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# TRANSFER OF DEXTRAN THROUGH ULTRAFILTRATION MEMBRANES: A STUDY OF REJECTION DATA ANALYSED BY GEL PERMEATION CHROMATOGRAPHY

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## Summary

A method is proposed for obtaining a measure of the flux distribution through an ultrafiltration membrane. In a previous paper [9], the mechanisms of mass transfer of polydisperse polymer solutes through a membrane were studied using the molecular weight distributions of the feed and of the permeates corresponding to different operating conditions. As a result, partial rejection coefficients were defined, each one characteristic of a given molecular weight fraction. For the ultrafiltration of a dextran solution having a widely spread molecular weight distribution (mixture of various commercial fractions) through a polysulfone outer-skinned hollow fiber, we show that these partial rejection coefficients give information on the characteristics of the membrane. More precisely, for operating conditions chosen in order to minimize the phenomena that cause deformation of the macromolecules, it is possible to use the variations in the partial rejection coefficients extrapolated to zero applied pressure to obtain a measure of the flux distribution through the membrane, related to dextran molecular weight. To determine to what extent the method developed could give information about fouling, it has been applied to an inorganic membrane before and after ultrafiltration of a protein solution.

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## Introduction

Most of the membranes used in ultrafiltration, either organic or inorganic, have a complex porous structure, with a bundle of pores of various sizes ranging from a few nanometers to a few tens of nanometers, that determines mass transfer and fouling during use. This porous structure is often represented by such global characteristics as solvent and solute permeabilities because they are easily determined from experimental results. In order to analyse and to

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understand the transfer mechanisms, it has become necessary to obtain more precise information about the porous structure of the membranes.

Among the direct methods, the most commonly used is electron microscopy [1,2], in spite of the fact that it requires a sample preparation that can modify the observed structure and its lower detection limit is about 5 nm, a value that does not allow observation of the smallest pores of an ultrafiltration membrane. Among the indirect methods, the most commonly cited in the literature are those of bubble point, or fluid permeability [1,3], and those deduced from solute transport data [4,5]. However, to obtain data about the pores of the membrane from experimental results from one or other of these methods requires assumptions about the pore geometry (cylindrical pores, parallel to each other, etc.), the shape of the pore size distribution curve (generally assumed to be Gaussian), or the solute transport mechanisms.

Cooper and Van Derveer [6] were among the first to use gel permeation chromatography (GPC) for analysis of polydisperse dextran retentate and ultrafiltrate. They defined partial rejection coefficient for each molecular weight fraction and showed that its variations with molecular weight are well represented by a log-normal relationship for various ultrafiltration membranes. Michaels [7] extended the validity of the log-normal relationship to mammalian glomerular membranes. Despite the lack of any theoretical background, this empirical correlation is useful, since a complete sieving curve is defined by two parameters: a geometric mean molecular radius and a geometric standard deviation about this mean. However, any physical interpretation of the meaning of these two parameters would remain questionable. Schock and Miquel [8] have recently shown that the variations of the partial rejection coefficients versus dextran molecular weight can depend on applied pressure or crossflow velocity. In a previous work [9], we demonstrated that this dependence is due to the effects of concentration and shear stress at the pore entrance on the shape of flexible molecules, such as dextran. Fixed conditions of pressure and crossflow velocity applied to various membranes, as suggested by Schock and Miquel, could then lead to various concentration and flux levels that would affect the validity of any comparison between membranes, since it would also depend on module geometry and operating conditions. However, the method used by Schock and Miquel can be improved if the influence of operating parameters on the apparent size of the molecules and on mass transfer can be avoided, thereby obtained data depending only on the solute-membrane system, as proposed in the present paper.

The aim of this study is to show why it is important to minimize concentration polarization ( $\Delta P \rightarrow 0$ , low concentration and high Reynolds number), even when the macromolecules have no interaction with the membrane material, so that the curve of partial rejection coefficient versus dextran molecular weight can be correlated with intrinsic membrane properties. Using a polysulfone outer-skinned hollow fiber membrane as a typical example, it is demonstrated

that the data obtained from HPLC analysis about the transfer of a dextran solution having a wide molecular weight distribution can be used to provide a measure of the flux distribution of the membrane. The method is also used to compare the flux distribution of an inorganic membrane before and after fouling by a protein solution. As a result, it is shown that the indirect method proposed in this paper for obtaining a measure for the flux distribution of a membrane can be used with either organic or inorganic membranes, and that it is thus possible to derive information about the change in membrane characteristics due to fouling.

## Materials and methods

### 1. Solutes and analytical equipment

The solutes used in this work were commercial dextran fractions, whose characteristics are summarized in Table 1. Dextran was chosen because it is not adsorbed on the membrane and because it has a broad molecular weight distribution. The solutions were prepared by dissolving a given quantity of powder in distilled water containing 1 mg/l of  $\text{NaN}_3$  to prevent bacterial contamination. Permeate and feed samples were analyzed by GPC using a TSK G4000 column coupled with a Beckman 156 refractive index detector. The analyses were carried out at 20°C using distilled water containing 1 mg/l of  $\text{NaN}_3$  as eluent at a flow rate of 0.50 ml/min.

To interpret the results obtained by GPC, first a calibration curve that gives retention volume versus dextran molecular weight was established. For various commercial fractions, the retention volume (Table 1) corresponding to the maximum of the elution curve was noted; this was assumed to correspond to the average molecular weight, MW, given by the manufacturer. From these points, the calibration curve was drawn that was used to determine the retention volumes for other molecular weight. From a comparison between the elution curves of the feed and of the permeate, we calculated (as indicated in Fig. 1) the partial rejection coefficients defined by the relationship:

TABLE 1

Retention volumes and molecular weights of the commercial fractions used in this work

Product	Retention volume (ml)	$M_n \times 10^{-3}$ (daltons)	MW $\times 10^{-3}$ (daltons)	MW/ $M_n$
Ethylene glycol	12	-	-	-
Dextran T10	11	4900	9500	1.94
Dextran T40	9.4	29,500	39,500	1.34
Dextran T70	8.2	36,000	70,800	1.97
Dextran T500	6.0	165,000	468,000	2.84

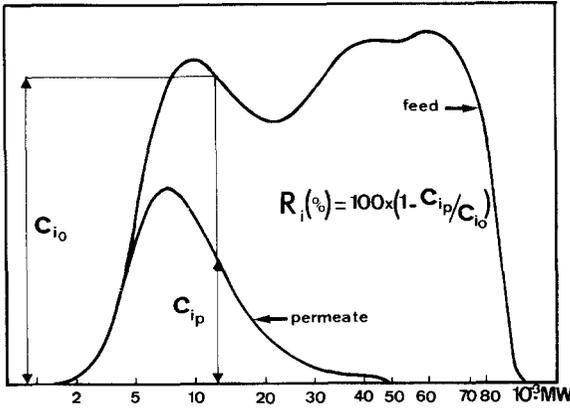


Fig. 1. Calculation of the partial rejection coefficients from elution curves of the feed and the permeate.

$$R_i = 1 - C_{i,p}/C_{i,o} \quad (1)$$

where each is related to a fraction of given molecular weight  $MW_i$ .

In addition, the overall rejection coefficient, defined by

$$R = 1 - C_p/C_o \quad (2)$$

was determined from comparison between the areas of the elution curves of the feed and the permeate. The dextran solution to be used for the ultrafiltration experiments should have a broad molecular weight distribution, corresponding to partial rejection coefficients ranging from 0 to 100%, and a concentration as uniform as possible over the whole range of molecular weight. To satisfy these two conditions, different mixtures were examined, containing various quantities of commercial dextran fractions. The mixture T10: 24%wt., T40: 35%wt., T70: 41%wt., whose molecular weight distribution is reported in Fig. 1, was found to be the most suitable.

## 2. Ultrafiltration apparatus and procedure

All the ultrafiltration experiments were carried out at 20°C using the equipment shown in Fig. 2. The feed concentration was kept constant by recirculating the permeate. A valve located at the end of the loop made it possible to adjust feed flow velocity and pressure independently from one another. From inlet and outlet gauge pressures [7], an average transmembrane pressure was calculated, as follows:

$$\Delta P = (P_{\text{inlet}} + P_{\text{outlet}})/2 \quad (3)$$

The flux and the overall rejection coefficient were always measured and steady-state conditions.

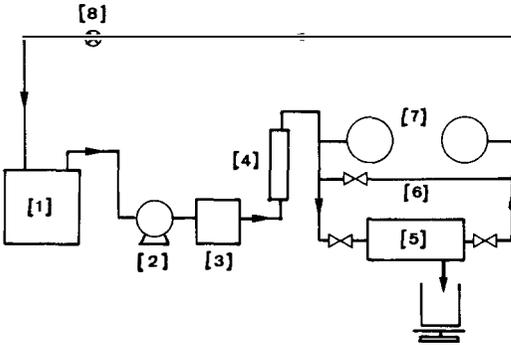


Fig. 2. Ultrafiltration apparatus: (1) feed tank; (2) recirculating pump; (3) thermostat; (4) flow meter; (5) ultrafiltration module; (6) by-pass; (7) pressure gauges; (8) pressure control valve.

Two sets of experiments were performed, with two different types of membrane:

- A polysulfone outer-skinned hollow fiber membrane, manufactured according to French patent IRCHA-CNRS No. 8409225, of outer diameter  $d_e = 0.37$  mm. The module was a bundle of 40 fibers sealed in a Plexiglass tubular envelope 0.25 m long of internal diameter  $d_i = 16$  mm. The active length,  $l$ , of the fibers, which were plugged at one end, was 0.22 m. The total exchange area  $A$  was  $99 \times 10^{-4}$  m<sup>2</sup>.
- A Carbosep membrane, type M4, manufactured by S.F.E.C. (France). It is a tube made of porous carbon, of inner diameter 6 mm, with an inner dense skin of zirconium oxide. A 0.5 m length of tube was sealed in a Plexiglass tubular envelope and the total exchange area was  $94 \times 10^{-4}$  m<sup>2</sup>.

Before beginning the experimental study, the following procedure was performed: after washing the membrane to eliminate traces of solvent or impurities left over from the manufacturing process, an ultrafiltration operation was carried out with distilled water under a pressure of  $3 \times 10^5$  Pa until the permeate flux became constant; then a dextran mixture solution (4 g/l;  $3 \times 10^5$  Pa) was ultrafiltered for 2 h.

The hydraulic permeabilities,  $L_p$ , of the membranes were measured before and after each run, and were found to be entirely constant and equal to  $10.8 \times 10^{-11}$  m·sec<sup>-1</sup>·Pa<sup>-1</sup> for the polysulfone membrane, and  $8.3 \times 10^{-11}$  m·sec<sup>-1</sup>·Pa<sup>-1</sup> for the Carbosep membrane. These constant values mean that no fouling occurred during ultrafiltration runs.

A third set of experiments was also performed with the Carbosep membrane after it had been used to ultrafilter a bovine serum albumin (BSA) solution. This operation was carried out at a feed concentration of 1 kg/m<sup>3</sup> under a pressure of  $3 \times 10^5$  Pa for 1 h. After this run, the hydraulic permeability of the membrane was  $5.4 \times 10^{-11}$  m·sec<sup>-1</sup>·Pa<sup>-1</sup>; this value did not change during ultrafiltration experiments subsequently carried out with the dextran mixture.

## Results and discussion

### 1. Polysulfone outer-skinned hollow fiber membrane

#### 1.1 Permeate flux and overall rejection coefficient

In Fig. 3 the experimental results obtained with the dextran mixture are presented in terms of permeate flux,  $J$ , and the overall rejection coefficient,  $R$ , as function of the applied pressure  $\Delta P$ . It can be observed that these curves have the traditional shape already reported by other authors [10,11] as well as in a previous work [9] for solution of a single solute.

#### 1.2 Elution curves: partial rejection coefficients

Figures 4a–c give the variation in the elution curves of the permeate with the applied pressure for Reynolds numbers of 500, 2000 and 4000, respectively.

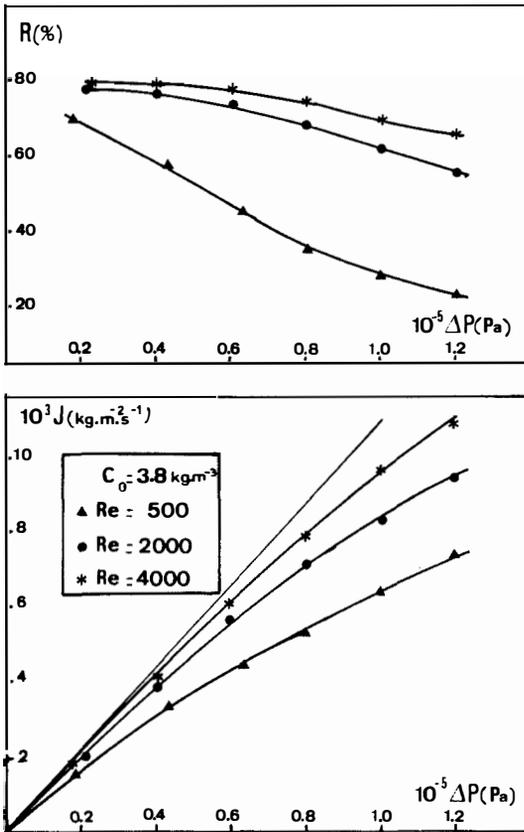


Fig. 3. Polysulfone membrane: variations in the permeate flux and the overall rejection coefficient versus the applied pressure for various Reynolds numbers.

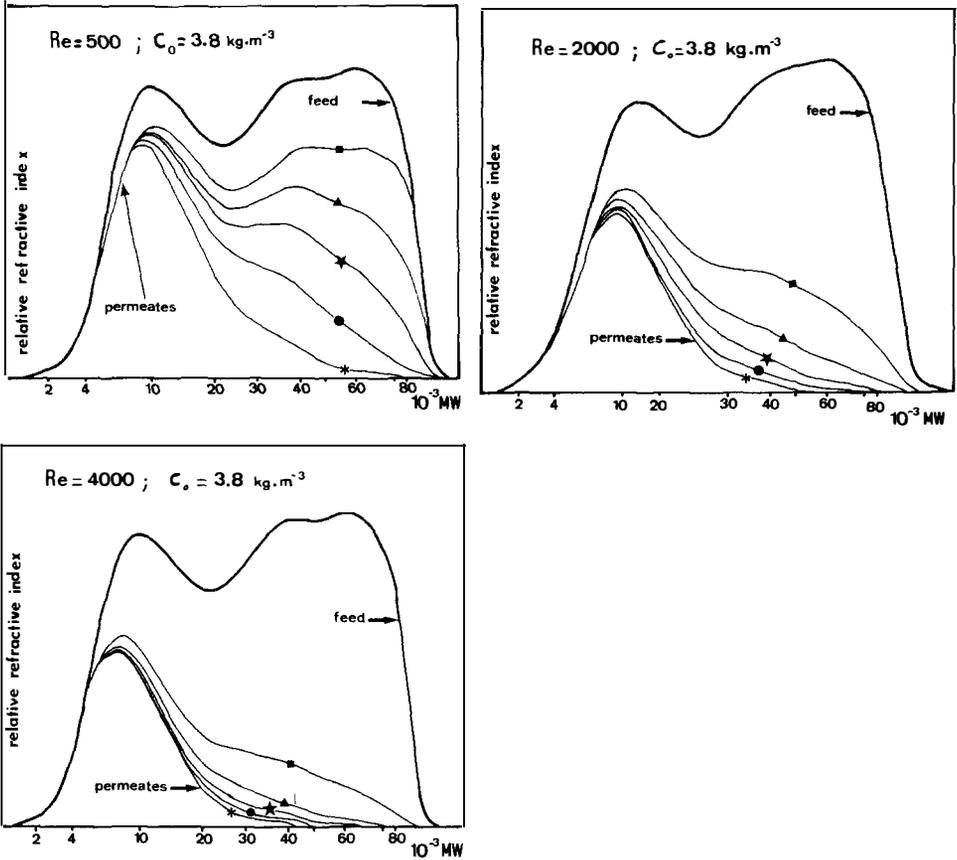


Fig. 4. Polysulfone membrane: variation in the elution curve of the permeate versus the applied pressure for various Reynolds numbers: (a)  $Re=500$ ; (b)  $Re=2000$ ; (c)  $Re=4000$ . (\* )  $\Delta P=2 \times 10^4$  Pa; (●)  $\Delta P=4 \times 10^4$  Pa; (★)  $\Delta P=6 \times 10^4$  Pa; (▲)  $\Delta P=8 \times 10^4$  Pa; (■)  $\Delta P=1.2 \times 10^5$  Pa.

They show that not only are the permeate flux and the overall rejection coefficient strongly dependent on the operating conditions, but so too is the molecular weight distribution in the permeate. When the applied pressure is increased the molecular weight distribution of the permeate changes in the higher molecular weight region, and this change is more important for the lowest value of the Reynolds number. The value of about 10,000 daltons, which corresponds to the maximum of the elution curves of the permeate at low applied pressures, is the same as that obtained in a previous work [9] with the same membrane and a single dextran T70 solution.

The observations made about the way in which the molecular weight distribution of the permeate varies with the operating conditions put into question the real meaning of the overall rejection coefficient when it concerns polydisperse solutes. A comparison, in terms of concentration only, between the two

solutions that have molecular weight distributions greatly different one from the other would have little significance. For this reason, it is more appropriate to express experimental results using partial rejection coefficients,  $R_i$ , each one related to a given molecular weight fraction, and providing more quantitative information. These values, calculated from the elution curves shown in Figs. 4a-c are plotted in Figs. 5, 6 and 7 versus the applied pressure. For a given Reynolds number, the decrease in partial rejection coefficient with the applied pressure becomes more important when the molecular weight increases. For the lowest molecular weights ( $< 10,000$  daltons), the rejection coefficients are almost independent of the pressure. For a given molecular weight fraction, the slope of the  $R_i$  versus  $\Delta P$  curve increases with decreasing Reynolds number because of higher polarization. These results, by providing quantitative description complement the discussion about the influence of the operating conditions (Figs. 4a-c).

Conversely, it is interesting to determine to what extent the partial rejection

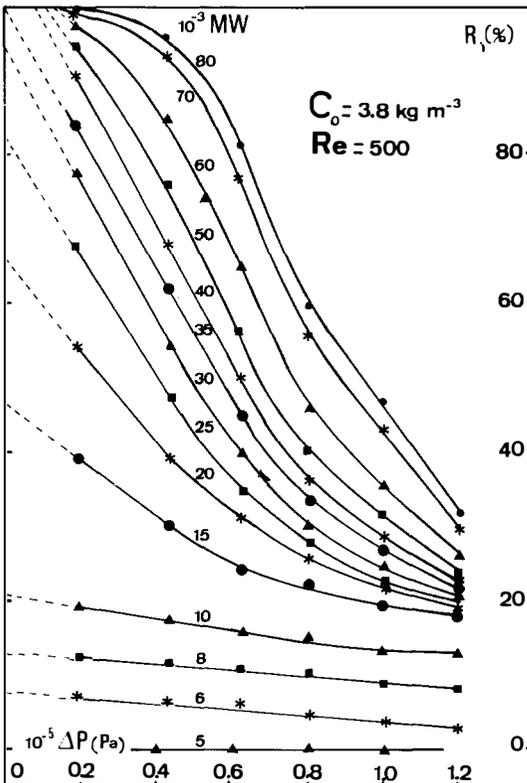


Fig. 5. Polysulfone membrane: variations in the partial rejection coefficients versus the applied pressure.  $C_0 = 3.8 \text{ kg/m}^3$ ;  $Re = 500$ .

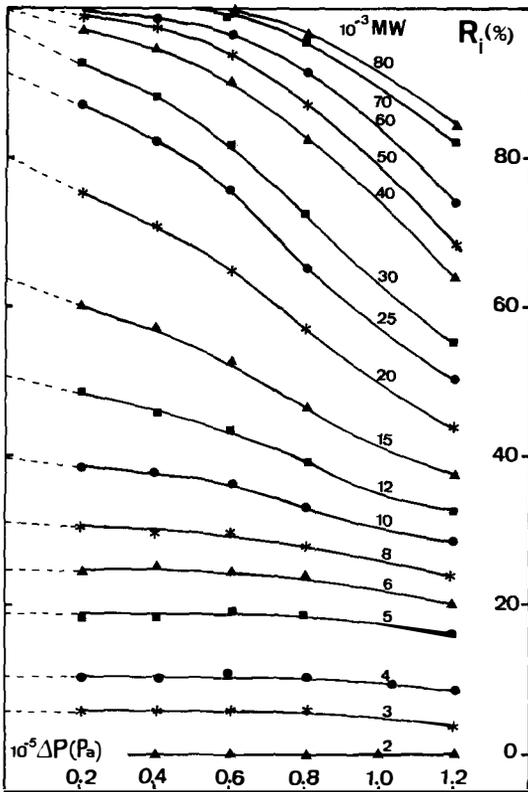


Fig. 6. Polysulfone membrane: variations in the partial rejection coefficients versus the applied pressure:  $C_o = 3.8 \text{ kg/m}^3$ ;  $Re = 2000$ .

coefficients could be used to provide some information about the characteristics of the membrane. In Fig. 8, partial rejection coefficients are plotted versus molecular weight, to emphasize the importance of operating conditions. All the curves have the same shape as the traditional “cut-off” curves. As already discussed by Schock and Miquel [8], the operating conditions have a great influence on the values of the partial rejection coefficients, i.e., on the position of these curves.

According to our previous work [9], this influence of the operating parameters, such as transmembrane pressure or crossflow velocity, is explained by the deformation of dextran molecules under chemical forces (molecules are more compact in concentrated than in dilute solutions) or shear forces (molecules appearing as coils at rest could be elongated under shear stress and thus enter pores more easily). Because two different membranes, even tested at the same conditions, would provide different levels of polarization, the comparison on the basis of the dextran sieving curves obtained for given operating condi-

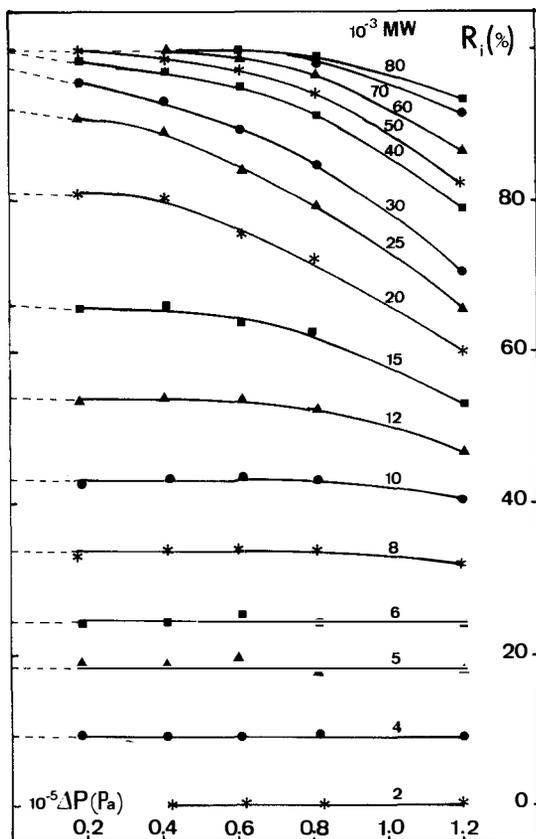


Fig. 7. Polysulfone membrane: variations in the partial rejection coefficients versus the applied pressure.  $C_o = 3.8 \text{ kg/m}^3$ ;  $Re = 4000$ .

tions, as suggested by Schock and Miquel [8], would lead to systematic error. To avoid this drawback, the data used to plot the sieving curves should be collected under conditions where the effects of concentration polarization are eliminated. This could be achieved at very low pressures and high feed flow velocities.

Thus, the partial rejection coefficients used later on are those obtained by extrapolating their values to zero applied pressure. These values, determined from Figs. 5, 6 and 7, are reported in Table 2. For Reynolds numbers equal to 2000 and 4000 these values are almost the same for the whole range of molecular weights investigated. However, for a Reynolds number of 500, the corresponding values are always smaller. The reason is probably that, in this case, the concentration polarization is too high for the shape of the  $R_i$  vs.  $\Delta P$  curves to allow accurate extrapolation. It would have been desirable, but impossible with our device, to work at pressures below  $2 \times 10^4 \text{ Pa}$ , to reach a range where

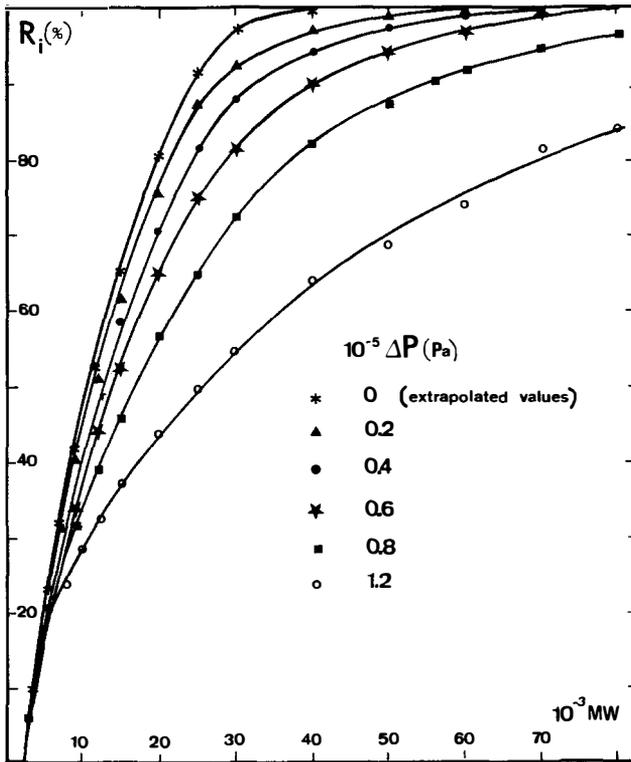


Fig. 8. Polysulfone membrane: partial rejection coefficient versus molecular weight for different applied pressures.  $C_0 = 3.8 \text{ kg/m}^3$ ;  $Re = 2000$ .

polarization was low enough to allow accuracy. The partial rejection coefficients, even when extrapolated to zero applied pressure, can thus depend on operating conditions.

The relative importance of polarization and filtration, both of which determine solute transfer in ultrafiltration, depends on the operating conditions. Consequently, to relate solute transport data to membrane properties, it is necessary to choose operating conditions for which the solute transfer is actually limited by the filtration step. This means that they must be such as to allow the permeate flux not to differ significantly from that of the pure solvent ( $Re$  equal to 2000 or 4000 in Fig. 3). Thus, it may be concluded from the results obtained in these two cases (Table 2) that the membrane retains completely the dextran fractions of molecular weight higher than 40,000 daltons, since the value of the extrapolated partial rejection coefficient that corresponds to 40,000 daltons equals 100%. This value represents, in terms of molecular weight of dextran, the upper of the pore size of the membrane. In the range of low molecular weights, smaller than about 3000 daltons, the concentration in the feed

TABLE 2

Polysulfone membrane: extrapolated values of the partial rejection coefficients

MW $\times 10^{-3}$ (daltons)	$R_i$ (%)		
	$Re=500$	$Re=2000$	$Re=4000$
80	100	100	100
70	100	100	100
65	100	100	100
60	100	100	100
50	100	100	100
40	100	100	100
35	100	100	100
30	95	98	98
25	82	92	92
20	66	80	81
15	47	64	66
12	35	51	54
10	21	40	43
6	8	24	24
4	0	10	9
2	0	0	0

solution is not high enough to give good precision for values derived from comparison between the elution curves of the feed and the permeate. As a result, it is difficult to determine precisely the value of the molecular weight below which the curves are superimposed, which should represent the lower limit of the pore size distribution of the membrane. For molecular weights that correspond to partial rejection coefficients ranging from 0 to 100%, assuming that the dextran molecules are uniformly distributed at the membrane-solution interface, we can consider the membrane with a pore size distribution such that a fraction of the pores does not retain the molecule while the remainder retain it totally, as suggested by Le and Howell [12]. This arbitrary partition of the membranes into two regions is defined according to the size of the molecules, and the solute mass balance can be written according to the following relationship:

$$J_{uf} C_{i,p} = J_{uf,1} C_i \quad (4)$$

where  $C_i$  is the concentration and  $J_{uf,1}$  the flux of the solution flowing through the non-rejecting pores of the membrane. For conditions where the concentration polarization is negligible (high Reynolds number and low applied pressure), the wall concentration of each molecular weight fraction can be assumed to be uniform and the same as in the bulk, i.e.  $C_i = C_{i,0}$  and the mass transfer through the membrane is determined according to the filtration step. Then,

the ratio between the solution fluxes  $J_{uf,i}$  and the pure solvent fluxes  $J_{s,i}$  flowing through the two parts of the membrane are related to the viscosity ratio  $\mu(C_{i,o})/\mu_s$ . Furthermore, for sufficiently low bulk concentrations, the viscosity of the permeate is not very different from that of the solvent  $\mu_s$  (for example, when  $C_o$  is  $3 \text{ kg/m}^3$ , the ratio  $\mu(C_o)/\mu_s$  for a dextran T70 solution is 1.08). Then eqn. (4) can be rewritten to obtain for each molecular weight a relationship that gives the flux partition of the membrane versus the rejection coefficient:

$$\begin{aligned} J_{s,1} &= J_s (1 - R_i) && \text{for } MW_i \text{ non-rejecting pores} \\ J_{s,2} &= J_s R_i && \text{for } MW_i \text{ rejecting pores} \end{aligned} \quad (5)$$

It means that the  $R_i$  versus  $MW_i$  curve can be related to a cumulated percentage of flux ( $J_{s,2}/J$ ) versus  $MW_i$  curve. For example, the value 92% in Table 2

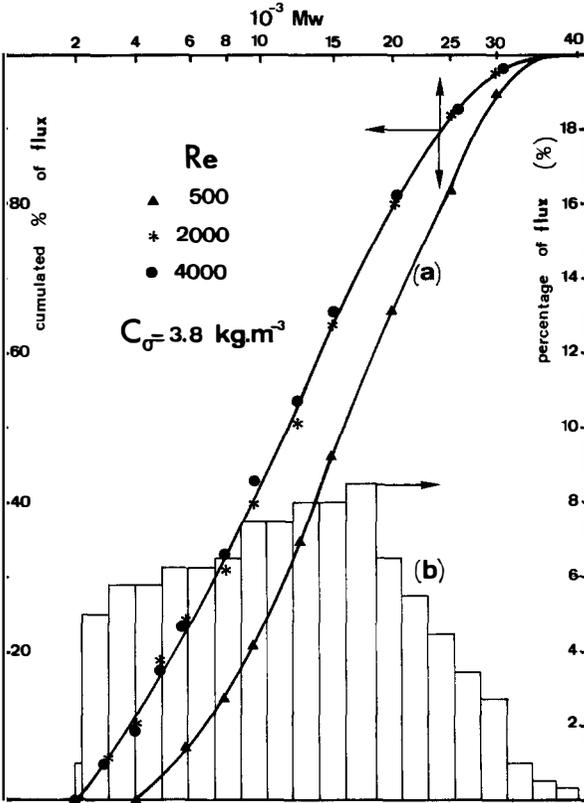


Fig. 9. Polysulfone membrane: cumulated percentage of flux (a) and flux distribution diagram (b) as a function of dextran molecular weight.

corresponding to 25,000 daltons means that 8% of the flux passing through the largest pores carries molecules whose molecular weight is less than or equal to 25,000 daltons.

It is important to note that this translation of  $R_i$  into a cumulated percentage of flux of the membrane applied only to conditions where the viscosity of the solution is almost the same as that of the solvent and the concentration at the membrane–solution interface equals that in the bulk (i.e.  $\Delta P \rightarrow 0$ , low concentrations and high Reynolds number).

According to relationship (5), curve (a) in Fig. 9 represents the flux that carries through the membrane molecules smaller than a given molecular weight. The derivative of the function  $J_{s,2}/J$  versus MW should thus provide the flux carrying molecules of a given molecular weight. As no analytical function was available to describe  $J_{s,2}/J$  versus MW data, the derivative was calculated point by point, i.e., the experimental data of curve (a) being considered as the integrals of the points represented here in the histogram (b). The height of each bar represents the flux carrying molecules whose molecular weights fall within the bar width.

## 2. Inorganic membrane

The approach described above was applied to an inorganic membrane before and after it had been used to ultrafilter a BSA solution, in order to promote fouling and to check the sensitivity of the method to the subsequent changes in the porous structure.

### 2.1 Permeate flux: overall rejection coefficient

The ultrafiltration results with the dextran mixture solution corresponding to the two states of the membrane are reported in Figs. 10(a) and (b), showing the variations in the permeate flux  $J$  and the overall rejection coefficient  $R$  with the applied pressure. From the results obtained with the polysulfone membrane, the Reynolds number ( $Re = 5000$ ) was chosen to minimize the concentration polarization, i.e., to have a flux that is not too different from that with pure solvent. Figure 10 shows that fouling with a BSA solution leads to a decrease of around 35% in the hydraulic permeability of the membrane and to a significant increase in the overall rejection coefficient.

### 2.2 Elution curves: partial rejection coefficients

In Figs. 11 and 12 the elution curves are shown of the feed and of the permeates obtained at different applied pressures, before and after fouling, respectively. The molecular weight distribution in the permeate is still strongly dependent on the pressure. The increase in the overall rejection coefficient due to fouling correlates with significant differences in the molecular weight distribution of the permeate. For given operating conditions, the fouled membrane retains fractions that can pass through the clean one. This difference can be interpreted as a measure of the variation in pore size distribution due to fouling when the membrane is used to ultrafilter a protein solution. The

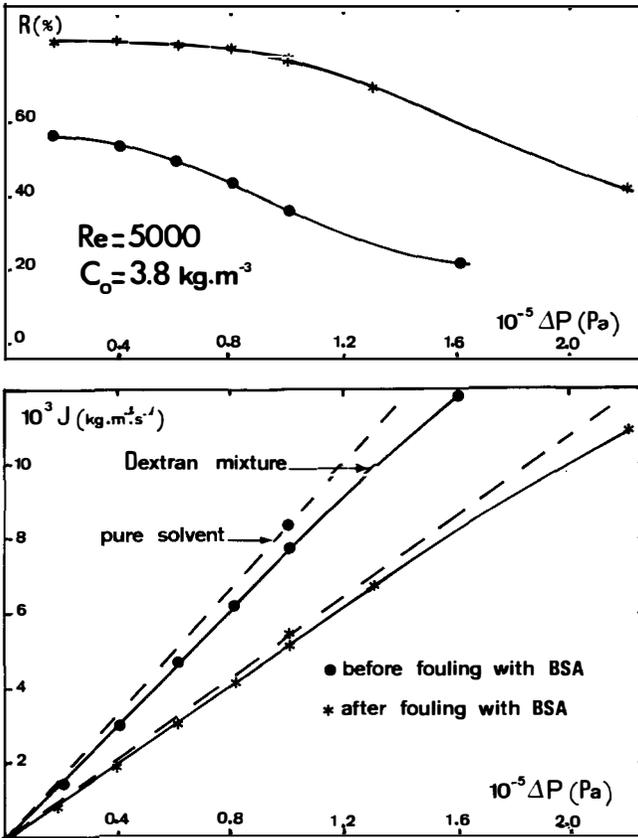


Fig. 10. Inorganic membrane: variations in the permeate flux and the overall rejection coefficient versus the applied pressure.

variations in the partial rejection coefficients with the applied pressure are determined from the elution curves. The extrapolated data ( $\Delta P \rightarrow 0$ ) are reported in Table 3. It can be observed that the extrapolated values from the fouled membrane are higher than those from the clean one over the whole range of molecular weights. Before fouling, the smallest component that can be completely retained by the membrane is about 80,000 daltons, while afterwards it is about 65,000.

Using the interpretation of these extrapolated values as cumulated percentage of fluxes, we have plotted the curves giving the cumulated percentage of fluxes of the membrane versus the molecular weight of dextran (Figs. 13 and 14). The same figures show the histograms that give the flux distribution corresponding to the two states of the membrane. These histograms show that the flux distribution of the clean membrane has an asymmetrical shape, with higher values in the large molecular weight region. After fouling, the flux dis-

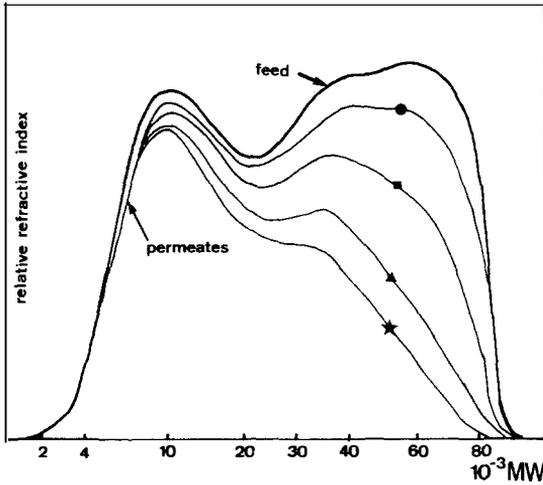


Fig. 11. Inorganic membrane before fouling with BSA: variation in the shape of the elution curve (permeate) versus the applied pressure: (★)  $\Delta P=2 \times 10^4$  Pa; (▲)  $\Delta P=6 \times 10^4$  Pa; (■)  $\Delta P=1.0 \times 10^5$  Pa; (●)  $\Delta P=1.6 \times 10^5$  Pa.

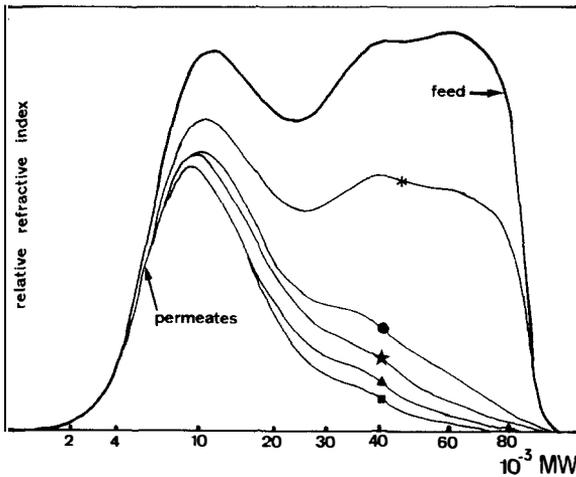


Fig. 12. Inorganic membrane after fouling with BSA: variation in the shape of the elution curve (permeate) versus the applied pressure: (■)  $\Delta P=4 \times 10^4$  Pa; (▲)  $\Delta P=8 \times 10^4$  Pa; (★)  $\Delta P=1.0 \times 10^5$  Pa; (●)  $\Delta P=1.3 \times 10^5$  Pa; (\*)  $\Delta P=2.2 \times 10^5$  Pa.

tribution again has an asymmetrical shape, but with higher values in the low molecular weight region.

When a membrane is used to ultrafilter a foulant solution, some of its pores that have dimensions large enough to allow the passage of the molecules might be plugged or reduced in size by either physico-chemical or mechanical effects.

TABLE 3

Carbosep membrane: extrapolated values of the partial rejection coefficients ( $Re=5000$ )

$MW \times 10^{-3}$ (daltons)	$R_i$ (%)	
	before fouling	after fouling
80	100	100
70	98	100
60	86	98
50	73	96
40	59	93
30	43	84
25	34	76
20	27	61
15	19	51
10	10	29
8	7	18
6	2	7
4	0	0

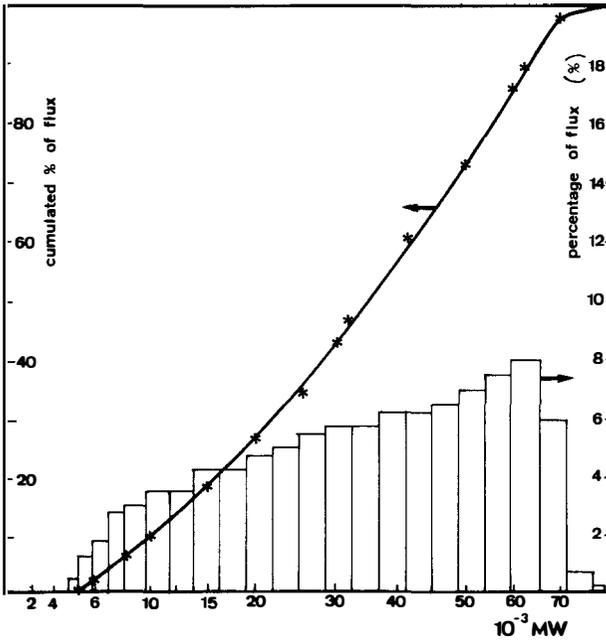


Fig. 13. Inorganic membrane before fouling with BSA: cumulative percentage of flux and flux distribution diagram as a function of dextran molecular weight.

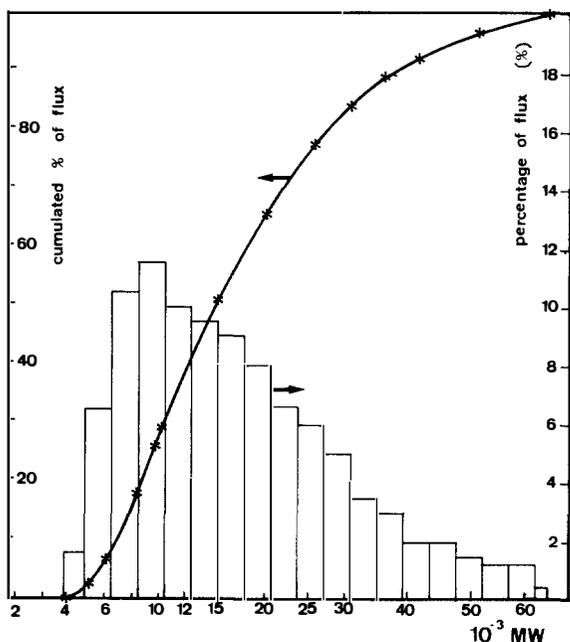


Fig. 14. Inorganic membrane after fouling with BSA: cumulative percentage of flux and flux distribution diagram as a function of dextran molecular weight.

The dimensions of the largest pores of the membrane are reduced, so leading to a decrease in the percentage of flux in the large size region, and a corresponding relative increase in the small size region. Although the permeability reduction was not so pronounced in the present case (35%), the method proposed here is sensitive to the modifications induced in the skin layer structure by the fouling mechanisms. The qualitative information that can be obtained from this approach could be of great interest in the study of membrane processes.

## Conclusion

The transfer of macromolecular solutes through ultrafiltration membranes is determined by the influence of filtration and polarization, both of which depend on operating conditions. For operating conditions chosen such that the concentration polarization is negligible, it is possible to relate the solute transport data to membrane properties. Using polydisperse solutions featuring to interaction with the membrane material, the comparison between the molecular weight distributions of the feed and of the permeate obtained in these conditions give a flux distribution that is a real picture of the distribution in the properties of the skin layer.

This method is not specific for a given geometry or material, since it has

been applied to polysulfone hollow fibers as well as to inorganic tubes, but it is essential that the solutes have no physico-chemical interaction with the membrane. The method could be useful for on-line control, or for comparing characteristics of different lots obtained under various conditions of manufacture. In addition, the method appears to be able to provide information about changes in porous media due to fouling by adsorption, particle deposition or pore blockage.

### List of symbols

$C$	concentration, $\text{kg/m}^3$
$d_h$	hydraulic diameter of the module, m
$J$	ultrafiltration flux, $\text{kg/m}^2\text{-sec}$
$L_p$	hydraulic permeability, $\text{m/sec-Pa}$
MW	molecular weight, g/mol
$\Delta P$	transmembrane pressure, Pa
$R$	rejection coefficient
$R_h$	hydraulic resistance, $\text{m}^{-1}$
$u$	feed flow velocity, m/sec

### Greek letters

$\mu$	viscosity, Pa-sec
$\rho$	density $\text{kg/m}^3$
$\eta$	intrinsic viscosity, ml/g

### Subscripts

1	non-rejecting pores of the membrane
2	rejecting pores of the membrane
$i$	fraction of given molecular weight
o	bulk
p	permeate
s	solvent
uf	dextran solution

### Reynolds number definition

$$Re = d_h u \rho / \mu$$

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