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REVIEW

Gaseous Transfer Coefficients in Membranes

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Abstract

Permeabilities are transfer coefficients in flow of fluids through membranes. In the case of gaseous diffusion there is normally very little, if any, interaction of the permeating components. Thus the separation of gas or vapor mixtures by means of membranes can easily be predicted when appropriate transfer coefficients of the pure components are known. The utility of a comprehensive collection of such permeabilities is therefore self-evident.

A theoretical equation which expresses a transport mechanism becomes of practical value only if an appropriate transfer coefficient is available. Thus the knowledge of such coefficients is imperative for design purposes. Of course, when the transfer coefficient is defined in precise units, it provides the complete transport equation.

In the separation of gases and vapors by means of membranes the transfer coefficients are the permeabilities of the respective components. The amount of information which is available is extensive. As one might expect, many attempts have been made to correlate data (*41*, *43*, *61*, *70*, *87*, *103*). While some efforts have been reasonably successful, the situation remains marginal and one has to rely for the most part on original data in publications.

The main reason for this state of affairs is that a great many parameters can affect the coefficients. Consequently, it is impossible to create a universally valid correlation which would incorporate all possible variations. The plot of hydrogen permeabilities in Fig. 1 through a variety of plastic films, including the temperature effect, gives a clear picture of the multitudinous variations.

It is evident that a comprehensive compilation of permeability data would be of considerable value, even without attempts at parametric correlations. Thus Choi (*144*) made an extensive survey and prepared concise summaries by using a permeability ratio. There, the permeability of a gas or vapor is referred to the permeability of a "standard" gas through the respective membrane. The reference gases are primarily oxygen and nitrogen for which values have been reported for most materials. By presenting permeability ratios referred to a reference gas, the reader can screen the listed polymers to find, hopefully, one which is structurally close to that in which he is interested. Then by procuring an experimental value for the reference gas only, it is possible to obtain an estimate of values for the other gases.

Data are given for only one temperature and this, of course, represents a limitation. To compensate for this shortcoming the available literature has been covered with considerable care, and to make the references more usable a cross-listing has been provided so that references can be identified with classes of polymers. This will permit easy location of original data, and effects of parameters such as temperature, pressure, polymer structure, and density can be obtained from the respective publications. The yearly editions of the *Modern Plastics Encyclopedia* and *Modern Packaging Encyclopedia* always contain a number of property charts with permeability data for gases and some water vapor transmissions. While the coverage is limited, it does represent worthwhile reference material.

The units used to express permeabilities, Q, of gases and vapors are given in the metric system. Conventionally, they are:

$$\frac{\text{(std cc)(cm thickness)}}{\text{(sec)(sq cm area)(cm Hg pressure drop)}}$$

Most of the numerical values cited are to be multiplied by the factor 10^{-9}. However, in the present instance the factor 10^{-10} is used to avoid decimal fractions as much as possible.

The overall permeability equation is commonly stated as

$$F = QA\frac{P_H - P_L}{l}$$

where F is the amount of fluid passing through the membrane in unit time;

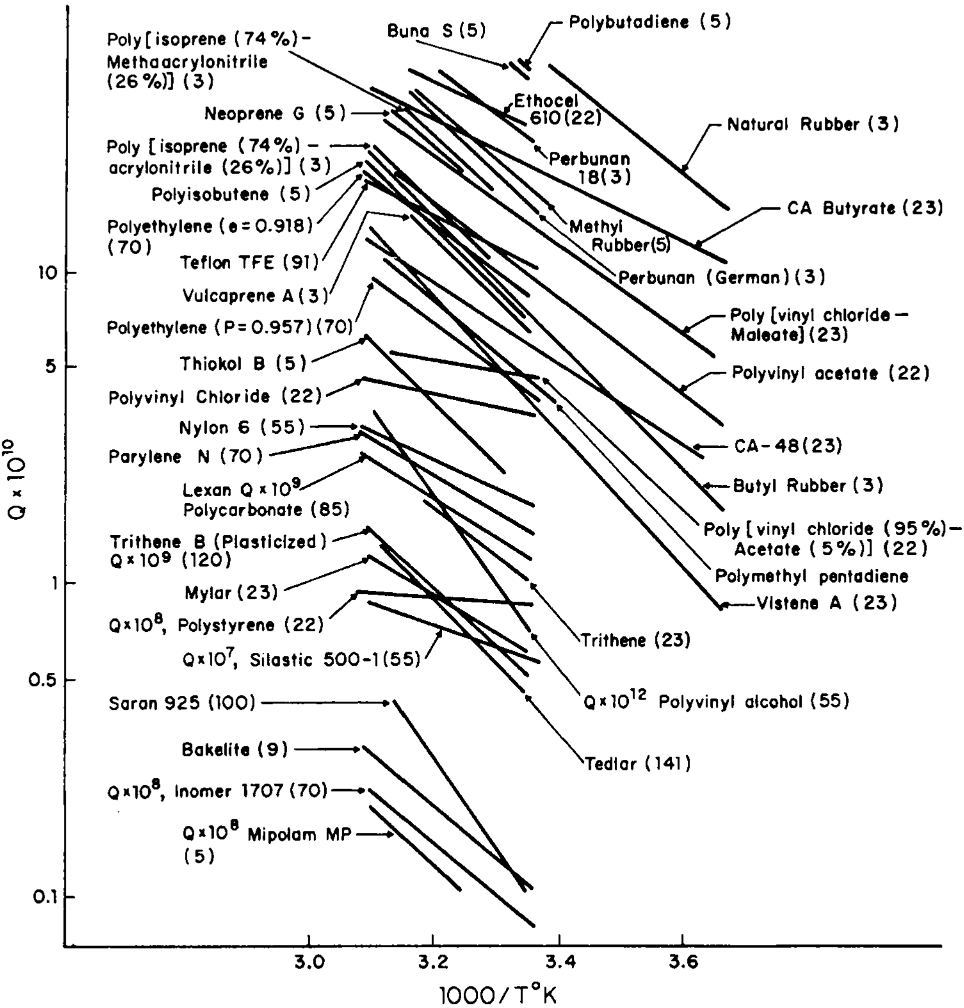

FIG. 1. Plot of hydrogen permeabilities through a variety of plastic films.

TABLE 1

Permeabilities of Various Polymer Membranes

Membrane barrier	Reference gas			Permeability ratio ($Q_{gas}/Q_{ref\ gas}$)							Refs.[a]
	T(°C)	Gas	$Q \times 10^{10}$	A	H_2	He	N_2	O_2	CO_2	CH_4	
1. Microporous Vycor Glass (No. 7930)	25	N_2	56700	0.827	3.44	2.47	1.00	0.935	1.17	1.40	42,44
2. Cellulose acetate											
Lumarith P-912	25	N_2	0.248	—	—	—	1.00	2.98	—	—	126
CA-48	25	H_2	5.81	—	1.00	—	—	—	1.08	—	23
CA-43	25	H_2	8.00	—	1.00	—	—	—	0.707	—	23
3. Cellulose triacetate (43% acetyl)	30	N_2	0.17	—	—	—	1.00	5.88	33.5	—	103
4. Cellulose acetate–butyrate	25	N_2	1.30	—	—	—	1.00	2.98	23.5	—	100
	25	He	14.3	—	1.47	1.00	—	—	2.22	—	23
5. Cellulose acetate–styrene											
Graft 0%	25	O_2	0.610	—	—	—	—	1.00	1.80	—	132
Graft 18.2%	25	O_2	0.490	—	—	—	—	1.00	3.88	—	132
Graft 44.1%	25	O_2	1.55	—	—	—	—	1.00	6.45	—	132
Graft 100%	25	O_2	2.50	—	—	—	—	1.00	2.76	—	132
6. Cellulose propionate	30	N_2	1.97	—	—	—	—	1.00	3.11	—	131
7. Epoxy											
Epon 1001	29	O_2	0.049	—	—	—	—	1.00	1.76	—	69
Hysol	30	O_2	1.6	—	—	—	—	1.00	0.875	—	69
8. Ethyl cellulose											
Ethoxy 49.5%	25	N_2	4.43	2.36	—	12.1	1.00	3.32	25.5	—	38
Cast from TDF	25	N_2	2.04	—	—	12.1	1.00	4.26	23.3	—	100
Cast from ethanol	25	N_2	1.88	—	—	13.1	1.00	4.09	25.0	—	100
Ethocel 610	30	N_2	3.30	2.32	1.49	10.8	1.00	3.40	14.4	2.27	130
9. Ethylene–vinyl acetate	30	N_2	2.8	—	—	7.50	1.00	—	—	3.93	118

10.	Hydropol (hydrogenation of emulsion butadiene)	25	N_2	4.00	2.78	—	3.95	1.00	2.83	12.1	3.25	77
11.	Hypalon (chlorosulfonated	30	O_2	3.3	—	—	—	—	1.00	5.06	—	69
	polyethylene)	23	N_2	1.16	—	12.2	8.19	1.00	2.11	1.79	—	103
12.	Methyl cellulose	23	N_2	0.174	—	—	—	1.00	2.90	15.1	—	103
13.	Nitrocellulose (Butanol 30%)	25	N_2	0.116	0.948	—	59.5	1.00	16.8	18.3	—	38
14.	Nitrosorubber	25	N_2	29.8	—	—	—	1.00	2.76	6.41	1.18	89
15.	Phenol–formaldehyde (Bakelite)	25	N_2	0.012	—	8.5	—	1.00	—	—	—	9
16.	Polyamide (nylon 6)	25	N_2	0.0246	1.98	77.2	98.8	1.00	3.77	11.5	—	55
17.	Polybutadiene											
	Butadiene rubber	25	N_2	6.45	—	6.53	—	1.00	2.96	21.4	—	5
	cis-4	25	N_2	19.6	1.09	—	1.70	1.00	—	—	—	92
18.	Poly (Butadiene–Acrylonitrile)											
	Perbunan	25	N_2	1.17	—	12.9	9.74	1.00	3.59	25.9	2.70	5
	Perbunan 18	25	N_2	2.53	—	10.0	6.72	1.00	3.24	25.1	—	3
	Vistan A	25	H_2	3.60	—	1.00	—	—	—	0.555	—	23
	Visten C	25	H_2	3.60	—	1.00	—	—	—	1.16	—	23
	Hycar OR 15	25	N_2	0.236	—	30.2	28.9	1.00	4.07	31.7	—	3
	Hycar OR 25	25	N_2	0.605	—	19.5	16.3	1.00	3.87	30.7	—	3
19.	Poly(butadiene–methyl methacrylate)	25	N_2	2.83	2.90	—	—	1.00	—	—	—	10
20.	Poly(butadiene–styrene)											
	Buna-S	25	N_2	6.32	—	6.34	1.80	1.00	2.71	19.6	3.34	5
	Ameripol 1502	25	N_2	5.41	2.50	—	4.42	1.00	—	—	—	92
	Hycar 2001	25	N_2	1.69	2.63	—	7.87	1.00	—	—	—	92
21.	Polycarbonate (Lexan)	25	N_2	0.300	2.67	40.0	33.3	1.00	4.67	26.7	—	85

(*continued*)

TABLE 1 (continued)

	Membrane barrier	Reference gas			Permeability ratio ($Q_{gas}/Q_{ref\ gas}$)							Refs.[a]
		T (°C)	Gas	$Q \times 10^{10}$	A	H_2	He	N_2	O_2	CO_2	CH_4	
22.	Polychloroprene											
	Neoprene G	25	N_2	1.17	—	11.6	—	1.00	3.38	22.0	—	5
	Neoprene	25	N_2	1.12	—	10.4	—	1.00	—	—	—	10
23.	Polydialkyl siloxane (silicone rubber)											
	Silicone rubber (S.R.)	30	N_2	150	—	—	1.54	1.00	—	—	3.93	118
	Nitrile S.R.	30	N_2	21.0	—	—	3.76	1.00	—	—	5.24	118
	Phenylene S.R.	30	N_2	40.0	—	—	3.75	1.00	—	—	5.00	118
	Silastic 500–1	25	N_2	276	2.13	2.00	1.14	1.00	2.09	13.0	—	55
	Polydimethyl siloxane	25	N_2	281	—	2.31	1.26	1.00	2.15	11.5	—	137
	Silastic RTV-501	25	N_2	274	—	—	—	1.00	2.04	10.8	—	96
24.	Poly(Dibutylmaleate–Ethylene)	25	A	1.91	1.00	—	2.23	—	—	—	1.15	75
25.	Polydimethylbutadiene (methyl rubber)	25	N_2	0.474	—	36.1	30.6	1.00	4.45	15.8	1.66	5
26.	Poly(esteramide–Diisocyanate) (Vulcaprene A)	25	N_2	0.491	—	12.8	—	1.00	3.08	37.9	—	3
27.	Polyesterurethane											
	Estane 5710	30	N_2	1.50	0.237	13.2	4.21	1.00	3.88	—	—	140
	Estane 5714	30	N_2	2.74	5.11	7.23	1.16	1.00	2.12	—	—	140
	TEXIN 4804	30	N_2	1.45	1.47	5.91	2.90	1.00	2.14	—	—	140
	ECD 651	30	N_2	6.86	2.06	4.18	2.02	1.00	2.27	—	—	140
	Adiprene-L	29	O_2	4.8	—	—	—	—	1.00	8.33	—	69
28.	Polyethylene (P.E.)											
	Density 0.918	30	N_2	1.00	2.80	8.70	5.60	1.00	5.00	13.2	3.00	70
	Density 0.928	30	N_2	0.70	2.29	8.57	5.57	1.00	2.71	11.4	2.71	70

Density 0.935	30	N_2	0.40	3.00	11.3	7.25	1.00	3.25	14.0	3.50	70
Density 0.957	30	N_2	0.40	2.75	11.0	7.25	1.00	3.25	13.3	3.00	70
Alathon 15	25	N_2	2.06	—	8.11	5.44	1.00	3.21	14.0	—	120
Alathon 14	25	N_2	0.974	2.81	—	5.06	1.00	2.97	12.9	2.97	77
Grex	25	N_2	0.143	2.53	—	7.97	1.00	2.83	11.9	3.27	77
P.E. DE-2400	25	N_2	0.800	—	9.93	6.44	1.00	3.45	14.8	—	23
P.E. DE-2500	25	N_2	0.930	—	8.82	5.97	1.00	3.29	14.2	—	23
29. Polyethylene–acrylonitrile											
Graft 0%	25	N_2	1.48	—	—	—	1.00	3.32	13.9	—	79
Graft 20.8%	25	N_2	0.687	—	—	—	1.00	3.46	15.1	—	79
Graft 31.3%	25	N_2	0.473	—	—	—	1.00	3.46	16.4	—	79
30. Poly(ethylene–propylene)											
EPR 3806	25	N_2	4.44	2.57	—	4.55	1.00	—	—	—	92
EPR 3480	25	N_2	5.87	2.61	—	5.16	1.00	—	—	—	92
EPR 3418	25	N_2	5.08	2.68	—	6.34	1.00	—	—	—	92
31. Polyethylene–styrene											
Graft 0%	25	N_2	1.48	—	—	—	1.00	3.32	13.9	—	79
Graft 4.8%	25	N_2	1.04	—	—	—	1.00	3.22	15.3	—	79
Graft 20.9%	25	N_2	0.713	—	—	—	1.00	3.60	20.2	—	79
Graft 0%	25	N_2	1.25	—	—	—	1.00	—	—	2.58	54
Graft 29.5%	25	N_2	0.442	—	—	—	1.00	—	—	3.23	54
Graft 48.2%	25	N_2	0.698	—	—	—	1.00	—	—	3.35	54
32. Polyethylene terephthalate											
Mylar	25	N_2	0.006	—	—	167	1.00	—	—	1.00	118
Mylar A	25	N_2	0.00966	—	—	—	1.00	3.89	—	—	126
Amorphous film	25	N_2	0.0144	2.06	—	206	1.00	4.42	20.9	0.660	76
Mylar	25	H_2	0.580	—	1.00	1.67	—	—	0.203	—	23
33. Polyethylenimine–polyvinylbutyral(67/33%) (Epon 834 20%)	30	N_2	0.69	—	—	—	1.00	1.00	1.22	—	121

(continued)

TABLE 1 (continued)

Membrane barrier	Reference gas			Permeability ratio ($Q_{gas}/Q_{ref\ gas}$)							Refs.[a]
	T (°C)	Gas	$Q\times10^{10}$	A	H_2	He	N_2	O_2	CO_2	CH_4	
34. Polyethylene–vinylpyridine											
Graft 0%	25	N_2	1.48	—	—	—	1.00	3.32	13.8	—	79
Graft 34%	25	N_2	0.399	—	—	—	1.00	4.26	22.1	—	79
Graft 60%	25	N_2	0.099	—	—	—	1.00	4.13	17.6	—	79
35. Polyethyl methacrylate	25	N_2	0.225	2.56	—	30.8	1.00	5.20	22.5	—	111
36. Polyformaldehyde (acetal)	30	N_2	0.17	—	—	—	1.00	17.3	86.4	—	103
37. Polymide	25	H_2	1.78	—	1.00	—	—	—	—	—	142
38. Polyisobutylene	25	N_2	0.289	—	22.3	38.8	1.00	4.08	17.3	2.51	5
39. Poly(isobutylene–isoprene) (98/2%) (butyl rubber)	25	N_2	0.325	—	22.3	25.9	1.00	4.00	15.9	—	3
40. Polyisoprene (natural rubber)											
Gutta percha	25	N_2	2.24	—	6.47	—	1.00	2.76	15.8	—	4
Polyisoprene, pure	25	N_2	7.07	—	7.06	—	1.00	—	—	—	3
Density 0.9689	25	N_2	8.68	—	5.91	3.49	1.00	2.73	15.4	3.32	5
S 1.7%	40	N_2	17.3	—	—	—	1.00	—	—	2.90	8
S 11.3%	40	N_2	1.66	—	—	—	1.00	—	—	2.17	8
Smoke sheet (Hevea)	25	A	22.9	1.00	—	—	—	1.02	6.74	1.32	77
41. Poly(isoprene–(acrylonitrile) (74/26%)	25	N_2	0.182	—	40.9	42.9	1.00	4.70	23.8	—	3
42. Poly(isoprene–methacronitrile) (74/26%)	25	N_2	0.599	—	22.7	23.7	1.00	3.94	23.7	—	3
43. Polymethyl acrylate	25	A	0.298	1.00	—	28.3	—	—	—	—	25
44. Polymethylene	25	N_2	0.124	—	—	—	1.00	—	—	—	103
45. Polymethylpentadiene	25	N_2	2.75	—	15.5	—	1.00	3.64	16.4	—	3
46. Polymethylpentene	25	N_2	8.85	—	17.9	13.4	1.00	4.21	12.4	—	137

47.	Poly-α-olefin (Ionomer 1707)	25	N_2	0.556	1.54	13.4	10.0	1.00	2.39	9.17	1.76	70
48.	Polyoxymethylene–butadiene											
	Graft 0%	25	CO_2	180	—	—	—	—	—	1.00	—	134
	Graft 2.8%	25	CO_2	510	—	—	—	—	—	1.00	—	134
49.	Poly-*p*-xylene (Parylene)	25	N_2	0.132	—	26.8	—	1.00	3.57	20.0	—	70
50.	Polyphenylene oxide	25	N_2	3.81	—	29.6	20.5	1.00	4.41	19.9	—	137
51.	Polypropylene											
	Polypropylene	25	N_2	0.219	—	27.3	28.4	1.00	4.01	13.2	—	137
	Monoaxially oriented	25	N_2	0.222	—	—	—	1.00	5.00	16.7	—	69
	Biaxially oriented	25	N_2	0.149	—	—	26.7	1.00	4.38	10.6	—	100
	Density 0.907	25	N_2	0.303	—	—	—	1.00	5.37	22.5	—	80
52.	Polystyrene	30	N_2	2.55	2.13	22.0	16.0	1.00	2.93	9.13	1.07	130
		25	N_2	7.80	—	11.6	—	1.00	3.09	4.62	—	22
		25	N_2	0.788	—	29.6	23.7	1.00	3.34	13.3	—	137
53.	Poly(styrene–acrylonitrile)	23	N_2	0.046	—	—	—	1.00	7.61	23.5	—	103
54.	Poly(styrene–methyl methacrylate)	30	N_2	0.021	—	—	—	1.00	7.62	—	—	103
55.	Polysulfide											
	Thiokol B	25	O_2	0.289	—	5.47	—	—	1.00	10.9	—	5
	Thiokol Rubber	23	O_2	7.7	—	—	—	—	1.00	1.38	—	69
56.	Polytetrafluoroethylene (Teflon TFE)	25	N_2	1.40	—	7.00	—	1.00	3.00	8.38	—	91
57.	Poly(tetrafluoroethylene–	25	N_2	1.59	—	—	—	1.00	3.08	7.99	0.544	88
	hexafluoropropylene)	25	N_2	2.21	—	—	26.0	1.00	—	—	0.534	119
	(Teflon FEP)	25	N_2	2.15	—	6.51	18.6	1.00	2.74	7.91	—	103
		25	N_2	2.37	—	—	—	1.00	—	—	0.474	39
58.	Teflon FEP–acrylonitrile											
	Graft 0%	25	N_2	2.47	—	—	—	1.00	—	—	0.474	54
	Graft 5.5%	25	N_2	1.27	—	—	—	1.00	—	—	0.458	54
	Graft 19.9%	25	N_2	0.505	—	—	—	1.00	—	—	0.382	54

(*continued*)

TABLE 1 (continued)

	Membrane barrier	Reference gas T (°C)	Reference gas Gas	Reference gas $Q\times 10^{10}$	Permeability ratio ($Q_{gas}/Q_{ref\ gas}$) A	H_2	He	N_2	O_2	CO_2	CH_4	Refs.[a]
59.	Teflon FEP–styrene											
	Graft 0%	25	N_2	2.47	—	—	—	1.00	—	—	0.474	54
	Graft 14.0%	25	N_2	1.37	—	—	—	1.00	—	—	0.421	54
	Graft 18.5%	25	N_2	1.29	—	—	—	1.00	—	—	0.410	54
60.	Polytrifluoromono	30	N_2	0.120	—	—	284	1.00	—	—	0.700	118
	chloroethylene	25	N_2	0.119	—	—	—	1.00	4.08	—	—	126
	(Trithene B)	25	CO_2	1.82	—	1.76	—	—	—	1.00	—	23
		25	CH_4	0.0348	—	131	—	—	—	—	1.00	120
61.	Polyvinyl acetate	25	A	0.153	1.00	47.4	70.6	—	2.51	—	—	72
62.	Polyvinyl alcohol	25	N_2	0.000572	1.96	12.5	90.9	1.00	3.23	3.11	—	55
63.	Polyvinyl butyral	25	N_2	2.82	—	—	—	1.00	—	—	—	18
64.	Polyvinyl chloride (PVC)	27	O_2	24.2	—	—	—	—	1.00	1.07	—	69
	Cast from TDF	25	N_2	0.086	—	—	40.8	1.00	2.98	15.1	—	100
	DOP 16.8%	25	O_2	0.640	—	—	8.19	—	1.00	4.70	—	100
	DOP 19.3%	25	O_2	0.990	—	—	6.25	—	1.00	4.31	—	100
	Pure PVC	25	CO_2	0.990	—	3.43	—	—	—	1.00	—	22
	Plasticized	30	CH_4	2.0	—	—	7.00	—	—	—	1.00	118
	Press polish	25	CO_2	35.0	—	5.29	—	—	—	1.00	—	22
65.	PVC–acetate	30	N_2	2.63	—	—	—	1.00	1.50	—	—	131
		25	N_2	0.65	—	15.2	14.1	1.00	4.00	26.00	—	23
66.	PVE–methyl acrylate	25	N_2	0.263	—	22.0	—	1.00	3.50	20.0	—	5
67.	PVC–vinylmaleate	25	CO_2	8.00	—	1.70	—	—	—	1.00	—	23
68.	PVC–vinylidene chloride (9%/3%)	25	H_2	0.785	—	1.00	—	—	—	10.8	—	22
69.	Polyvinyl fluoride	25	N_2	0.0042	—	83.3	231	1.00	4.76	21.4	1.35	103
		30	N_2	0.019	—	—	94.8	1.00	—	—	0.342	118

70.	Polyvinylidene chloride											
	Saran 925	25	O_2	0.00838	—	13.0	29.6	—	1.00	2.34	—	100
	Saran 517	25	N_2	0.000792	—	—	—	1.00	5.40	31.8	—	126
	Saran	25	N_2	0.00018	—	—	366	—	1.00	—	1.39	118
71.	Poly(vinylidene fluoride–hexafluoropropylene) (Viton A)	26	O_2	2.2	—	—	—	—	1.00	2.32	—	69
72.	Polyvinyl toluene	23	N_2	0.46	—	—	—	1.00	7.61	23.5	—	103
73.	Regenerated cellulose	25	H_2	0.0052	—	1.00	—	—	—	—	—	142
	(Cellophane)	45	He	7.97	—	—	1.00	—	—	—	—	9
74.	Rubber hydrochloride											
	Pliofilm FM-1	25	N_2	0.132	—	—	—	1.00	3.67	7.14	—	126
	Pliofilm 120-P4	25	CO_2	1.48	—	1.53	—	—	—	1.00	—	23
	Pliofilm 140-N2	25	CO_2	0.640	—	2.50	—	—	—	1.00	—	23
	Pliofilm NO	30	N_2	0.008	—	—	—	1.00	3.13	21.3	—	103
	Pliofilm	27	CO_2	8.8	—	—	—	—	0.274	1.00	—	69

[a]Other references for membranes:

No. 1: Refs. 19, 21, 31, 32, 45, 46, 47, 48, 51, 56, 67, 68, 82, 93, 110, 123, and 129.

No. 2: Refs. 33, 34, 128, 133, and 142.

No. 8: Refs. 22, 34, 99, 105, 131, and 134.

No. 16: Refs. 18, 21, 27, 33, 34, 105, 127, and 142.

No. 18: Refs. 10, 83, and 103.

No. 20: Ref. 10.

No. 21: Refs. 27 and 69.

No. 22: Refs. 83 and 103.

No. 23: Refs. 6, 7, 11, 12, 14, 19, 49, 66, 69, 86, 96, 100, and 124.

No. 28: Refs. 2, 15, 16, 17, 21, 22, 27, 28, 33, 34, 35, 36, 57, 58, 59, 60, 61, 62, 63, 65, 69, 74, 75, 78, 80, 86, 90, 95, 100, 101, 103, 104, 108, 109, 112, 113, 115, 116, 122, 126, 127, 128, 131, and 137.

No. 29: Refs. 54 and 80.

No. 31: Refs. 40 and 80.

(*continued*)

TABLE 1 (continued)

No. 32: Refs. 69, 122, 134, and 142.
No. 39: Refs. 8, 83, and 103.
No. 40: Refs. 1, 9, 10, 13, 83, 112, and 141.
No. 46: Ref. 102.
No. 48: Ref. 135.
No. 49: Ref. 142.
No. 50: Ref. 138.
No. 51: Refs. 18 and 127.
No. 52: Refs. 28, 69, 86, 128, 132, and 142.
No. 56: Refs. 17, 39, and 119.
No. 57: Refs. 17 and 54.
No. 62: Ref. 33.
No. 63: Refs. 18, 33, and 34.
No. 64: Refs. 23, 28, 127, 135, 137, and 142.
No. 65: Refs. 22 and 28.
No. 68: Ref. 27.
No. 69: Refs. 141 and 142.
No. 70: Refs. 28, 34, 81, 107, and 128.
No. 71: Ref. 103.
No. 73: Refs. 9, 33, 81, 94, and 142.
No. 74: Refs. 28, 33, and 34.
General References: 20, 24, 29, 30, 37, 50, 52, 53. 64, 71, 73, 84, 97, 98, 106, 114, 117, 125, and 126.

A is the total area of membrane; P_H is the upstream pressure, that is, high pressure; P_L is the downstream, or low, pressure; l is the thickness of membrane; and Q is the permeability or mass transfer coefficient.

The results of a comprehensive literature review on permeabilities of various polymer membranes are compiled in Table 1.

WATER VAPOR TRANSMISSION DATA

Actually, a comprehensive presentation of water vapor transmission data would also require a very elaborate treatise so as to demonstrate the simultaneous effects of temperatures and varying relative humidity conditions. An extensive compilation of literature values is presented in Table 2. If temperature and relative humidity were to be considered for presentation, the required amount of information would become unmanageable.

A recent publication by Hadge et al. (*143*) describes a method to obtain water vapor permeability for thick sections, up to 1/4 in. thickness, and this work is the only one that has attempted such determinations. The paper contains data for ten polymers and should be consulted when thicknesses greater than about 50 mils are encountered. It is significant to note that Hadge's values are appreciably lower than data reported for thin films; see, for instance, the listings for silicone rubber. Past experience indicates that the low values may be due to insufficient time to allow the thick specimens to come to equilibrium.

TABLE 2

Water Vapor Permeation[a]

Membrane	Temp (°C)	%RH[b]	$Q \times 10^{10}$	Ref.
Cellulose acetate	25	40–100	4790– 6000	33
	23	—	7730– 8440	58
Cellulose acetate–polystyrene				
Graft 0%	25	0–80	11000–22600	132
Graft 18.2%	25	0–80	6400–15700	132
Graft 44.1%	25	0–80	5900–13900	132
Graft 100%	25	0–100	1040–1100	132
Cellulose triacetate	25	20–80	12700	26
Chlorotrifluoroethylene (Halon)	38	100	3.62	143
Diallyphthalate	38	100	116	143
Epoxy	25	NR	14800	86
Epiall 1970	38	100	82.2	143

(*continued*)

TABLE 2 (continued)

Membrane	Temp (°C)	%RH[b]	$Q \times 10^{10}$	Ref.
Ethyl cellulose	25	0–50	22000	133
	25	20–100	15800–19900	105
	25	95	8930	38
Ethyl cellulose–nylon 6 (composite)	25	20–100	923–5000	105
Ethylene–chlorotrifluoroethylene (Halar)	60	100	14.8	143
Nylon 6–ethyl cellulose (composite)	25	20–100	1430–15600	105
Phenolic (Phenall 8700)	60	100	14.7	143
Polyamide (nylon 6)	25	20–100	417–5040	105
	25	NR	940	86
	23	NR	480–770	58
Polycarbonate (Lexan)	25	NR	1400	85
Polydialkylsiloxane (silicone rubber)				
Silicone	38	100	1119	143
Silastic Medical Grade	25	NR	18300	86
Dimethylsiloxane	25	NR	72000	11
Dimethylmethylphenylsiloxane	25	NR	41100	11
Trifluoropropylsiloxane	25	NR	21400	11
Polyethylene				
Calendered	25	NR	61.0	28
Cast	25	NR	42.4	28
Density 0.922	25	NR	88.8	80
Density 0.91–0.95	25	NR	33.5–16.9	57
Density 0.915	25	NR	113	86
Density 0.935	25	NR	93.5	86
Density 0.960	25	NR	55.8	86
Density 0.913–0.933	23	NR	318–163	58
Polyethylene–acrylonitrile				
Graft 0%	25	20–100	106	79
Graft 20.8%	25	20–100	160	79
Polyethylene–styrene, graft 20.9%	25	20–100	190	79
Polyethylene–vinyl pyridine, graft 34%	25	20–80	7740–13200	79
Polyethylene terephthalate	25	10–90	151	122
Polyethyl methacrylate	25	20	3180	111
Polyisoprene (natural rubber)	25	20–40	2290	26
Polyoxymethylene–acrylonitrile				
Graft 0%	25	0–100	910–1390	134
Graft 2.4%	25	0–100	705–1220	134
Graft 7.1%	25	0–100	190–314	134
Polyoxymethylene–butadiene				
Graft 0%	25	0–100	910–1390	134
Graft 2.8%	25	0–100	1330–1810	134
Graft 10.8%	25	0–100	1780–2410	134
Polyphenylene oxide	25	85	4100	138

(*continued*)

TABLE 2 (continued)

Membrane	Temp (°C)	%RH[b]	$Q \times 10^{10}$	Ref.
Polypropylene	23	—	130–190	58
	25	84–96	47.4	80
	30	0–100	8.96–22.6	127
Polystyrene	25	NR	650	86
	25	NR	835–895	28
Polystyrene–ethyl acrylate				
No emulsifier	25	20–80	2700–3300	139
5% emulsifier	25	20–84	2900–3300	139
Polytetrafluoroethylene (Halon G-183)	38	100	8.45	143
Polyvinyl alcohol	25	40–100	9.03–4190	33
Polyvinyl butyral	25	40–100	811	33
Polyvinyl chloride	25	NR	116–123	28
	25	0–100	280	135
	30	0–100	7.78–16.1	127
Polyvinyl fluoride	38	100	34.0	143
Poly(vinyl chloride–acetate)	25	NR	288–325	28
Polyvinylidene chloride	25	NR	2.00	28
Poly(vinylidene chloride–acrylonitrile)	25	40–100	7.18	33
Regenerated cellulose	25	40–100	989–8140	33
Rubber hydrochloride	25	—	12.4	28

[a]Reference *26* contains additional information.
[b]NR means not specified.

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