

# Molecular Migration of Aromatic Liquids into a Commercial Fluoroelastomeric Membrane at 30, 40, and 50°C

Sangeeta B. Kulkarni, Mahadevappa Y. Kariduraganavar, Tejraj M. Aminabhavi

Center of Excellence in Polymer Science, Karnatak University, Dharwad 580 003, India

Received 8 February 2003; accepted 17 April 2003

**ABSTRACT:** A study of sorption profiles and diffusion anomalies of benzene, methyl-substituted benzenes, and other substituted benzenes (viz., chlorobenzene, nitrobenzene, bromobenzene, and anisole) into commercial fluoroelastomer (FC-2450) was carried out by gravimetric method. The liquid sorption was studied at 30, 40, and 50°C and the results were analyzed in terms of Fick's diffusion equation. Liquid concentration profiles were also computed by using Fick's equation with the appropriate initial and boundary conditions and these are presented as a function of penetration depth of molecular migration and time of immersion. The temperature dependencies of sorption, diffusion, and permeation were used to compute the Arrhenius activation

parameters and the results were discussed in terms of molecular size of liquids and interactions. Similarly, the diffusion coefficients and activation energies for diffusion exhibit systematic dependence on the size of the penetrant molecules and in some cases these are influenced by the interactions between the membrane and liquid molecules. The results reported here are useful in the applications of fluoroelastomer in hazardous waste chemical ponds and other similar situations. © 2003 Wiley Periodicals, Inc. *J Appl Polym Sci* 90: 3100–3106, 2003

**Key words:** diffusion; barrier; swelling; activation energy

## INTRODUCTION

The interactions between polymer membrane and organic solvents were extensively studied in our laboratory<sup>1–6</sup> on the basis of the molecular transport phenomenon. These studies have great relevance in the application of engineering and membrane-based separation processes including reverse osmosis,<sup>7,8</sup> pervaporation,<sup>9</sup> ultrafiltration,<sup>8</sup> and electrodialysis, etc., and also in the diverse applications of polymeric materials used as packaging and barrier films.<sup>10–12</sup> For successful operation of these processes, it is important to have a detailed knowledge of sorption, diffusion, and permeation of small organic molecules through the membrane material, which helps us to understand the polymer characteristics such as flexibility, chain entanglement, structural and morphological features of the membranes, and their interactions with different liquids.

Further, the study of sorption and diffusion of organic molecules through polymeric membrane is cru-

cial for the optimization of polymerization rates, mixing of additives, devolatilization, and other barrier properties of the materials. Solvent diffusivity can also be influenced profoundly by relatively minor changes in the chemical structure of diffusant molecules and of the membrane.

In continuation of our ongoing program in this area,<sup>1–6</sup> we present here some important barrier properties of commercial fluoroelastomer (FC-2450) to various low sorbing organics (viz., benzene, toluene, anisole, xylene chlorobenzene, nitrobenzene, and bromobenzene). The solvents of varying polarity and molecular size were chosen keeping in view of their wide diversity and relevance in chemical engineering and other allied areas. Sorption experiments were performed at 30, 40, and 50°C and these data have been used to compute the concentration-independent diffusion coefficients from the Fick's diffusion equation. In addition, the analytical solutions of Fick's equation have been used to calculate the liquid concentration profiles at different times and depths of liquids inside the membrane materials. The temperature dependence of these parameters was used to predict the activation parameters. The concentration profiles as well as activation parameters were used to discuss the extent of polymer–solvent interactions and diffusion anomalies in terms of size and shape of liquid molecules.

Correspondence to: M. Y. Kariduraganavar (mahadevappak@yahoo.com).

Contract grant sponsor: Department of Science and Technology, New Delhi; contract grant number: SP/S1/H-31/2000.

TABLE I  
Physical Properties and Sorption Coefficients of Aromatic Liquids through Fluoroelastomeric Membrane

Liquids	Molar volume (cm <sup>3</sup> /mol)	Sorption coefficients (mol %)		
		30°C	40°C	50°C
Benzene	89.4	0.033	0.071	0.081
Toluene	106.9	0.024	0.048	0.058
Anisole	109.3	0.017	0.024	0.046
Xylene	123.9	0.009	0.039	0.049
Chlorobenzene	102.2	0.019	0.025	0.049
Nitrobenzene	102.9	0.028	0.055	0.074
Bromobenzene	154.4	0.006	0.013	0.026

## EXPERIMENTAL

### Reagents/chemicals

The reagent-grade chemicals such as benzene, toluene, and chlorobenzene were obtained from S. D. Fine Chemicals Ltd. (Mumbai, India). Anisole was procured from Sisco Research Laboratory (Mumbai, India). Nitrobenzene and bromobenzene were purchased from Ranbaxy Chemicals and Thomas Baker Chemicals (Mumbai, India), respectively. Xylene was obtained from Spectrochem Pvt. Ltd. (Mumbai, India). All chemicals were of analytical grade and used without further purification.

### Materials

Fluorel FC 2450 is a low-viscosity incorporated cure copolymer designed for injection molding sealing components that meet the major fluoroelastomer O-ring specifications. The gift sample was received from Nina McAllum (3M Co., St. Paul, MN). The typical properties of the elastomer are as follows: specific gravity, 1.80; color, off-white; solubility, in ketones and esters; Mooney viscosity, ~ 25 ML1+10 at 121°C. The press-cured sample for 10 min at 177°C possesses the following mechanical properties: tensile strength, 1260 psi; % elongation at break, 235; hardness (shore A), 75. The sample was compounded with standard fillers and ingredients utilized in typical fluoroelastomer formulations

### Sorption experiments

Sorption experiments were performed at 30, 40, and 50°C by using circularly cut disc-shaped membrane samples of diameter ≈ 2 cm were kept in a vacuum oven at 25°C for 45 h before being used in sorption experiments. The samples were then immersed in about 15–20 mL of liquid taken in airtight bottles kept in a thermostatically controlled oven (WTB Binder, Germany) at the desired constant temperature (±0.5°C). The samples were periodically removed from the test bottle; adhered liquid was wiped out by using smooth tissue papers and samples were imme-

diately weighed on a Mettler balance (Model AE 240, Switzerland) with an accuracy of ±0.01 mg. The samples were taken out no longer than 30–40 s outside the temperature-controlled oven. The procedure was continued until no more liquid uptake by the membrane was observed (equilibrium saturation).

Sorption coefficients were expressed as mol % and calculated by using the equation:

$$M_t = \left( \frac{W_t - W_0}{W_0} \right) \times \frac{100}{M} \quad (1)$$

where  $W_0$  is the initial mass of the sample,  $W_t$  is the mass at time  $t$ , for the immersion period, and  $M$  is the molar mass of the liquid.

### Diffusion coefficients and concentration profiles

Diffusive migration of liquids depends on the concentration and temperature, together with the type of polymer barrier and the nature of migrating liquids. The dynamic swelling properties of a polymer film include the solvent sorption rate, the rate of approach to equilibrium swelling, and the solvent transport

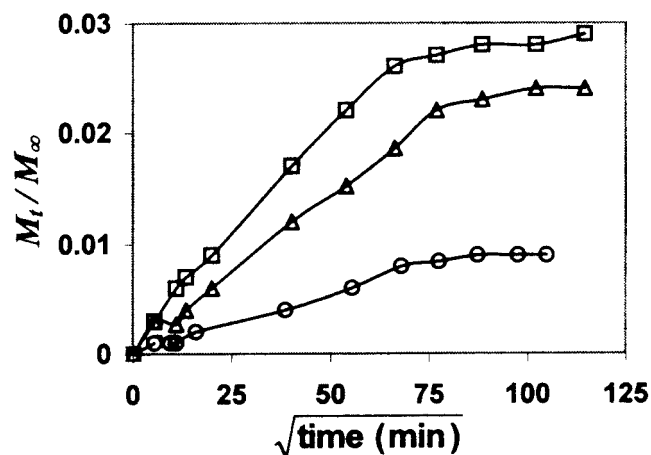


Figure 1 Plots of  $M_t/M_\infty$  versus square root of time for fluoroelastomer at 30°C with (□) benzene, (△) toluene, and (○) xylene.

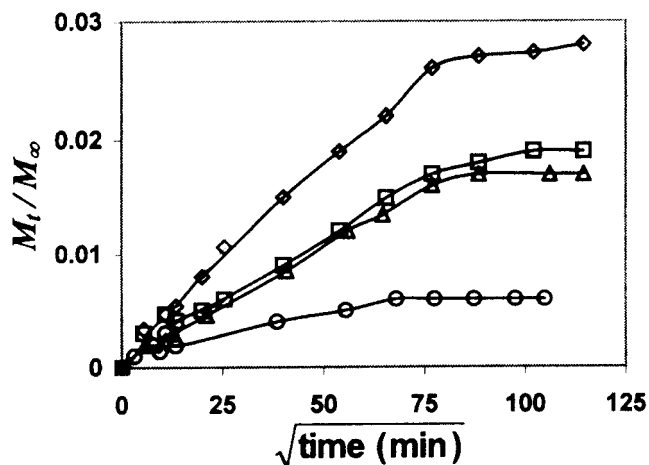


Figure 2 Plots of  $M_t/M_\infty$  versus square root of time for fluoroelastomer 30°C with ( $\Delta$ ) anisole, ( $\square$ ) chlorobenzene, ( $\circ$ ) bromobenzene, and ( $\diamond$ ) nitrobenzene.

mechanism controlling solvent transport. For the Fickian transport, the rate of equilibrium approach can be characterized by the diffusion coefficient. For a plane geometry of the polymer sheet, the diffusion coefficient  $D$  can be calculated from<sup>13</sup>:

$$\frac{M_t}{M_\infty} = 1 - \sum_{n=0}^{\infty} \left[ \frac{8}{(2n+1)^2 \pi^2} \right] \exp \left[ -(2n+1)^2 \pi^2 \left( \frac{Dt^2}{h^2} \right) \right] \quad (2)$$

Here  $M_t$  and  $M_\infty$  are the cumulative masses sorbed from the polymer sample at time  $t$  and  $\infty$ , respectively, and  $h$  is the initial thickness of the polymer sample. Although this equation can be solved readily, it is suitable to consider the short time-limiting expression as well<sup>13</sup>:

$$\frac{M_t}{M_\infty} = \left[ \frac{4}{\pi^{1/2}} \right] \left[ \frac{Dt}{h^2} \right]^{1/2} \quad (3)$$

A single curve is obtained from the plot of  $M_t/M_\infty$  versus square root of time, which is linear initially.

Thus  $D$  can be calculated from the rearrangement of eq. (3) as<sup>14-18</sup>:

$$D = \pi \left[ \frac{h\theta}{4M_\infty} \right]^2 \quad (4)$$

where  $M_\infty$  is the equilibrium mass uptake at  $t \rightarrow \infty$  and  $\theta$  is the slope of initial linear portion of sorption curves. Similarly, permeability coefficient can be calculated by using the relation:  $P = D \times S$ , which follows nearly the same pattern as those of diffusivities. This simple relation holds for the permeation process when  $D$  obeys the Fick's diffusion law and  $S$  obeys the Henry's law.<sup>19</sup> For the penetrant-polymer systems used in this study, it is not certain to what degree one or both laws are obeyed. Thus, the  $P$  values are considered as estimates of the permeability coefficients.

For successful application of fluoroelastomers, it is essential to know the liquid concentration profiles of migrating liquids. This is done by solving eq. (5) under suitable initial and boundary conditions to yield an equation for solvent uptake inside the fluoroelastomer of thickness  $h$ , at time  $t$ , and distance  $x$  as<sup>20-22</sup>:

$$\left( \frac{C_{(x,t)}}{C_\infty} \right) = 1 - \frac{4}{\pi} \sum_{m=0}^{\infty} \frac{1}{(2m+1)} \exp \left[ -\frac{D(2m+1)^2 \pi^2 t}{h^2} \right] \sin \left[ \frac{(2m+1)\pi x}{h} \right] \quad (5)$$

where  $m$  is an integer. By solving eq. (5), we obtain concentration profiles of the migrating liquids developed within the fluoroelastomer. These data are useful to study the liquid migration as a function of time and penetration depth of the liquids from the face to the middle of the fluoroelastomer along the thickness direction.

## RESULTS AND DISCUSSION

### Sorption anomaly

Molecular transport of liquids through the membranes can be studied in terms of sorption/diffusion

TABLE II  
Diffusion ( $D$ ) and Permeation ( $P$ ) Coefficients of Aromatic Liquids at Different Temperatures through Fluoroelastomeric Membrane

Liquids	Dipole moment ( $\mu$ )	$D$ ( $10^8$ ) ( $\text{cm}^2/\text{s}$ )			$P$ ( $10^8$ ) ( $\text{cm}^2/\text{s}$ )		
		30°C	40°C	50°C	30°C	40°C	50°C
Benzene	0.00	1.14	1.28	1.35	0.62	0.80	1.09
Toluene	0.31	1.02	1.15	1.25	0.72	0.83	0.92
Anisole	1.25	0.61	0.70	0.87	0.43	0.68	0.78
Xylene	0.02	0.93	1.06	1.17	0.57	0.62	0.73
Chlorobenzene	1.62	0.63	0.75	0.82	0.42	0.65	0.72
Nitrobenzene	4.22	0.71	0.96	1.64	0.39	0.52	0.76
Bromobenzene	1.70	0.81	0.90	1.04	0.46	0.71	0.94

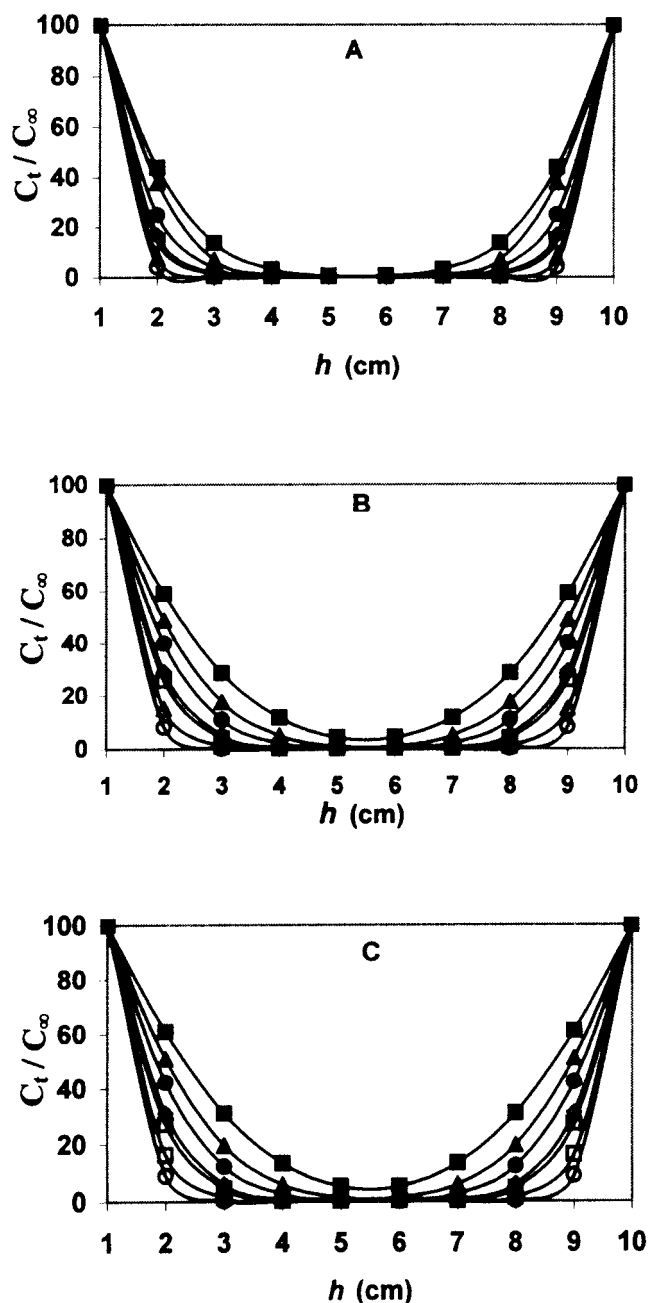


Figure 3 Concentration profiles calculated from eq. (5) for benzene through fluoroelastomer membrane at (A) 30°C, (B) 40°C, and (C) 50°C for (○) 25 min, (△) 50 min, (□) 100 min, (◇) 120 min, (●) 200 min, (▲) 300 min, and (■) 500 min.

phenomenon. Sorption data generated at three different temperatures are presented in Table I, whereas the mol % sorption plots at 30°C are displayed in Figures 1 and 2. It is observed that there is a systematic sorption trend for benzene and its substituted derivatives and in accordance, the sorption coefficients decrease with an increase in the size of liquid molecules. For instance, benzene with lower molar volume (89.4 cm<sup>3</sup>/mol) than other substituted benzenes shows higher equilibrium sorption at all temperatures, fol-

lowed by toluene and xylene, which have higher molar volumes 106.9 and 123.9 cm<sup>3</sup>/mol, respectively. However, in the case of other substituted benzenes, the molar volumes of chlorobenzene (102.2 cm<sup>3</sup>/mol) and nitrobenzene (102.9 cm<sup>3</sup>/mol) are almost same, but the equilibrium sorption values of nitrobenzene are much higher than chlorobenzene, as observed in Figure 2, and the same trend remained at higher temperatures. Similar observations are made in our previous investigations.<sup>5,6</sup> This implies that sorption not only depends on the size of the penetrant, but also on

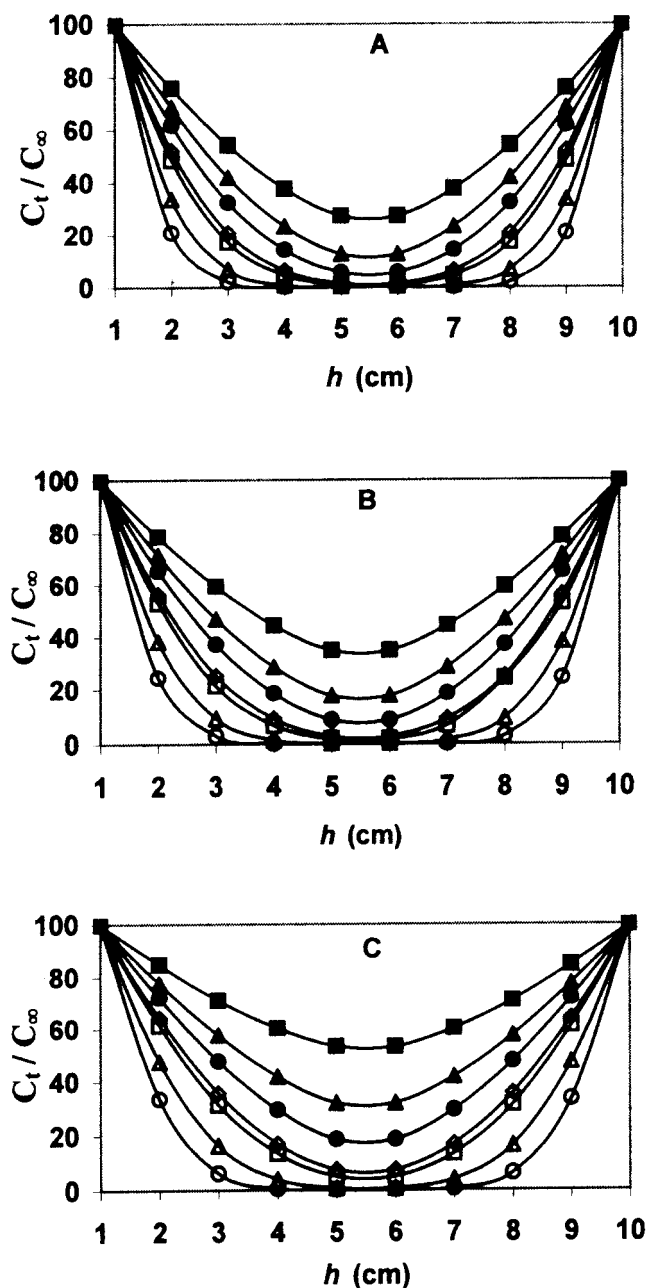
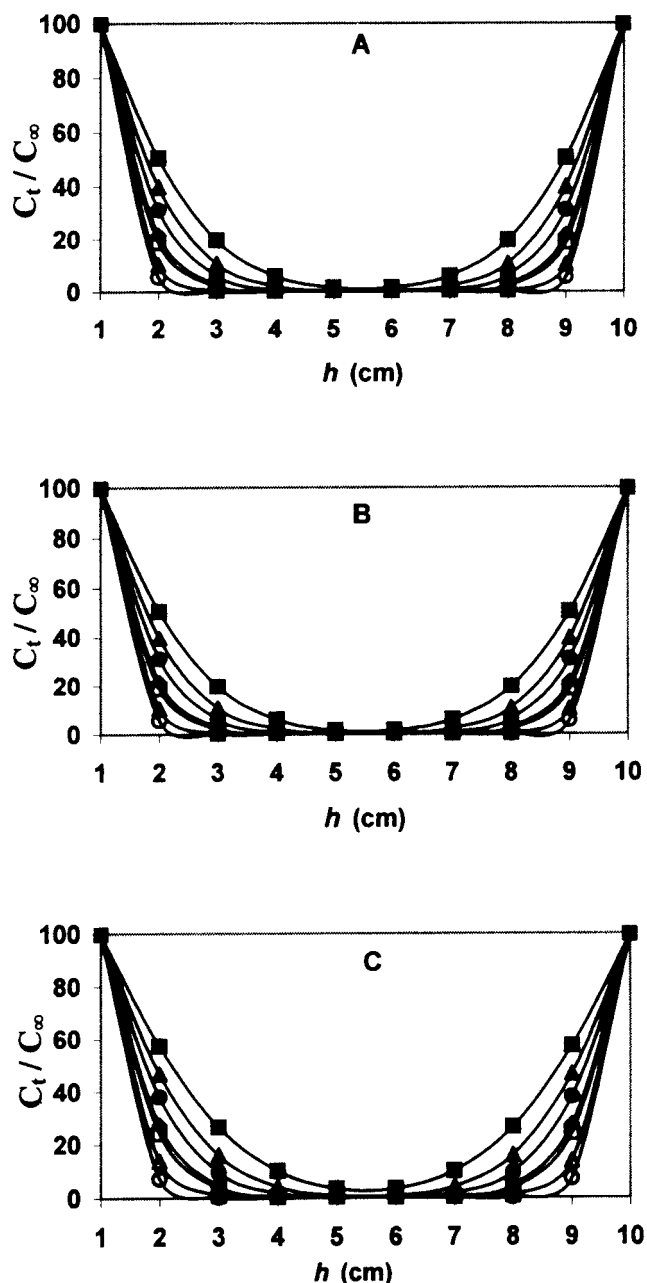


Figure 4 Concentration profiles calculated from eq. (5) for anisole through fluoroelastomer membrane at (A) 30°C, (B) 40°C, and (C) 50°C for (○) 25 min, (△) 50 min, (□) 100 min, (◇) 120 min, (●) 200 min, (▲) 300 min, and (■) 500 min.



**Figure 5** Concentration profiles calculated from eq. (5) for nitrobenzene through fluoroelastomer membrane at (A) 30°C, (B) 40°C, and (C) 50°C for (○) 25 min, (△) 50 min, (□) 100 min, (◇) 120 min, (●) 200 min, (▲) 300 min, and (■) 500 min.

the liquid property which leads to more interactions in the membranes, thereby liquid sorption increases significantly. On the other hand, bromobenzene, which has higher molar volume (154.02 cm<sup>3</sup>/mol), shows lower equilibrium sorption values as expected than all other aromatics at all temperatures. In all cases, sorption increased with increasing temperatures.

The results of diffusion coefficients are presented in Table II. It is observed that the values of diffusion coefficients decreased systematically from benzene to

anisole as the size of the migrating liquids increased at all temperatures, suggesting the dependence of  $D$  on the molecular size of penetrant. However, xylene shows higher  $D$  values than that of anisole, even though the size of the xylene molecules is bigger than those of anisole molecules. This may be due to specific interactions occurring between liquid molecules and the membrane.

On the other hand, polar liquids such as chlorobenzene and bromobenzene exhibit intermediary  $D$  values falling between anisole and xylene. Similarly, nitrobenzene is still higher polar than those of chlorobenzene and bromobenzene, which exhibits slightly higher  $D$  values than those of chlorobenzene and bromobenzene. This clearly signifies that transport phenomenon not only depends on the size of the migrating liquids, but also on the molecular interactions between liquids and the membrane. Permeability coefficients calculated from the kinetic gravimetric sorption experiments are also included in Table II. It is generally observed that permeability results follow the same pattern as those of diffusion coefficients in the investigated temperature range.

In areas where polymeric membranes are used as barriers toward aggressive liquids, it is important to know the liquid penetration rates calculated in terms of liquid concentration profiles. These are calculated from eq. (5) at different exposure times and membrane thickness for all the liquids. However, only a few typical graphs are displayed in Figures 3-5. These plots show a dependence on temperature, depth of penetration, as well as the nature of liquids chosen. For instance, diffusivity of benzene is higher than that of anisole and hence its concentration profiles are higher at all temperatures (see Fig. 3). In the case of anisole, diffusivity is quite small and its concentration profiles are shown in Figure 4. From this we could observe a clear-cut dependence of  $D$  values on temperature. Similar effects are also observed in the case of nitrobenzene, as displayed in Figure 5.

Sorption anomaly has been studied by fitting sorption data in an empirical relation<sup>23</sup>:

$$\frac{M_t}{M_\infty} = Kt^n \quad (6)$$

The estimated values of  $n$  and  $K$  are presented in Table III. The parameter  $K$  represents the extent of interactions between the liquids and membrane. These values increase with an increase in dipole moments of the liquids. The values of  $K$  increase systematically with increasing temperature. The value of exponent  $n$  represents the nature of the transport mechanism. For instance, if  $n$  lies between 0.5 and 0.75, then the transport is anomalous (i.e., it slightly deviates from the Fickian trend). In the present systems, the obtained

TABLE III  
Estimated Parameters for Aromatic Liquids Calculated from eq. (6) at Different  
Temperatures for Fluoroelastomeric Membrane

Liquids	<i>n</i>			<i>K</i>		
	30°C	40°C	50°C	30°C	40°C	50°C
Benzene	0.52	0.58	0.52	1.02	2.56	5.29
Toluene	0.55	0.50	0.53	2.52	3.71	4.23
Anisole	0.55	0.61	0.53	3.68	5.42	6.34
Xylene	0.57	0.54	0.52	1.92	4.54	5.12
Chlorobenzene	0.53	0.55	0.60	2.46	3.21	5.35
Nitrobenzene	0.57	0.51	0.54	3.26	4.52	5.43
Bromobenzene	0.56	0.51	0.57	1.95	4.87	5.63

values of *n* vary from 0.5 to 0.61; thus, the transport is found to follow anomalous type of behavior.<sup>2,6,24,25</sup>

### Activation parameters

The temperature dependency of diffusion was followed by carrying out the sorption experiments at 30, 40, and 50°C. From the typical plots (Figs. 6 and 7), it is clear that mol % uptake increased with the temperatures. From the values of diffusion and permeation coefficients at different temperatures, the corresponding activation energy values  $E_D$  and  $E_P$  were calculated by using the Arrhenius-type equation<sup>18</sup>:

$$X = X_0 \exp\left(\frac{-E_x}{RT}\right) \quad (7)$$

where *X* refers to either *D* or *P*;  $X_0$  is a constant representing  $D_0$  or  $P_0$ ;  $E_x$  gives the value of either  $E_D$  or  $E_P$ , depending upon the transport process under consideration. The mechanism by which small molecules permeate through rubbery or glassy amorphous polymers has been described by many authors.<sup>26-30</sup> From a least-squares fit of the linear plots of log *X* versus  $1/T$ , the diffusivity ( $E_D$ ) and permeability ( $E_P$ ) values were calculated. The heat of sorption was also

calculated from the differences:  $\Delta H_S = E_P - E_D$ . These results are given in Table IV.

The  $E_D$  values increase from benzene 6.9 to 9.36 kJ/mol for xylene, but for methoxybenzene the  $E_D$  value is 14.41 kJ/mol, which is higher than that observed for toluene and xylene. However, the values of  $E_D$  for other substituted benzenes (viz., chlorobenzene, nitrobenzene, and bromobenzene) do not show any systematic variation with the size of liquids. These values range from 10.16 to 33.97 kJ/mol.

Heats of sorption provide additional information about the molecular transport of liquids into the polymeric membranes. The quantity  $\Delta H_S$  is a composite parameter involving both Henry's law and Langmuir's (hole filling) type of sorption mechanisms. The Henry's mode of sorption requires both the formation of a site in the polymer matrix and the dissolution of species into that site. The formation of a site involves an endothermic contribution to this process. On the other hand, with the Langmuir's mode, the site already exists within the polymer matrix, and consequently, the sorption by hole filling gives higher exothermic heats of sorption.

In the present system,  $\Delta H_S$  values decrease in the following order: nitrobenzene > bromobenzene > benzene > chlorobenzene > anisole > toluene

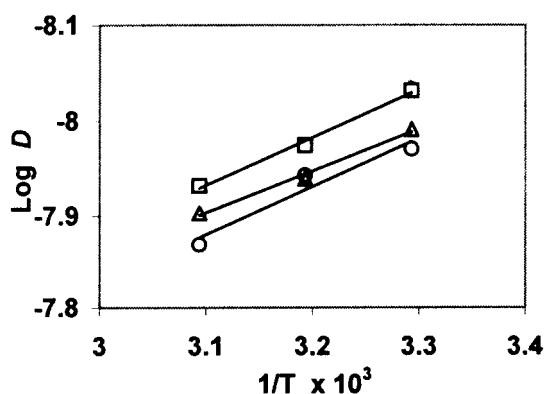


Figure 6 Arrhenius plots of log *D* versus  $1/T$  for fluoroelastomer membrane for (□) benzene, (Δ) toluene, and (○) xylene.

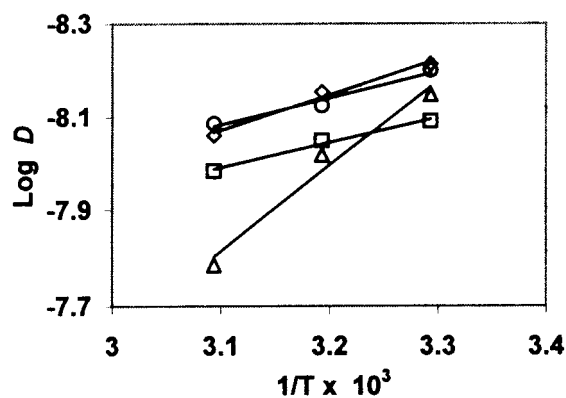


Figure 7 Arrhenius plots of log *D* versus  $1/T$  for fluoroelastomer membrane for (Δ) anisole, (○) chlorobenzene, (□) bromobenzene, and (◇) nitrobenzene.

TABLE IV  
Activation Energy for Diffusion, Permeation, and Heat of Sorption of Aromatic Liquids for Fluoroelastomeric Membrane

Liquids	$E_D$ (kJ/mol)	$E_p$ (kJ/mol)	$\Delta H_s$ (kJ/mol)
Benzene	6.91 ± 1.75	22.95 ± 3.53	16.04
Toluene	8.29 ± 2.75	9.99 ± 3.50	1.70
Anisole	14.41 ± 1.83	24.39 ± 7.20	9.98
Xylene	9.36 ± 3.83	10.03 ± 3.05	0.67
Chlorobenzene	10.76 ± 4.75	22.06 ± 2.82	11.3
Nitrobenzene	33.97 ± 4.67	56.71 ± 1.23	22.74
Bromobenzene	10.16 ± 1.83	29.16 ± 4.07	19.00

> xylene. The  $\Delta H_s$  values are positive in all the cases, suggesting that the sorption mechanism in these cases is mainly dominated by Henry's mode of sorption, giving an endothermic contribution.

### CONCLUSION

The molecular transport of aromatic liquids into fluoroelastomeric membranes is a subject of both fundamental and technical importance because the factors, such as molecular interactions and polymer morphology, which control diffusion, have not been well understood. Such a study is important in applications including pervaporation, barrier packing, controlled delivery of biologically active materials, plasticizer migration, and physical aging. The transport coefficients determined in the present study (viz., sorption, diffusion, and permeation) decreased with an increase in the size of the penetrants. In contrast, diffusion coefficients for polar liquids do not show any dependency on the size of the molecules; instead they depend on the molecular interactions. Permeability coefficients calculated from the product of diffusivity and solubility are nearly the same pattern as those of diffusivities. The liquid concentration profiles calculated from analytical solution Fick's equation are dependent on the size of liquid molecules and diffusivity values. Molecular transport was found to follow the anomalous-type behavior in all the cases over the investigated temperature range. The Arrhenius activation parameters for benzenes and methyl-substituted benzenes have also shown a dependence on the size of liquid molecule. However, the polar liquids do not show any systematic variation with the size of liquids. These values range from 10.16 to 33.97 kJ/mol. Heat of sorption values are positive in all the cases indicative of the endothermic contribution dominated by Henry's mode of sorption. The membrane is stable in all the liquids chosen, as evidenced by no chemical degradation. Hence, the fluoroelastomeric membrane (FC-2450) studied here can be used in field applications containing these liquids.

Authors are thankful to the Department of Science and Technology, New Delhi (Grant No.SP/S1/H-31/2000) for financial support.

### References

- Aminabhavi, T. M.; Harogoppad, S. B.; Khinnavar, R. S.; Balundgi, R. H. *J Macromol Sci Rev Macromol Chem Phys C* 1991, 31, 433.
- Aminabhavi, T. M.; Naik, H. G. *J Hazard Mater* 1998, 60, 175.
- Kulkarni, P. V.; Rajur, S. B.; Antich, P.; Aminabhavi, T. M.; Aralaguppi, M. I. *J Macromol Sci Rev Macromol Chem Phys C* 1990, 30, 441.
- Aminabhavi, T. M.; Munnolli, R. S. *Polym Int* 1994, 34, 59.
- Kariduraganavar, M. Y.; Kulkarni, S. B.; Aminabhavi, T. M. *J Appl Polym Sci* 2003, 88, 840.
- Kulkarni, S. B.; Kariduraganavar, M. Y.; Aminabhavi, T. M. *J Appl Polym Sci* 2003, 89, 3201.
- Rangarajan, R.; Mazid, M. A.; Matsuura, T.; Sourirajan, S. *Ind Eng Chem Process Des Dev* 1985, 24, 978.
- Rangarajan, R.; Matsuura, T.; Sourirajan, S. *Reverse Osmosis and Ultrafiltration*; ACS Symposium Series 281; American Chemical Society: Washington, DC, 1985.
- Aminabhavi, T. M.; Khinnavar, R. S.; Harogoppad, S. B.; Aithal, U. S.; Nguyen, Q. T.; Hansen, K. C. *J Macromol Sci Rev Macromol Chem Phys C* 1994, 34, 139.
- Aithal, U. S.; Aminabhavi, T. M. *J Chem Ed* 1990, 67, 82.
- Aminabhavi, T. M.; Harogoppad, S. B. *J Chem Ed* 1991, 68, 543.
- Aboutaybi, A.; Bouzon, J.; Vergnaud, J. M. *Eur Polym J* 1990, 26, 285.
- Crank, J. *The Mathematics of Diffusion*; Clarendon Press: Oxford, 1975.
- Harogoppad, S. B.; Aminabhavi, T. M. *Macromolecules* 1991, 24, 2598.
- Khinnavar, R. S.; Aminabhavi, T. M. *Polym Plast Technol Eng* 1991, 30, 529.
- Harogoppad, S. B.; Aminabhavi, T. M. *Polym Commun* 1991, 32, 120.
- Khinnavar, R. S.; Aminabhavi, T. M. *J Appl Polym Sci* 1991, 42, 2321.
- Aithal, U. S.; Aminabhavi, T. M. *J Appl Polym Sci* 1991, 42, 2837.
- Garbarini, G. R.; Eaton, R. F.; Kwei, T. K.; Tobolsky, A. V. *J Chem Ed* 1971, 48, 226.
- Aminabhavi, T. M.; Phayde, H. T. S.; Ortego, J. D.; Vergnaud, J. M. *Polymer* 1996, 37, 1677.
- Vergnaud, J. M. *Liquid Transport Processes in Polymeric Materials, Modeling, and Industrial Applications*; Prentice Hall: Englewood Cliffs, NJ, 1991.
- Aminabhavi, T. M.; Phayde, H. T. S.; Ortego, J. D.; Vergnaud, J. M. *Eur Polym J* 1996, 32, 1117.
- Alfrey, T., Jr.; Gurnee, E. F.; Lloyd, W. G. *J Polym Sci, Part C: Polym Lett* 1961, 11, 249.
- Aminabhavi, T. M.; Munnolli, R. S.; Ortego, J. D. *Waste Manage* 1995, 15 (1), 69.
- Aminabhavi, T. M.; Harlapur, S. F.; Balundgi, R. H.; Ortego, J. D. *J Appl Polym Sci* 1996, 59, 1857.
- Stannett, Y. T.; Hopfenberg, H. B.; Petropoulos, J. H. *Int Rev Phys Chem Ser I* 1972, 8, 329.
- Rogers, C. E.; Machin, E. *CRC Crit Rev Macromol Sci* 1972, 245.
- Aminabhavi, T. M.; Aithal, U. S.; Shukla, S. S. *J Macromol Sci Rev Macromol Chem Phys C* 1988, 28, 421.
- Petropoulos, J. H. *J Polym Sci, Polym Phys Ed* 1985, 23, 1309.
- Billovits, G. F.; During, C. J. *Chem Eng Commun* 1989, 82, 21.