

Permeabilities of Coagulated Cellulose Acetate Dialysis Membranes

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Synopsis

The diffusive flux of NaCl and the hydraulic flux of pure water through coagulated cellulose acetate membranes are examined. Coagulated cellulose acetate membranes (without densification by heat treatment or drying) possess higher permeability than what may be expected from the permeabilities of the dry polymer. Their overall hydraulic permeability (ultrafiltration rate of water) is greatly dependent upon the membrane casting conditions and the resulting asymmetry of the membrane. On the other hand, the asymmetry of a membrane does not play as great a role in the diffusive permeability of a solute. With homogeneous membranes, higher diffusive flux is always accompanied by higher hydraulic permeability. With asymmetric membranes, this is not always true. The diffusive permeability of NaCl and the hydraulic permeability of water through coagulated cellulose acetate membranes can be controlled nearly independently. Consequently, high diffusive (NaCl) permeability with low hydraulic water permeability and vice versa can be obtained by varying the casting conditions and also by partially saponifying the denser portion of the membrane.

INTRODUCTION

Cellulose acetate film is one of the best desalination membranes for reverse osmosis, rejecting sodium chloride over 99% under reverse osmosis conditions. Consequently, the transport of solutes through unmodified cellulose acetate is expected to be very poor when it is used as a dialysis membrane in which high transport rates of solutes are required.

On the other hand, cellulose acetate has the unique property of being able to form asymmetric functional membranes, such as the structure known as the Loeb-Sourirajan type or, in more general terms, as modified cellulose acetate reverse osmosis membranes. In these modified cellulose acetate membranes, a very thin layer (0.1–0.2 μ) of dense cellulose acetate is formed on one side of a membrane and the remaining thickness of the 20–30 μ thick membrane consists of a very porous layer acting as the supporting layer in the composite structure.

Since cellulose acetate can be easily saponified to cellulose in film form, it was first thought that the saponification of the dense layer of modified cellulose acetate and also the saponification of the entire structure might lead to improved cellulose dialysis membranes.

This turned out not to be the case, but it was found that cellulose acetate or partially saponified cellulose acetate can be formed into membranes which possess higher dialysance of sodium chloride than does cuprophane (which is a cellulose membrane widely used in hemodialysis), with various degrees of ultrafiltration of water at the desired dialysance level.

This paper discusses only membranes composed of a single polymeric species, i.e., one-component membranes. If such a membrane is cast from solution and dried, no phase separation occurs and the membrane is termed homogeneous. If the membrane is cast and coagulated in a bath, varying degrees of phase separation between polymer and coagulating agent may occur, depending on the conditions used. If phase separation occurs to the extent that the membrane is opaque, it is considered heterogeneous. If it remains clear, it may be homogeneous or it may be heterogeneous on a submicroscopic scale. Obviously, the line between homogeneous and heterogeneous is somewhat arbitrary. Membranes may be further distinguished as symmetric or asymmetric. A symmetric membrane is one which does not have a microscopic density gradient perpendicular to the surface. An asymmetric membrane may have a uniform or nonuniform density gradient from one side to the other. If the nonuniformity is distinct enough, the term composite may be applied.

BASIC CONSIDERATIONS

Diffusive Permeability and Dialysance of a Solute

In a diffusive process such as dialysis in which no significant pressure gradient across the membrane exists, the transport of a solute can be described by the equation relating the diffusive permeability of a solute, P_2 , and the flux per unit area, J_2 ,

$$J_2 = \frac{P_2}{l} \Delta C \quad (1)$$

or

$$P_2 = J_2 \frac{l}{\Delta C} \quad (2)$$

P_2 thus defined, therefore, is a constant characteristic of the material if the membrane is symmetric. However, for asymmetric and composite membranes, P_2 does not have this significance as a material constant.

Dialysance, in this paper, is defined as

$$Q_2 \equiv \frac{J_2}{\Delta C} = \frac{P_2}{l} \quad (3)$$

Thus, Q_2 is a coefficient descriptive of a particular membrane and is directly related to the transport performance of a membrane in dialysis regardless of the membrane structure.

Ultrafiltration Rate and Hydraulic Permeability of Water

The diffusive permeability of water, P_1 , can be defined exactly as P_2 is defined, but must be distinguished from the permeability of water measured under a hydraulic pressure gradient, i.e., the hydraulic permeability, K_1 :

$$J_{F,1} = \frac{K_1}{l} \Delta p \quad (4)$$

or

$$K_1 = J_{F,1} \frac{l}{\Delta p} \quad (5)$$

The ultrafiltration rate of a membrane,

$$L_1 = \frac{J_{F,1}}{\Delta p} = \frac{K_1}{l}$$

is distinguished from the hydraulic permeability in a similar manner as the dialysance of a membrane is distinguished from the diffusive permeability. L_1 is a membrane constant and is directly related to the performance of a membrane in ultrafiltration of water regardless of the membrane structure.

It should be noted that K_1 and P_1 do not have identical units. By multiplying K_1 and L_1 by RT/v_1 , where v_1 is the molar volume of water, a modified hydraulic permeability K_1' and modified ultrafiltration rate L_1' are obtained which have the same units as P_1 and L_1 , respectively:

$$K_1' = K_1 \frac{RT}{v_1}$$

$$L_1' = L_1 \frac{RT}{v_1}$$

Although K_1' has the same units as P_1 , actual values of K_1' are not always identical with P_1 , and their difference is due to the basic movement of water in a membrane under diffusive and hydraulic conditions.¹⁻³

Effect of Composite Structure on Q and L

A steady-state flux under both diffusive and hydraulic flow, through a composite membrane which consists of n layers of various permeabilities, can be generally expressed (without subscript) by

$$\frac{1}{Q} = \frac{l}{P} = \sum_{i=1}^n \frac{l_i}{P_i} \quad (6)$$

$$\frac{1}{L} = \frac{l}{K} = \sum_{i=1}^n \frac{l_i}{K_i} \quad (7)$$

where P_i and K_i are the diffusive and hydraulic permeabilities, respectively, of the i^{th} layer, l_i is the thickness of the i^{th} layer, and

$$l = \sum_{i=1}^n l_i \quad (8)$$

The similarity of eqs. (6) and (7) appears to imply that the hydraulic and diffusive fluxes should behave similarly. Clearly, a reduction in thickness of a rate-determining layer in the composite structure should increase the total flux in both cases. However, there is a practical limitation which makes a great difference in the effectiveness of composite or asymmetric structure increasing total flux in the two types of transport mechanism.

With a simplified capillary model of membrane, which consists of parallel alleys of n capillaries of radius r in a unit membrane area, P_1 and K_1 are given by

$$P_1 = D_1 \epsilon b \quad (9)$$

$$K_1 = \epsilon \frac{r^2}{8\eta_1} \quad (10)$$

where D_1 is the self-diffusion constant of water, ϵ is the porosity ($\epsilon = n\pi r^2$), b is a factor which represents inversely the tortuosity of the capillary ($1 \geq b \geq 0$), and η_1 is the viscosity of water. By comparing eq. (9) with eq. (10), it is clear that P_1 is not dependent on r , while K_1 is dependent on r^2 .

It has been shown that the maximum value of the diffusive permeability of a solute is the diffusion constant of the permeant in pure water,^{4,5} but there is no theoretical upper limit in the hydraulic water permeability K_1 , as seen in eq. (10).

As pore size r increases, l_i/K_i for water quickly approaches zero, but l_i/P_i does not follow this trend. In other words, the highly porous portion of an asymmetric or a composite membrane contributes a considerable portion of overall transport resistance of the membrane in the diffusive process, while it is negligible in the hydraulic process. Therefore, the hydraulic flux of a composite membrane can be increased to a great extent, but the increase of diffusive flux by a composite structure is much more restricted.

The reduced diffusive permeability, which is the ratio of the diffusive permeability of a membrane to the diffusion constant of the solute in pure water, can be given by the following expressions for small solutes. For porous membranes,⁵

$$\frac{P}{D_0} = \epsilon b \quad (11)$$

where D_0 is the diffusion constant of the solute in water (the self-diffusion constant of water for P_1). For homogeneous polymer membranes, it can be generally expressed as⁵

$$\frac{P}{D_0} = H e^{-B(1/H-1)} \quad (12)$$

where H is the volume fraction of water in a membrane and B is a proportionality constant.

For porous membranes, the maximum practical parameters obtainable may be estimated as $\epsilon = 0.8$ and $b = 1.0$; consequently, P_2/D_0 of roughly 0.8 would be expected as the practical limit. On the other hand, P_2/D_0 of sodium chloride through cellulose membranes was found to be roughly 0.4 ($H = 0.5$ and $e^{-B(1/H-1)} = 0.8$). Therefore, no matter how porous a membrane becomes, the diffusive permeability cannot be improved to more than approximately twice that of cellulose membranes. Therefore, the ultimate membrane performance, which may be characterized by the dialysance Q , is influenced much more strongly by membrane thickness.

This situation also sets the limitations and requirements of asymmetric cellulose acetate membranes. Therefore, it is expected that the ultrafiltration rate L_1 of asymmetric cellulose acetate membranes can be increased in orders of magnitude by making the supporting layer very porous; however, unless it is possible to make the total membrane thickness similar to that of cuprophane, not much improvement in dialysance can be expected. This is one of the major reasons why the saponification of desalination membranes known as the Loeb-Sourirajan-type cellulose acetate membranes does not necessarily yield improved hemodialysis membranes; i.e., most desalination membranes have a considerably larger total thickness than cuprophane.

Asymmetry of Coagulated Cellulose Acetate Membranes

The hydraulic permeability and diffusive permeability of water and solutes in homogeneous (dense) cellulose acetate is much lower than that of cellulose, due to the more hydrophobic nature of the polymer. However, the permeabilities (both diffusive and hydraulic) of coagulated cellulose acetate membranes are considerably higher than those of dense cellulose acetate, and the hydraulic water permeabilities of such membranes are often higher than those of cellulose membranes.⁶ As discussed in a separate work,⁷ the coagulated cellulose acetate membranes prepared by the method used in this study do seem to have a density gradient, with the top surface having the highest density. The permeability of this top layer without heat treatment is still considerably higher than the value for dense cellulose acetate but usually lower than that for cellulose.⁶ The layers which have higher densities (and consequently lower permeabilities) exert the main part of the transport resistance.

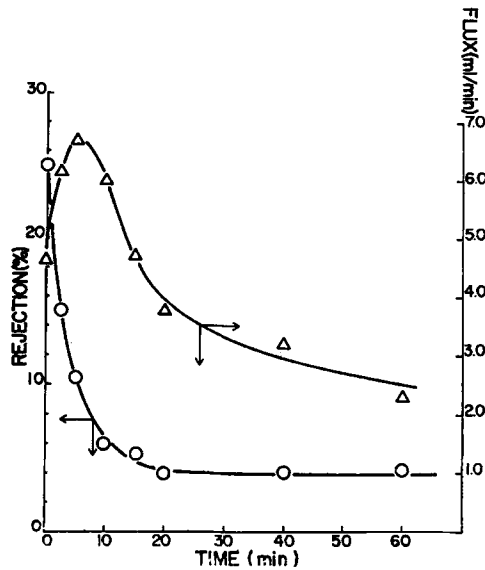


Fig. 1. Change of water flux and salt rejection by a nonheat-treated cellulose acetate modified membrane as a function of asymmetric saponification time. Saponification was effected by 0.1*N* NaOH at room temperature from the active side of the membrane. Reverse osmosis test was done with 3.5% NaCl solution at 1500 psi applied pressure.

It was found that asymmetric saponification by NaOH solution from the top surface of coagulated cellulose acetate membrane can be utilized to examine the tightness of the top layer and the extent of asymmetry.^{6,7} A distinct difference between heat-treated and nonheat-treated membranes has been observed in the relationship of the ultrafiltration rate to the amount of asymmetric saponification.⁶ Heat-treated membranes before saponification have a lower ultrafiltration rate than comparable cellulose membranes, but this rate increases after a certain characteristic saponification time. In contrast to this, most coagulated cellulose acetate membranes without heat treatment or saponification have an ultrafiltration rate which is actually higher than that of the more hydrophilic cellulose. The ultrafiltration rate of these membranes, however, increases briefly and then decreases sharply with asymmetric saponification time. This effect is clearly seen in a change in reverse osmosis performance of asymmetrically saponified nonheat-treated membranes, as shown in Figure 1, which is in strong contrast to similar plots for heat-treated membranes.⁷

The ultrafiltration rates of both heat-treated nonheat-treated membranes approach an identical value as saponification becomes complete. The dialysance of sodium chloride for heat-treated membranes before saponification is lower than that of nonheat-treated membranes. After a short saponification time of the dense layer (e.g., 20 min by 0.1*N* NaOH), there is no appreciable difference in NaCl dialysance between

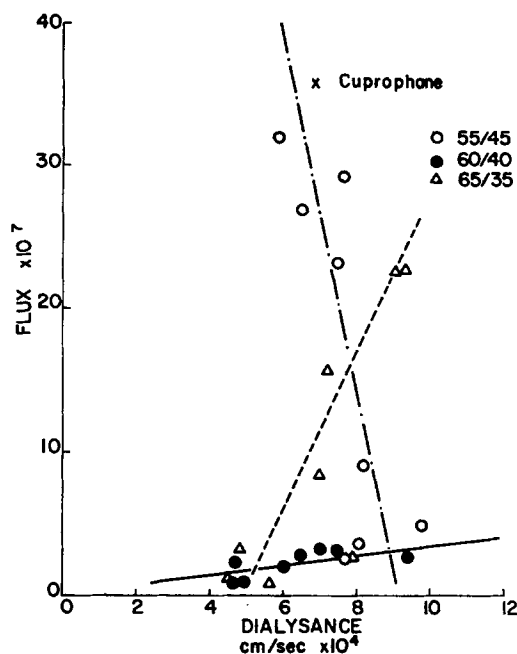


Fig. 2. Correlation between NaCl dialysance and ultrafiltration water flux of coagulated and partially (asymmetrically) saponified cellulose acetate membranes. Volume ratio of acetone/formamide used as solvent of casting solution: (O) 55/45; (●) 60/40; (Δ) 65/35. Units of water flux are cm/sec · mm Hg.

heat-treated and nonheat-treated membranes, although there is still an appreciable difference in ultrafiltration rates.⁶

These observations are compatible with the results of a separate investigation⁷ in which it became clear that the structure of the so called "Loeb type" cellulose acetate membrane is greatly influenced by the heat treatment of the coagulated membranes which seems to produce a very thin and dense surface layer. The nonheat-treated membranes do not seem to possess such a discrete composite structure, although they are apparently asymmetric.

For dialysis membranes, the effect of the heat treatment in creating the tight surface layer is undesirable, since high dialysance is always wanted. However, with nonheat-treated membranes the preceding observations suggested that by varying the casting conditions (and thereby the asymmetry) and by using partial asymmetric saponification to modify the permeability of the denser portion of the asymmetric membrane, it might be possible to demonstrate a practical means of controlling the balance between the dialysance and the ultrafiltration rate. Therefore, a series of coagulated cellulose acetate membranes was prepared varying separately the solvent used, the polymer concentration, and the casting thickness, with addition of asymmetric saponification from the dense side by 0.1N NaOH for 5 min at 25°C.

EXPERIMENTAL

The cellulose acetate used in this study is the commercial product of Eastman designated as E-398-3. Acetyl constant is 39.8%, and the falling ball viscosity is 3 sec. This brand of cellulose acetate is widely used in the preparation of reverse osmosis desalination membranes, and its recipes are well known. A basic recipe using acetone-formamide mixed solvent⁸ was adopted in this study, and the solvent mixture ratio of acetone-formamide was varied as follows: 55/45, 60/40, 65/35, 70/30. In one series of experiments, 5% water, based on the solvent mixture, was added to the 70/30 acetone-formamide mixture.

Polymer was dissolved in the mixed solvent in concentrations of 15, 20, and 25 wt-% (30% in 60/40 mixture only). The solution were cast on a glass plate at room temperature and kept in the air for 30 sec and then immersed in a water bath at 0°C.

The coagulated membranes were kept in the ice water for at least 2 hr and then stored in water before testing. The membranes were treated with 0.1N NaOH solution from the top side (side exposed to air) of the membrane for 5 min unless otherwise specified. For this asymmetric treatment, the membrane was clamped in a ultrafiltration cell, top side up, and the alkali solution was poured into the cell for a given time. At the end of treatment, an equal amount of 0.1N HCl was added to the cell to neutralize the alkali, and the solution was poured out and washed by distilled water several times before the dialysance was measured. The reason why this particular treatment condition was selected was mentioned in the preceding section.

Sodium chloride dialysance was measured at 25°C in a stirred cell at a stirring rate of 175 rpm. Sodium chloride concentration was determined by conductivity measurement. The details of the measurement and the calculations have been presented previously.^{4,6,9}

Measurement of ultrafiltration rate was made by applying 30 psig of air pressure up to the distilled water. For this measurement, Amicon ultrafiltration cells, Model-50, were used. The samples used for the ultrafiltration rate measurement were cut from the center part of the specimen used for the dialysis test.

RESULTS AND DISCUSSION

Results obtained with coagulated and asymmetrically partially saponified cellulose acetate membranes are summarized in Table I. In order to see more easily the relationship between ultrafiltration rate and sodium chloride dialysance, data (collected from Table I) for membranes cast using polymer concentrations and casting thicknesses which would result in nearly equal weight of polymer per unit membrane area are summarized in Table II as relative dialysance and ultrafiltration rates, using cuprophane as standard since it is the most widely used membrane in hemodialysis.

TABLE I
Diffusive Permeability, Dialysance of NaCl, and Ultrafiltration Rate of Water Through
Coagulated and Partially (Asymmetrically) Saponified Cellulose Acetate Membranes

Polymer concentration, %	Membrane		Time of asymmetric saponification by 0.1N NaOH, min	NaCl dialysance Q_2 , cm/sec $\times 10^4$	NaCl permeability P_2 , cm ² /sec $\times 10^6$	Ultrafiltration rate of water L_1 , cm/sec \cdot mm Hg $\times 10^7$
	Casting thickness, cm $\times 10^4$	Membrane thickness, cm $\times 10^3$				
Acetone/formamide solvent ratio 70/30						
15	18	2.5	5	10.89	2.72	84.6
15	20	3.6	5	7.19	2.59	48.3
15	23	4.6	5	5.76	2.65	35.6
15(+5% H ₂ O)	18	4.5	5	7.93	3.57	96.8
15(+5% H ₂ O)	20	4.1	5	8.45	3.46	135.
20	15	2.1	5	7.92	1.66	1.48
20	18	3.5	5	6.69	2.34	5.13
20(+5% H ₂ O)	15	3.2	5	8.44	2.35	6.70
20(+5% H ₂ O)	18	3.7	5	7.72	2.85	4.69
25	13	2.0	5	4.05	0.809	0.46
25	15	2.7	5	5.13	1.38	0.84
25	18	2.9	5	8.44	2.44	1.45
25(+5% H ₂ O)	13	1.9	5	7.29	1.38	1.80
25(+5% H ₂ O)	15	3.7	5	6.34	2.34	1.76
25(+5% H ₂ O)	18	4.5	5	4.64	2.09	1.89
Acetone/formamide solvent ratio 65/35						
15	18	3.5	5	9.11	3.19	22.5
15	20	3.7	5	7.26	2.68	15.8
15	23	3.0	5	9.34	3.83	22.6
20	15	2.7	5	7.00	1.89	8.32
20	18	2.6	5	7.81	2.03	2.60
25	10	2.1	5	5.65	1.18	0.792
25	13	2.1	5	4.53	0.95	1.31
25	15	3.3	5	4.80	1.58	3.29
Acetone/formamide solvent ratio 60/40						
15	20	6.2	5	6.29	3.90	—
15	25	2.5	5	6.94	1.7	—
20	13	1.7	10	7.53	1.28	3.01
20	15	2.4	5	8.44	2.03	—
20	15	2.5	10	6.53	1.63	2.76
20	15	3.4	20	6.97	2.37	—
20	18	2.4	10	9.41	2.26	2.65
25	13	2.8	10	6.02	1.68	2.09
25	15	3.7	5	7.06	2.61	3.35
25	15	3.4	10	7.43	2.52	—
25	15	3.5	20	7.32	2.56	—
25	18	4.4	10	4.75	2.09	2.17
25	18	4.6	20	5.66	2.60	—
30	10	3.4	5	4.77	1.62	0.853
30	13	7.2	5	4.99	3.59	1.00
Acetone/formamide solvent ratio 55/45						
15	18	3.8	5	8.23	3.12	8.80
15	20	5.9	5	7.54	4.45	23.4
15	23	8.2	5	6.57	5.38	27.1
20	13	2.3	5	9.84	2.26	4.84
20	15	—	5	—	—	3.22
20	18	3.1	5	8.01	2.48	3.55
25	10	2.7	5	5.91	1.59	32.2
25	13	2.4	5	7.71	1.85	2.53
25	15	2.6	5	7.65	1.99	29.4

TABLE II
Relative NaCl Dialysance and Ultrafiltration Rate (% of Cuprophane) of Coagulated and Partially (Asymmetrically) Saponified Cellulose Acetate Membranes^a

Acetone/formamide solvent ratio	Polymer concentration, %	Casting thickness, cm × 10 ³	Membrane thickness, cm × 10 ³	NaCl		Ultrafiltration rate
				P	Dialysance	
(Cuprophane reference)			22	100	100	100
55/45	25	13	24	122	114	7
	20	15	31	164	118	10
	15	20	59	285	111	65
60/40	**25	13	28	111	89	6
	20	15	24	134	123	—
	15	20	62	258	93	—
65/35	25	13	21	63	67	4
	20	15	27	125	103	23
	15	20	37	177	107	44
70/30	25	13	20	53	60	1
	20	15	21	110	117	4
	15	20	36	171	106	134
70/30 + 5% H ₂ O	25	13	19	91	107	5
	20	15	32	155	124	19
	15	20	41	229	124	375

^a Polymer: cellulose acetate E-398-3; room temperature casting, 30 sec air dry, 0°C coagulation; asymmetric saponification from top side by 0.1N NaOH at room temperature for 5 min.

^b Asymmetric saponification 0.1N NaOH 10 min.

Despite numerous investigations of the preparation of asymmetric membranes for desalination, and the development of many modified recipes and procedures, the real mechanism of forming such asymmetric membranes and the roles of the ingredients in the recipes and steps of membrane preparation are still not quite clear. This ambiguity of the mechanism of asymmetric membrane structure formation was reflected in unexpected results in attempts to make thinner membranes. Some factors may be differentiated in discussing the variables involved in preparation of the asymmetric membrane.

The first is the dependence on the casting thickness. For instance, the recipe and procedure which produce an ideal desalination membrane at a casting thickness of 10 mils do not produce a similar structure when cast at smaller casting thickness. In Table I, among other results, it can be seen that the thickness of the coagulated and partially saponified membrane is not simply proportional to the casting thickness. From these results, it is seen that the thicker the original casting thickness, the lower is the density of the resulting membrane. This may also be seen from the tendency of a lower casting thickness to produce a more translucent or even clear membrane. Thus, increase in casting thickness increases the degree of heterogeneity of the coagulated membrane.

A similar phenomenon may be observed from some of the data in Table II where, for a given solvent system, the concentration of polymer and the casting thickness are varied so that the approximate amount of polymer per unit area in the membrane is the same. The results show that the lower the concentration of polymer in the casting solution, the lower is the resulting membrane density. This is of course not independent of the effect mentioned above, but a look at the data of Table I indicates that it cannot be explained entirely by the effect of casting thickness, and so the second factor is the polymer concentration of the casting solution.

The third factor which obviously plays a role in determining membrane properties is the composition of the solvent; however, the effect of solvent composition overlaps with two other factors mentioned and cannot be singled out.

As mentioned earlier, the overall membrane permeability does not have a significant meaning as a material constant for asymmetric membranes, and evaluation must rely upon the values of Q and L rather than P and K . In doing this, values often must be compared for membranes that have different thicknesses. In such cases, the distinction and limitations of diffusive permeability and hydraulic permeability mentioned in an earlier section play an important role in a proper interpretation of the results.

Taking the model of porous membranes, the dialysance Q depends only on porosity ϵ and on the reciprocal membrane thickness l^{-1} , whereas the ultrafiltration rate L_1 depends on ϵ , l^{-1} , and on the pore size r^2 . It should also be remembered that the effect of l^{-1} becomes much less on L_1 than on Q if a membrane is asymmetric. Therefore, at least four independent factors, i.e., porosity, pore size, membrane thickness, and the asymmetry, must be considered to explain the results. Simple analysis of results will not distinguish the roles of these factors.

With homogeneous polymer membranes, it was found¹ that $L_1' \geq Q_1$, indicating that ϵ and r^2 considered in a simplified model are not independent variables, and that the increase in ϵ is always achieved by increase in r^2 . In this case, there should be a positive correlation between L_1 and Q_2 of sodium chloride (as long as a membrane does not reject NaCl). The results in Table I (with asymmetric membranes) show no clear correlation between L_1 and Q_2 , as seen in Figure 2. Here again, it is not possible to tell whether this is due to lack of unique relation between ϵ and r^2 in these heterogeneous membranes or to the asymmetry factor discussed above. Nevertheless, the results clearly point out that it is possible to control L_1 and Q more or less independently (which cannot be accomplished with homogeneous membranes) by manipulating factors involved in the preparation of coagulated cellulose acetate.

As expected from the basic consideration described earlier, despite of significant increase in the characteristic overall permeability P_2 over that of cellulose membranes, the actual increase in sodium chloride dialysance is marginal. The significance of coagulated cellulose acetate, therefore, is in its wide range of ultrafiltration rates. This aspect of asymmetric

membranes is anticipated to be found also with many other asymmetric membranes of various polymers other than cellulose acetate.

Notation and Terminology

J_1	flux of water per unit area of membrane, $\text{cm}^3/\text{cm}^2 \cdot \text{sec}$
J_2	flux of solute per unit area of membrane, $\text{mole}/\text{cm}^2 \cdot \text{sec}$
J_D	flux under diffusive condition
J_F	flux under hydraulic condition
P	diffusive permeability coefficients, cm^2/sec
Q	dialysance; diffusive flux of a solute per unit area of membrane, cm/sec
K_1	hydraulic permeability coefficient, $\text{cm}^2/\text{sec} \cdot \text{mm Hg}$
K_1'	modified hydraulic permeability coefficient, cm^2/sec
L_1	ultrafiltration rate of a membrane, $\text{cm}/\text{sec} \cdot \text{mm Hg}$
L_1'	modified ultrafiltration rate of a membrane, cm/sec
D_0	diffusion constant of a solute in pure water, cm^2/sec
ϵ	porosity, i.e., pore volume fraction of unit volume of a membrane, dimensionless
r	radius of capillary, cm
H	volume fraction of water in swollen polymer membranes, dimensionless
B	proportionality constant, dimensionless
b	tortuosity factor ($1 > b > 0$), dimensionless
l	thickness of membrane, cm
ΔC	concentration difference of a permeant in solutions on both sides of a membrane, moles/liter water
ΔX	effective capillary length, cm
Δp	pressure difference across a membrane, mm Hg
	subscript 1 denotes water
	subscript 2 denotes solutes

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