelvey² and Gregor³ report a decrease in flow rate with pressure. The present authors⁶ found that the flow rate increases for cellophane at even higher pressures, but reaches a maximum at about 200 atm. Apparently the structure of PVM/MA-PVA is stable enough to prohibit large reductions in pore sizes at the pressures used. However, higher pressures might also reduce the slope of the flow rate curve for this membrane.

Function of the Supporting Membrane

High salt rejection by PVM/MA-PVA films cast on cellophane depends upon the bonding of the film to the cellophane. The function of the supporting membrane apparently is to restrict

the interchain distances of the PVM/MA-PVA film which swells more than the cellophane.

PVMK and PVAc membranes are effective salt filters only when supported by cellophane. They would not be expected to bond chemically to the cellophane; however, adhesion forces are presumably present. The dependence of the salt rejection upon the interaction at the PVMK-cellophane interface is evident from the following observations. PVMK membranes cast on cellophane gave a moderately high salt rejection. However, when tested in an inverted position, with PVMK on the downstream side, they behaved like cellophane alone. Preformed membranes laid on cellophane gave a moderately high salt rejection; in one case, the salt rejection started low and increased during the run to moderately high value.

Two methods were used to increase the interaction at the PVMK-cellophane interface. (a) The heat and pressure suggested by McLaren⁷ to increase the adhesion were applied to a sandwich of cellophane laid on PVMK cast on cellophane. (b) PVMK was cast on swollen cellophane to permit more penetration into the cellophane pores. The first treatment did not increase the salt rejection; in fact, it was somewhat lower. Similar results were obtained with PVAc. The second treatment resulted in high salt rejection and low flow rates (Table VII).

TABLE VII
Ultrafiltration Properties of PVMK Films Cast on Swollen Cellophane

Film cast on cellophane		Film cast on swollen cellophane	
Flow rate, λ /hr./cm. ²	Salt rejection, %	Flow rate, λ /hr./cm. ²	Salt rejection, %
46	52	13	85
40	58	9	94

Salt rejection by PVMK* membranes appears to be a property of the interface between the two polymers, and perhaps the barrier to the passage of ions occurs only in the interfacial region. The structure in this region is not known; however, a postulate consistent with the bound-water mechanism can be made. PVMK has a high concentration of hydrophilic groups, but the polymer is amorphous and not crosslinked. Thus, if the bound-water theory describes the mechanism by which the composite membrane rejects salt, the apparent role of the supporting membrane is to

stabilize the interchain distances of the PVMK in the interfacial region.

Another possible description is that the penetration of PVMK into the pores essentially reduces the pore sizes of the cellophane in the interfacial region and that this increases its salt rejection. However, this does not seem likely because it has been shown that, even at pressures as high as 340 atm., cellophane, which is readily compressed,⁸ rejects only about 40% of the ions.⁶ Also, the salt rejection was only 13% when PVA was cast on cellophane and 31% when PVM/MA was cast on cellophane and the composite membrane baked to enhance crosslinking.

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Synopsis

Salt-filtering properties of several polymeric membranes were investigated at 40 atm. applied pressure. The ultrafilters were classified as ion-excluding or ion-selective membranes according to their ohmic resistance to the ions of the sodium chloride test solution. Membranes containing hydrophilic groups which have a high resistance to both cations and anions are classified as ion-excluding. Polyelectrolyte membranes with high resistance to cations only are considered to be ion-selective. In addition to cellulose acetate, which has been investigated previously, cellulose isobutyrate, cellophane-supported polyvinyl methyl ketone, and cellophane-supported polyvinyl acetate were found to be ion-excluding membranes. The amorphous membranes, polyvinyl methyl ketone and polyvinyl acetate, do not reject salt alone; the cellophane appears to provide a supporting

matrix which restricts the interchain distances in the interfacial region. Membranes composed of mixtures of the 1:1 copolymer of methyl vinyl ether and maleic anhydride with polyvinyl alcohol were durable, ion-selective salt filters. Baking these membranes reduced swelling and flow rate and increased salt rejection. Those membranes containing high concentrations of the copolymer were flimsy and required bonding to a cellophane supporting membrane in order to obtain high salt rejection. The effects of process variables on the ultrafiltration properties of the ion-selective membranes were also investigated. The salt rejection by either class of membrane depends on both a high concentration of the required functional groups and restricted interchain distances. Despite differences in the mechanism, each class behaves as a filter, in that the smaller the pores, the more effective the separation and the lower the flow rate.

Résumé

Les propriétés filtrantes des différentes membranes polymériques à l'égard de sels, sont examinées à une pression de 40 atm. Les ultrafiltres sont classifiés comme des membranes excluant les ions ou sélectives aux ions suivant leur résistance ohmique à l'égard des ions d'une solution de chlorure de sodium. Des membranes contenant des groupes hydrophiliques qui ont une grande résistance pour les cations et les anions sont classifiées comme excluant aux ions. Des membranes de polyelectrolytes avec une grande résistance seulement vis à vis des cations, sont considérées comme sélectives aux ions. Outre l'acétate de cellulose, qui a été examiné précédemment, l'isobutyrate de cellulose, la polyvinylméthyl-cétone déposée sur la cellophane et l'acétate de polyvinyle déposé sur la cellophane sont des membranes excluant les ions. Les membranes amorphes de polyvinylméthylcétone et d'acétate de polyvinyle ne rejettent pas les sels lorsqu'elles sont seules. La cellophane semble produire une matrice supportante qui limite les distances dans la chaîne dans la région interfaciale. Des membranes composées de mélanges de copolymère 1:1 d'éther méthyl vinylique et d'anhydride maléique avec l'alcool polyvinylique étaient des filtres d'ions sélectifs. Le chauffage de ces membranes réduit leur gonflement et la vitesse d'écoulement, de même il accroît le refus des sels. Ces membranes, qui contiennent de grandes concentrations de copolymère étaient minces et étaient liées à une membrane supportante de cellophane afin d'obtenir une grande rejection saline. Les effets de processus variables sur les propriétés d'ultra filtration des membranes sélectives aux ions ont aussi été examinés. La réjection saline pour chaque classe de membranes dépend et de la grande concentration des groupes fonctionnels requis et des distances intercaténaire limitées. Malgré leur mécanisme différent chaque classe se comporte comme un filtre au travers duquel la séparation est d'autant plus effective et la vitesse d'écoulement d'autant plus faible que les pores en sont petites.

Zusammenfassung

Das Verhalten einiger Polymermembranen bei der Salzfiltration wurde unter einem Überdruck von 40 Atm untersucht. Die Ultrafilter wurden nach ihrem Ohm'schen Widerstand für die Ionen der Natriumchlorid-Testlösung als ionexklusive oder ionselektive Membranen klassifiziert.

Membranen mit einem Gehalt an hydrophilen Gruppen, die sowohl für Kationen als auch Anionen einen hohen Widerstand besitzen, werden als ionexklusiv klassifiziert. Polyelektrolytmembranen mit hohem Widerstand nur gegen Kationen werden als ionselektiv betrachtet. Zusätzlich zu dem früher untersuchten Celluloseacetate werden als ionselektive Membranen gefunden: Celluloseisobutyrat sowie Polyvinylmethylketon und Polyvinylacetat auf Cellophanträger. Die amorphen Membranen Polyvinylmethylketon und Polyvinylacetat sind für sich allein nicht salzabweisend; das Cellophan scheint eine Trägermatrix zu bilden, welche die Abstände zwischen den Ketten in der Grenzschicht herabsetzt. Membranen aus Mischungen des 1:1-Methylvinyläther-Maleinsäureanhydridcopolymeren mit Polyvinylalkohol bildeten dauerhafte, ionselektive Salzfilter. Erhitzen dieser Membrane setzte ihre Quellung und Durch-

trittsgeschwindigkeit herab und steigerte die Salzabweisung. Die Membranen mit einem hohen Gehalt an Copolymerem waren unbeständig und mussten zur Erreichung einer hohen Salzabweisung auf eine Cellophanträgermembrane aufgebracht werden. Weiters wurde der Einfluss der Herstellungsvariablen auf die Ultrafiltrationseigenschaften der ionselektiven Membranen untersucht. Die Salzabweisung jeder der beiden Membranklassen erfordert sowohl eine hohe Konzentration der betreffenden funktionellen Gruppen als auch einen beschränkten Abstand zwischen den Ketten. Ungeachtet des verschiedenen Mechanismus verhält sich jede Klasse wie ein Filter, bei dem eine kleinere Porengröße eine wirksamere Trennung und zugleich eine geringere Durchtrittsgeschwindigkeit bedingt.

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