

Water vapour transmission properties of free polymer films*

GILBERT S. BANKER, ASHOK Y. GORE AND JAMES SWARBRICK

The water vapour transmission properties of selected hydrophilic, lipophilic, and mixed hydrophilic-lipophilic polymer systems, cast as free films, have been examined as a function of time, film thickness, plasticiser concentration, and film formulation. An inverse linear relationship was established between the logarithm of the water vapour transmission rate (R_{wvt}) and the logarithm of film thickness in the presence of the various plasticiser concentrations for the three systems studied. The lipophilic *n*-butyl methacrylate films were found to be less permeable to moisture than either the hydrophilic hydroxypropyl cellulose or mixed methyl hydroxypropyl cellulose-ethyl cellulose films. The butyl methacrylate films closely follow Fickian diffusion, whereas the permeability constants of the other two films increased linearly with film thickness over the range of thicknesses studied. These phenomena are discussed with respect to the relative attractions these films have for water vapour.

ONE way of combatting drug instability has been to coat pharmaceutical products to prevent access of moisture or air or both. The shortcomings of the conventional methods of coating have led to the development of newer techniques, prominent among which is film coating. The many advantages of this process have been reviewed by Gross & Endicott (1960) who also discussed the desirable properties of an ideal polymer film suitable for pharmaceutical application. One such property of major importance is the permeability of these films to moisture.

An inverse linear relationship between the rate of water vapour transmission and film thickness has been shown for ethylcellulose and methylcellulose free films (Kanig & Goodman, 1962). In agreement with Higuchi & Aguiar (1959), it was found that the more polar the film, the greater was the rate at which water vapour was transmitted. Similar findings have been made by Munden, DeKay & Banker (1964). Patel, Patel & Lemberger (1964) observed that the permeability constant of cellulose ester films decreased with increasing chain length of the acid moiety used and that the plasticiser could enhance or retard moisture permeation, depending upon its concentration. The optimum plasticiser concentration at which a minimum water vapour transmission rate is obtained was found to be similar for all the plasticisers examined by Lachman & Drubulis (1964), working with cellulose acetate phthalate films. The rate of water vapour transmission was directly proportional to the relative humidity for both low and high plasticiser concentrations. A significant relationship between the number of carbon atoms in the alcohol chain of esterified polymers cast as films and the water vapour transmission properties of the films was established by Lappas & McKeehan (1965). But no detailed investigations of the water vapour transmission across polymer films deposited on single dose preparations

From The Industrial Pharmacy Department, School of Pharmacy and Pharmacal Sciences, Purdue University, Lafayette, Indiana 47907, U.S.A.

* Based on a dissertation submitted by Ashok Y. Gore to the Graduate School, Purdue University, in partial fulfilment of Master of Science degree requirements.

have been reported. Also, the results of water vapour transmission rates across free films may not necessarily reflect the water vapour transmission properties across films applied to a solid dosage form.

We present the results of work undertaken to elucidate the effect of time, film thickness, plasticiser concentration and film formulation on the water vapour transmission properties of selected hydrophilic, lipophilic and mixed hydrophilic-lipophilic polymers cast as free films.

Experimental

SELECTION AND PREPARATION OF FREE FILMS

A range of polymers in combination with various compatible plasticisers were screened for their film forming properties using FDA food-additive approved solvents. The films were evaluated on the basis of clarity, uniformity, flexibility, plasticiser compatibility and absence of stickiness. From these data, three polymer-plasticiser systems, representative of a hydrophilic, a lipophilic and a mixed hydrophilic-lipophilic system, were selected (Table 1).

Unplasticised and plasticised films of various thicknesses, with different plasticiser concentrations, were prepared by pouring solutions of the selected polymer-plasticiser-solvent combinations on to a pool of mercury contained in a petri dish, or on to a glass plate. In the mercury technique, the film thickness was controlled by the area of the petri dish and the volume of solution used. In the glass plate technique plastic rings limited the spread of solution and thereby controlled the film thickness. The solvents were allowed to evaporate overnight at ambient temperature after which the films were removed. The film samples were stored in air-tight containers in the presence of anhydrous calcium sulphate at ambient temperature.

Coherent films of the methyl hydroxypropyl cellulose-ethyl cellulose mixture could not be prepared in the absence of a plasticiser (propylene glycol).

DETERMINATION OF FILM THICKNESS

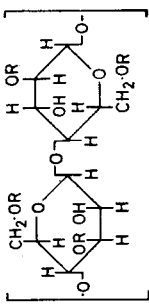
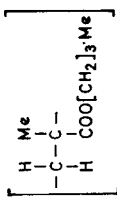
The film thickness was initially determined by five or six different measurements over the film samples using a micrometer screw gauge. The results showed large variations, due apparently to the compressibility of the film. The mean film thickness was therefore calculated from a knowledge of the density, weight and area of each film. The density was determined by weighing the film sample first in air and then in a non-solvent liquid. For hydroxypropyl cellulose and the mixed polymer films, n-hexane was used and for butyl methacrylate films water was used. No visible swelling of the films in these non-solvents was observed.

APPARATUS

Transmission cell. The transmission cell, similar in design to that used by Patel & others (1964), had a capacity of approximately 23 ml and contained 5 ml of a saturated sodium tartrate solution in contact with

WATER VAPOUR TRANSMISSION IN POLYMER FILMS

TABLE 1. DESCRIPTION AND PREPARATION OF FILM FORMULATIONS

Type of polymer and chemical name	Monomer unit composition	Plasticiser concentration used (% w/w of polymer)	Composition of solvent system (parts by volume)	Polymer concentration in film coat solution (% w/v)	Method of preparation of film samples
Hydrophilic Hydroxypropyl ether of cellulose ¹	Anhydroglucose unit  where R = -CH ₂ CH(OH)Me at a concentration not exceeding 4-6 groups per anhydroglucose unit	Propylene glycol 0, 10, and 20%	Methylene chloride 50 Methanol .. 50	10	Glass substrate technique
Hydrophilic: lipophilic Mixture of: Methylhydroxypropyl cellulose ²⁻³ —3 parts Ethyl cellulose ³ —1 part	Anhydroglucose unit as above, with: R = Me (28-30%) R = CH ₂ CH(OH)Me (7-12%) R = -CH ₂ Me (48-49.5%)	Propylene glycol 25 and 50%	Methylene chloride 40 Methanol .. 30 Isopropanol .. 30	3	Glass substrate technique
Lipophilic n-Butyl methacrylate ⁴		Diethyl phthalate 0, 2.5, and 5%	Methylene chloride 50 Ethyl acetate .. 50	10	Mercury substrate technique

¹ Klucel-L, Hercules Powder Company, Wilmington, Delaware, U.S.A.
² Methocel 60HG, 50 cps, Dow Chemical Company, Midland, Michigan, U.S.A.
³ Ethocel, Type N, Dow Chemical Company, Midland, Michigan, U.S.A.
⁴ Lucite 2044, E.I. Du Pont, De Nemours and Co., Inc., Wilmington, Delaware, U.S.A.

excess solid phase. This system had a vapour pressure of 29.0 mm Hg at 30° (Lowry & Morgan, 1924) which was maintained throughout the experiment. The area of the film available for permeation was 1.77 cm².

Temperature and humidity controlled chamber. This was an air-tight glove box. The temperature inside was controlled by circulating water from an external water bath to a radiator inside the chamber. A small fan behind the radiator circulated the air and maintained the temperature at 30 ± 1°. The humidity inside the chamber was kept at 0% by the presence of sufficient anhydrous calcium sulphate. This was checked by a relative humidity indicator inside the chamber.

DETERMINATION OF WATER VAPOUR TRANSMISSION

The assembled transmission cell, containing the film sample and the sodium tartrate solution, was placed inside the chamber and immediately weighed on an analytical balance in the chamber. It was also weighed at known time intervals over 72 hr. The amount of moisture transmitted through the film at any one time was given by the loss in weight of the cell at that time when compared to the weight at zero time. The balance was placed to allow the sample to be weighed without disturbing the temperature and humidity conditions. Each film sample was weighed just before, and immediately after, the transmission study to determine the amount of moisture held by the film as a result of sorption. Cells containing discs of aluminium, 0.015 cm thick, were used as controls; the weight loss after 72 hr was less than 1% of that with a polymer film present. All weight losses with polymer films were therefore attributed to the permeation of moisture.

Results and discussion

A number of equations, based on Fick's law of diffusion, have been used to obtain the rate of permeation through organic film coatings (American Society for Testing Materials, 1961; Utsumi, Ida, Takahashi & Sugimoto, 1961; Rains, 1962; Patel & others, 1964). Higuchi & Aguiar (1959) combined Fick's law with Henry's law of solubility of gases, since water permeability was held to involve diffusion of the vapour through the film and sorption of the vapour by the film. If, as was so in the present work, the amount of moisture sorbed is low in relation to the amount transmitted then it may be neglected (Patel & others, 1964). Even if this were not so, sorption of moisture by the film must occur before transmission begins and, under equilibrium conditions, the amount of moisture passing into the proximal surface of the film will equal that passing out of the distal surface.

The following relationship, based on Fick's law but modified to exclude film thickness, was used by us to calculate the water vapour transmission rates of the polymer films under investigation.

$$R_{wvt} = \frac{W}{A \cdot \Delta P} \quad \dots \quad \dots \quad \dots \quad \dots \quad (1)$$

WATER VAPOUR TRANSMISSION IN POLYMER FILMS

where R_{wvt} is the rate of water vapour transmission, W the amount of moisture transmitted through the film, in g/hr, A the area of the film exposed, in cm^2 , and ΔP the vapour pressure difference across the film, in mm Hg. The water vapour transmission rate, R_{wvt} , is defined as the amount of moisture transmitted per unit time through a film of unit area subjected to a vapour pressure difference of unity. R_{wvt} is expressed as $\text{g/hr/cm}^2/\text{mm Hg}$.

The weight in g of moisture transmitted through all the films studied was found to be directly proportional to time, over the period of 72 hr, when the temperature, vapour pressure, and area of the film exposed were held constant.

Curvi-linear relationships were apparent between R_{wvt} and film thickness for the various systems examined. However, log-log plots of R_{wvt} against film thickness were linear, as shown in Fig. 1. These relationships may be expressed by the following equation:

$$\log R_{wvt} = \log C_1 + m_1 \log t \quad \dots \quad (2)$$

which reduces to:

$$R_{wvt} = C_1 \cdot t^{m_1} \quad \dots \quad (3)$$

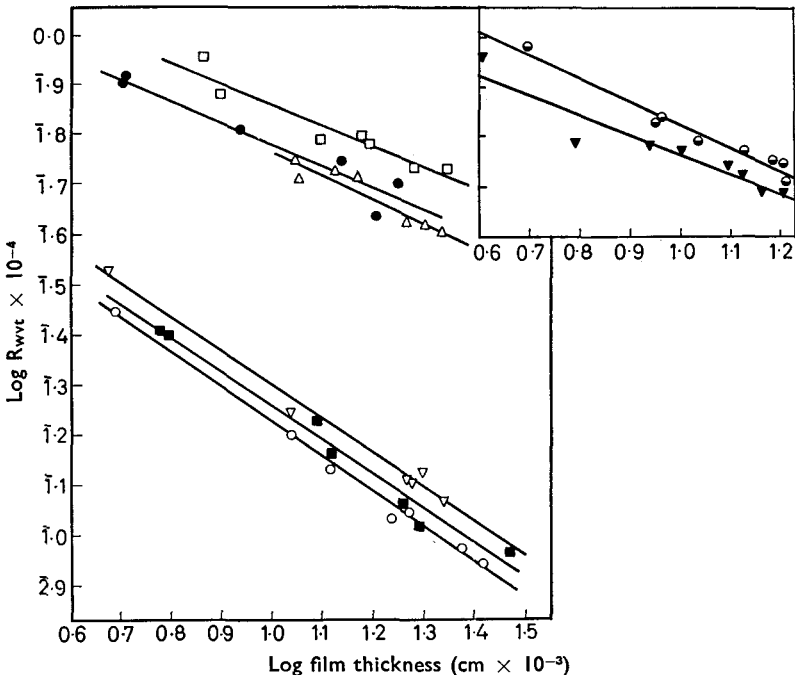


FIG. 1. Relationship between logarithm of water vapour transmission rate (R_{wvt}) and logarithm of film thickness for polymer films at 30° and under a vapour pressure difference of 29.0 mm Hg. Key: butyl methacrylate (unplasticised), \blacksquare ; butyl methacrylate + diethyl phthalate 2.5%, \circ ; 5.0%, ∇ ; hydroxypropyl cellulose (unplasticised), \bullet ; hydroxypropyl cellulose + propylene glycol 10%, \triangle ; 20%, \square ; methylhydroxypropyl cellulose: ethyl cellulose + propylene glycol 25%, \blacktriangledown ; 50%, \ominus .

where R_{wvt} is as previously defined, t is the film thickness in cm, C_1 the extrapolated ordinate intercept in water vapour transmission units, and m_1 the slope of the line. The statistical constants for these plots are given in Table 2.

It is apparent from the data in Fig. 1 that the water vapour transmission rates at equivalent film thicknesses through the hydroxypropyl cellulose and mixed polymer films are higher than those of the butyl methacrylate films. For example, at an equivalent film thickness of 0.01 cm, the R_{wvt} values are about $5.7-7.4 \times 10^{-5}$, $5.7-6.9 \times 10^{-5}$, and $1.7-2.0 \times 10^{-5}$ g/hr/cm²/mm Hg, for the hydroxypropyl cellulose, mixed polymer and butyl methacrylate films respectively. It is also apparent that the *rate* at which R_{wvt} decreases with increasing film thickness is greatest in the lipophilic butyl methacrylate systems (Table 2).

TABLE 2. STATISTICAL CONSTANTS FOR RELATIONSHIP BETWEEN LOG WATER VAPOUR TRANSMISSION RATES AND LOG FILM THICKNESS

System	Plasticiser concentration (% w/w of polymer)	Correlation coefficient r	Slope of line m	Ordinate intercept $\log C_1$ ($\times 10^{-4}$)
Butyl methacrylate + diethyl phthalate	0	-0.988	-0.687	1.944
	2.5	-0.996	-0.701	1.927
	5.0	-0.983	-0.672	1.964
Methylhydroxypropyl cellulose: ethyl cellulose (3:1) + propylene glycol	25	-0.943	-0.389	0.257
	50	-0.979	-0.456	0.384
Hydroxypropyl cellulose + propylene glycol	0	-0.959	-0.420	0.203
	10	-0.935	-0.468	0.238
	20	-0.954	-0.405	0.267

The % increases in weight per unit dry volume of film due to moisture sorption during the water vapour transmission studies are shown in Table 3. Moisture sorption is here compared on the basis of equal film thickness since the total cross-sectional area of all films used was constant. The weight increase per unit volume was used in preference to the weight increase per unit dry weight of film because the densities of the various film formulations were different. It may be seen from Table 3 that the amount of moisture sorbed decreases in the same order as R_{wvt} , i.e. hydroxypropyl cellulose, mixed polymer films and butyl methacrylate.

TABLE 3. MOISTURE SORPTION BY POLYMER-PLASTICISER FORMULATIONS CAST AS FREE FILMS

System	Plasticiser concentration (% w/w of polymer)	Moisture sorption (% w/v of dry film)
Butyl methacrylate + diethyl phthalate	0	0.68 ± 0.29
	2.5	0.63 ± 0.48
	5.0	0.23 ± 0.37
Methylhydroxypropyl cellulose: ethyl cellulose (3:1) + propylene glycol	25	1.27 ± 0.67
	50	0.22 ± 0.15
Hydroxypropyl cellulose + propylene glycol	0	4.01 ± 0.72
	10	2.73 ± 0.78
	20	2.55 ± 0.90

WATER VAPOUR TRANSMISSION IN POLYMER FILMS

For Fick's law of diffusion to be valid, the following relationship should be obeyed:

$$P = R_{wvt} \times t \quad \dots \quad (4)$$

where P is the permeability constant, and R_{wvt} and t are as previously defined. The permeability constant should be independent of thickness in those films which exhibit Fickian diffusion. Values of P , calculated from equation 4, have been plotted against film thickness in Fig. 2. With lipophilic butyl methacrylate films, the permeability constant is nearly independent of film thickness. This contrasts with the relationship obtained with the two relatively hydrophilic films, where P increases rapidly with film thickness.

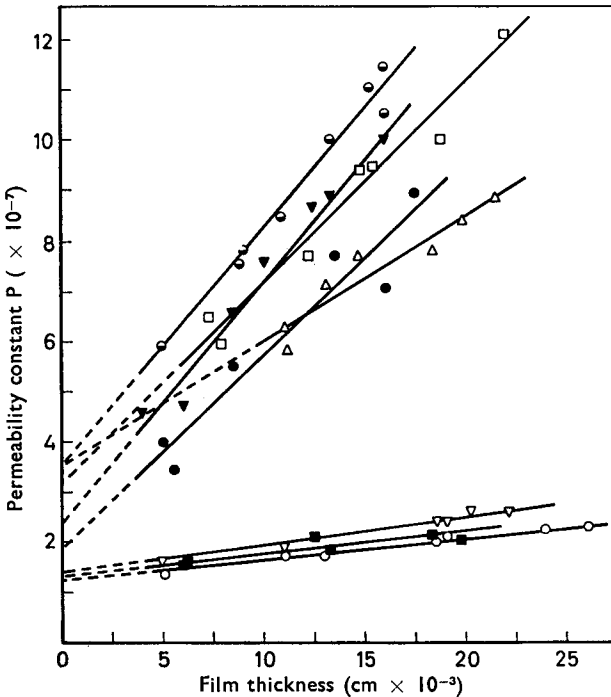


FIG. 2. Variation of permeability constant (P) with film thickness for the three film systems. Key: as in Fig. 1.

The observation that the diffusion of water vapour through the lipophilic butyl methacrylate films approximates to that predicted by Fick's law, implies that the vapour pressure gradient across the film is the major driving force. By the same reasoning, the increase in P with film thickness for the other two systems means that factors other than those considered in Fick's law are operative and are, presumably, superimposed on the diffusion due purely to the vapour pressure difference existing across the film.

Patel & others (1964) have also reported increases in P with film thickness for cellulosic films. The magnitude of this effect increased with decreasing chain length of the acid moiety used in the selected cellulose ester films, i.e. as the components of the film became more hydrophilic. The results of these workers show that P tended to reach a limiting value at film thicknesses in excess of approximately 0.025–0.03 cm. The range we investigated was from 0.004 to 0.026 cm, which encompasses the usual film coating thickness range. Over this range P was found to be linearly related to film thickness.

Two main mechanisms have been proposed to account for the permeation of materials through polymer films, namely a sieving mechanism and a solution process. Michaels & Parker (1959) consider the polymer as a porous medium in which the crystallites constitute the particulate skeleton and the amorphous phase the interstitial phase. According to Baddour, Graves & Vieth (1965), the evidence accumulated thus far indicates that the crystallites are impermeable to moisture. These workers point out that since the amorphous regions are networks of tangled chains, it is hardly likely that such regions would have precise pore diameters. Accordingly, the amorphous regions of the membrane may be viewed as a solvent in which the permeant dissolves and then moves under the influence of a concentration gradient to re-evaporate on the distal surface as proposed by Tuwiner (1962). This would seem to account for most of the transmission properties observed in view of the correlations between the ability of a polymer to hydrogen bond and its water vapour permeability and moisture sorption (Reid & Breton, 1959; Baddour & others, 1965). The volume fraction through which this mechanism could act would depend on the relative amounts of the crystalline and amorphous phases. Moisture sorption presumably leads to swelling of the amorphous regions of the film and this facilitates permeation. Other factors which may be involved are the degree of cross-linking, chain branching, the degree of substitution of the polymer and the molecular weight and shape of the permeant.

In the present work, the deviations from Fick's law observed for hydroxypropyl cellulose and the mixed polymer systems are probably associated with the attractive forces existing between these films and water molecules. As shown in Table 1, the cellulosic polymers consist of chains of variously substituted anhydroglucose units bearing a large number of hydroxyl groups. Propylene glycol, the common plasticiser, also possesses hydroxyl groups. The environment is therefore highly polar and affords ample opportunity for the existence of van der Waals' forces and hydrogen bonds. This, together with the swelling accompanying the sorption, facilitates water permeation. The butyl methacrylate films, on the other hand, are considerably less polar. Sorption, on the whole (Table 3), is less than that which occurs with the other two systems and the water vapour transmission is lower. The normal process of diffusion is not reinforced greatly by the presence of attractive forces and the permeability properties of these films more closely approach Fickian diffusion.

WATER VAPOUR TRANSMISSION IN POLYMER FILMS

The reciprocal of the rate of water vapour transmission is indicative of the resistance of the film to moisture permeation. Fig. 3 shows the results obtained when R_{wvt}^{-1} is plotted against t . The theoretical plot

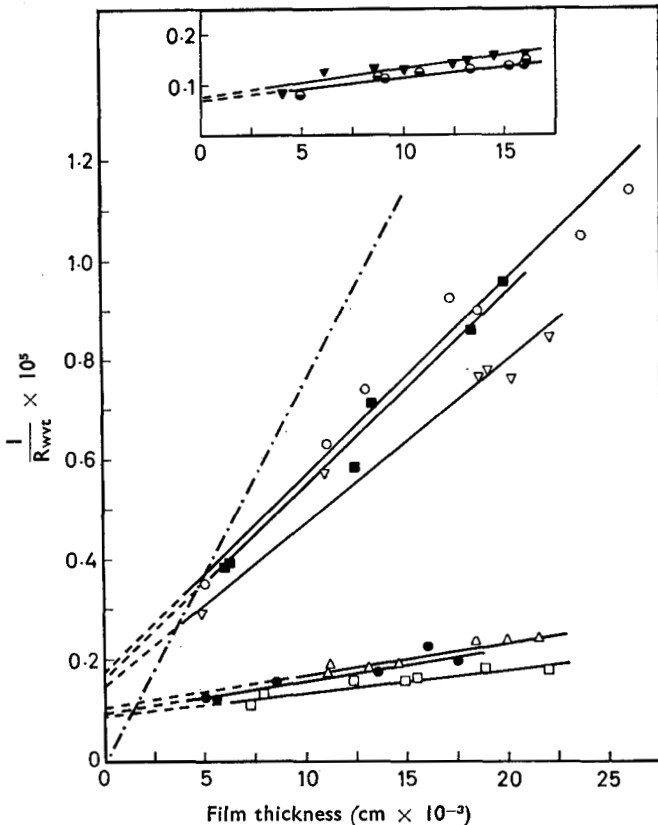


FIG. 3. Variation of the reciprocal of the water vapour transmission rate (R_{wvt}^{-1}) with film thickness for the three film systems. Key: as in Fig. 1; ●—●, theoretical plot for Fickian system having permeability constant of 0.013×10^{-5} .

for ideal Fickian diffusion is also shown for the case where $P = 0.013 \times 10^{-5}$ (the extrapolated permeability constant for butyl methacrylate films at zero thickness, taken from Fig. 2). Similar theoretical plots may be readily calculated for the other polymer systems. In all instances, the observed negative deviation of the experimental plots is an indication of the relative non-Fickian behaviour of the various films, the actual film resistance to moisture permeation being less than that predicted by Fick's law. Positive intercepts at zero film thickness, as found in Fig. 3, have also been observed by Patel & others (1964). These workers suggested that, with cellulosic films, this may be due to shrinkage of the fibres on the distal film surface when this surface is exposed to low

humidity conditions. The presence of a positive intercept with the non-cellulosic butyl methacrylate polymer films suggests that this is due to interactions between permeant and film, the intercept decreasing as the interaction decreases.

The slopes and ordinate intercepts contained in Table 2 are such as to preclude any absolute, quantitative evaluation of the data obtained. However, it appears that the mixed polymer and hydroxypropyl cellulose films are of a similar hydrophilic nature since the plot for the mixed polymer + 25% propylene glycol system is similar to that for the hydroxypropyl cellulose + 20% propylene glycol film. Examination of the structures of these polymer systems (Table 1) shows that this is not an unexpected result. The data also indicate that the plasticiser, on a % concentration basis, exerts a greater influence upon the water vapour transmission rates of the hydrophilic films than the lipophilic films studied. Insufficient plasticiser concentrations were investigated to establish the possible existence of minima in R_{wvt} as the plasticiser concentration is increased, as has been reported by Lachman & Drubulis (1964) and Patel & others (1964) for cellulose acetate films.

References

- American Society for Testing Materials (1961). *A.S.T.M. Standards on Plastics*, A.S.T.M. E-96-53T, pp. 1127-1129.
- Baddour, R. F., Graves, D. J. & Vieth, W. R. (1965). *J. Colloid Sci.*, **20**, 1057-1069.
- Gross, H. M. & Endicott, C. J. (1960). *Drug Cosmet. Ind.*, **86**, 170-291.
- Higuchi, T. & Aguiar, A. (1959). *J. Am. pharm. Ass., Sci. Edn*, **48**, 574-583.
- Kanig, J. L. & Goodman, H. (1962). *J. pharm. Sci.*, **51**, 77-83.
- Lachman, L. & Drubulis, A. (1964). *Ibid.*, **53**, 639-643.
- Lappas, L. & McKeehan, W. (1965). *Ibid.*, **54**, 176-181.
- Lowry, H. H. & Morgan, S. O. (1924). *J. Am. chem. Soc.*, **46**, 2192-2196.
- Michaels, A. S. & Parker, R. B. (1959). *J. Polym. Sci.*, **41**, 53-71.
- Munden, B. J., DeKay, H. G. & Banker, G. S. (1964). *J. pharm. Sci.*, **53**, 395-401.
- Patel, M., Patel, J. M. & Lemberger, A. P. (1964). *Ibid.*, **53**, 286-290.
- Rains, H. G. (1962). *Science of Surface Coatings*, editor, Chatfield, H. W., pp. 442-475, New York: Van Nostrand.
- Reid, C. E. & Breton, E. J. (1959). *J. appl. Polym. Sci.*, **1**, 133-143.
- Tuwiner, S. B. (1962). *Diffusion and Membrane Technology*, p. 215, New York: Reinhold.
- Utsumi, I., Ida, T., Takahashi, S. & Sugimoto, N. (1961). *J. pharm. Sci.*, **50**, 592-597.