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APPENDICES

Appendix A The calculation of the permeability and selectivity.

$$P_i = \frac{V_i \times 14.7 \times 273.15 \times l}{t \times A \times 76 \times (273.15 + T) \times \Delta P}$$

where

- P_i = permeability of component i (cm^3 (STP). cm/cm^2 .s.cmHg)
- V_i = volume of component i measured using bubble flow meter (cm^3)
- l = membrane thickness (cm)
- t = time for component passing to desired volume of bubble flow meter (s)
- A = area of membrane (cm^2)
- T = experiment temperature ($^{\circ}\text{C}$)
- ΔP = pressure different across membrane (psi)

$$S_{i/j} = \frac{P_i}{P_j}$$

$S_{i/j}$ = ideal selectivity

Appendix B The experimental flow rate of nitrogen (N_2), propane (C_3H_8), and propylene (C_3H_6) of mixed matrix membranes without modification surface of zeolite at pressure around 50 psia.

Table B1 Ultem membrane

Membrane thickness 0.00436 cm

Gas	P (psia)	Vol. (ml.)	time (sec)	Flow rate (ml./sec)	Average flow rate	Permeability (cm ³ (STP).cm/cm ² .sec.cmHg)	Average Permeability	STDEV of Permeability
N ₂	51	0.1	2923.68	3.420E-05	3.431E-05	1.192E-11	1.196E-11	3.265E-14
			2912.93	3.433E-05		1.197E-11		
			2908.12	3.439E-05		1.199E-11		
C ₃ H ₆	52	0.1	5113.31	1.956E-05	1.941E-05	6.686E-12	6.723E-12	1.979E-13
			5325.11	1.878E-05		6.546E-12		
			5025.23	1.990E-05		6.937E-12		
C ₃ H ₈	56	0.1	21720.81	4.604E-06	4.604E-06	1.462E-12	1.462E-12	1.226E-14
	54	0.1	21466.23	4.658E-06		4.658E-06		

$$\frac{C_3H_6}{C_3H_8} \text{ selectivity} = 4.60$$

Table B2 10%wt Silicalite-Ultem MMM

Membrane thickness 0.00436 cm

Gas	P (psia)	Vol. (ml.)	time (sec)	Flow rate (ml./sec)	Average flow rate	Permeability (cm ³ (STP).cm/cm ² .sec.cmHg)	Average Permeability	STDEV of Permeability
N ₂	52	0.1	1970.16	5.076E-05	5.171E-05	1.735E-11	1.768E-11	3.165E-13
			1900.93	5.261E-05		1.798E-11		
			1931.66	5.177E-05		1.770E-11		
C ₃ H ₆	50	0.1	4908.55	2.037E-05	2.047E-05	7.244E-12	7.278E-12	1.079E-13
			4805.33	2.081E-05		7.399E-12		
			4943.91	2.023E-05		7.192E-12		
C ₃ H ₈	50	0.1	4961.21	2.016E-05	2.003E-05	7.167E-12	7.121E-12	8.313E-14
			5043.95	1.983E-05		7.049E-12		
			4975.64	2.010E-05		7.146E-12		

$$\frac{C_3H_6}{C_3H_8} \text{ selectivity} = 1.02$$

Table B3 20%wt Silicalite-Ultem MMM

Membrane thickness 0.00496 cm

Gas	P (psia)	Vol. (ml.)	time (sec)	Flow rate (ml./sec)	Average flow rate	Permeability (cm ³ (STP).cm/cm ² .sec.cmHg)	Average Permeability	STDEV of Permeability
N ₂	52	0.1	2090.16	4.784E-05	4.775E-05	1.861E-11	1.857E-11	6.254E-14
			2102.43	4.756E-05		1.850E-11		
			2090.22	4.784E-05		1.861E-11		
C ₃ H ₆	50	0.1	4873.06	2.052E-05	2.000E-05	8.300E-12	8.134E-12	1.736E-13
			5085.33	1.966E-05		7.954E-12		
			4965.39	2.014E-05		8.146E-12		
	52	0.1	5086.13	1.966E-05	1.944E-05	7.647E-12	7.563E-12	1.020E-13
			5123.11	1.952E-05		7.592E-12		
			5221.12	1.915E-05		7.449E-12		
C ₃ H ₈	52	0.1	4527.58	2.209E-05	2.179E-05	8.590E-12	8.475E-12	1.882E-13
			4672.32	2.140E-05		8.324E-12		
			4570.00	2.188E-05		8.510E-12		

$$\frac{C_3H_6}{C_3H_8} \text{ selectivity} = 0.96$$

Table B4 30%wt Silicalite-Ultem MMM

Membrane thickness 0.0041 cm

Gas	P (psia)	Vol. (ml.)	time (sec)	Flow rate (ml./sec)	Average flow rate	Permeability (cm ³ (STP).cm/cm ² .sec.cmHg)	Average Permeability	STDEV of Permeability
N ₂	52	0.1	1377.42	7.260E-05	7.503E-05	2.334E-11	2.412E-11	7.577E-13
			1293.56	7.731E-05		2.485E-11		
			1330.18	7.518E-05		2.417E-11		
C ₃ H ₆	50	0.1	1945.63	5.140E-05	5.159E-05	1.718E-11	1.725E-11	8.991E-14
			1931.34	5.178E-05		1.731E-11		
	50	0.1	1855.13	5.390E-05	4.763E+02	1.802E-11	1.847E-11	5.200E-13
			1756.23	5.694E-05		1.904E-11		
			1823.66	5.483E-05		1.833E-11		
C ₃ H ₈	48	0.1	2483.22	4.027E-05	4.075E-05	1.403E-11	1.419E-11	2.385E-13
			2424.90	4.124E-05		1.436E-11		
			2455.11	4.073E-05		1.419E-11		

$$\frac{C_3H_6}{C_3H_8} \text{ selectivity} = 1.26$$

Table B5 10%wt NaX-Ultem MMM

Membrane thickness 0.0042 cm

Gas	P (psia)	Vol. (ml.)	time (sec)	Flow rate (ml./sec)	Average flow rate	Permeability (cm ³ (STP).cm/cm ² .sec.cmHg)	Average Permeability	STDEV of Permeability
N ₂	50	1	7391.07	1.353E-04	1.345E-04	4.634E-11	4.608E-11	1.788E-13
			7445.69	1.343E-04		4.600E-11		
			7436.66	1.345E-04		4.606E-11		
			7456.44	1.341E-04		4.593E-11		
C ₃ H ₆	52	0.1	2195.28	4.555E-05	4.590E-05	1.500E-11	1.512E-11	2.293E-13
			2200.55	4.544E-05		1.497E-11		
			2141.33	4.670E-05		1.538E-11		
C ₃ H ₈	50	0.1	10589.67	9.443E-06	9.488E-06	3.234E-12	3.250E-12	2.804E-14
			10594.11	9.439E-06		3.233E-12		
			10435.23	9.583E-06		3.282E-12		

$$\frac{C_3H_6}{C_3H_8} \text{ selectivity} = 4.65$$

Table B6 20%wt NaX-Ultem MMM

Membrane thickness 0.00641 cm

Gas	P (psia)	Vol. (ml.)	time (sec)	Flow rate (ml./sec)	Average flow rate	Permeability (cm ³ (STP).cm/cm ² .sec.cmHg)	Average Permeability	STDEV of Permeability
N ₂	52	0.1	652.11	1.533E-04	1.531E-04	7.708E-11	7.698E-11	1.342E-13
			654.26	1.528E-04		7.682E-11		
			652.53	1.532E-04		7.703E-11		
C ₃ H ₆	50	0.1	1333.57	7.499E-05	7.413E-05	3.920E-11	3.875E-11	1.289E-12
			1314.95	7.605E-05		3.975E-11		
			1401.59	7.135E-05		3.730E-11		
C ₃ H ₈	52	0.1	5745.63	1.740E-05	1.747E-05	8.748E-12	8.780E-12	2.574E-15
			5743.24	1.741E-05		8.752E-12		
			5685.33	1.759E-05		8.841E-12		

$$\frac{C_3H_6}{C_3H_8} \text{ selectivity} = 4.41$$

Table B7 30%wt NaX-Ultem MMM

Membrane thickness 0.00768 cm

Gas	P (psia)	Vol. (ml.)	time (sec)	Flow rate (ml./sec)	Average flow rate	Permeability (cm ³ (STP).cm/cm ² .sec.cmHg)	Average Permeability	STDEV of Permeability
N ₂	52	0.1	700.41	1.428E-04	1.426E-04	8.598E-11	8.588E-11	1.206E-13
			702.31	1.424E-04		8.575E-11		
			700.91	1.427E-04		8.592E-11		
C ₃ H ₆	52	0.1	1534.25	6.518E-05	6.628E-05	3.925E-11	3.992E-11	7.185E-13
			1480.42	6.755E-05		4.068E-11		
			1512.34	6.612E-05		3.982E-11		
C ₃ H ₈	50	0.1	6802.32	1.470E-05	1.456E-05	9.207E-12	9.116E-12	1.283E-13
			6939.11	1.441E-05		9.026E-12		

$$\frac{C_3H_6}{C_3H_8} \text{ selectivity} = 4.38$$

Table B8 10%wt AgX-Ultem MMM

Membrane thickness 0.00421 cm

Gas	P (psia)	Vol. (ml.)	time (sec)	Flow rate (ml./sec)	Average flow rate	Permeability (cm ³ (STP).cm/cm ² .sec.cmHg)	Average Permeability	STDEV of Permeability
N ₂	52	0.1	1095.44	9.129E-05	9.118E-05	3.014E-11	3.010E-11	5.065E-14
			1098.05	9.107E-05		3.006E-11		
			1096.25	9.122E-05		3.011E-11		
C ₃ H ₆	50	0.1	2610.21	3.831E-05	3.833E-05	1.315E-11	1.316E-11	1.077E-14
			2607.19	3.836E-05		1.317E-11		
C ₃ H ₈	52	0.1	7556.41	1.323E-05	1.310E-05	4.369E-12	4.324E-12	6.393E-14
			7716.10	1.296E-05		4.278E-12		

$$\frac{C_3H_6}{C_3H_8} \text{ selectivity} = 3.04$$

Table B9 20%wt AgX-Ultem MMM

Membrane thickness 0.0028 cm

Gas	P (psia)	Vol. (ml.)	time (sec)	Flow rate (ml./sec)	Average flow rate	Permeability (cm ³ (STP).cm/cm ² .sec.cmHg)	Average Permeability	STDEV of Permeability
N ₂	51	0.1	641.55	1.559E-04	1.555E-04	3.489E-11	3.482E-11	7.521E-14
			644.32	1.552E-04		3.474E-11		
			643.11	1.555E-04		3.481E-11		
C ₃ H ₆	50	0.1	1601.44	6.244E-05	4.027E-01	1.426E-11	1.424E-11	2.265E-14
			1603.10	6.238E-05		1.424E-11		
			1606.45	6.225E-05		1.421E-11		
C ₃ H ₈	50	0.1	4861.02	2.057E-05	2.049E-05	4.697E-12	4.678E-12	2.722E-14
			4901.19	2.040E-05		4.659E-12		

$$\frac{C_3H_6}{C_3H_8} \text{ selectivity} = 3.04$$

Table B10 30%wt AgX-Ultem MMM

Membrane thickness 0.0032 cm

Gas	P (psia)	Vol. (ml.)	time (sec)	Flow rate (ml./sec)	Average flow rate	Permeability (cm ³ (STP).cm/cm ² .sec.cmHg)	Average Permeability	STDEV of Permeability
N ₂	50	0.1	660.42	1.514E-04	1.512E-04	3.951E-11	3.945E-11	6.013E-14
			662.43	1.510E-04		3.939E-11		
			661.56	1.512E-04		3.945E-11		
C ₃ H ₆	50	0.1	1738.52	5.752E-05	5.757E-05	1.501E-11	1.502E-11	1.974E-14
			1734.52	5.765E-05		1.505E-11		
			1738.42	5.752E-05		1.501E-11		
C ₃ H ₈	52	0.1	4832.11	2.069E-05	1.998E-05	5.193E-12	5.013E-12	2.540E-13
			5191.28	1.926E-05		4.834E-12		

$$\frac{C_3H_6}{C_3H_8} \text{ selectivity} = 3.00$$

Appendix C The experimental flow rate of nitrogen (N₂), propane (C₃H₈), and propylene (C₃H₆) of mixed matrix membranes with modification surface of zeolite at pressure around 50 psia.

Table C1 10%wt Modified Silicalite-Ultem MMM

Membrane thickness 0.00315 cm

Gas	P (psia)	Vol. (ml.)	time (sec)	Flow rate (ml./sec)	Average flow rate	Permeability (cm ³ (STP).cm/cm ² .sec.cmHg)	Average Permeability	STDEV of Permeability
N ₂	50	0.1	2150.16	4.651E-05	4.686E-05	1.195E-11	1.204E-11	1.138E-13
			2140.93	4.671E-05		1.200E-11		
			2111.66	4.736E-05		1.216E-11		
C ₃ H ₆	50	0.1	4004.56	2.497E-05	2.598E-05	6.415E-12	6.673E-12	3.656E-13
			3705.89	2.698E-05		6.932E-12		
C ₃ H ₈	50	0.1	4351.48	2.298E-05	2.254E-05	5.903E-12	5.790E-12	1.606E-13
			4525.63	2.210E-05		5.676E-12		

$$\frac{C_3H_6}{C_3H_8} \text{ selectivity} = 1.15$$

Table C2 20%wt Modified Silicalite-Ultem MMM

Membrane thickness 0.00394 cm

Gas	P (psia)	Vol. (ml.)	time (sec)	Flow rate (ml./sec)	Average flow rate	Permeability (cm ³ (STP).cm/cm ² .sec.cmHg)	Average Permeability	STDEV of Permeability
N ₂	52	0.1	1712.72	5.839E-05	5.837E-05	1.804E-11	1.803E-11	1.825E-14
			1715.12	5.830E-05		1.801E-11		
			1711.75	5.842E-05		1.805E-11		
C ₃ H ₆	52	0.1	4120.56	2.427E-05	2.493E-05	7.498E-12	7.701E-12	2.873E-13
			3908.77	2.558E-05		7.904E-12		
C ₃ H ₈	48	0.1	6083.44	1.644E-05	1.614E-05	5.502E-12	5.402E-12	1.417E-13
			6313.45	1.584E-05		5.301E-12		

$$\frac{C_3H_6}{C_3H_8} \text{ selectivity} = 1.43$$

Table C3 30%wt Modified Silicalite-Ultem MMM

Membrane thickness 0.00381 cm

Gas	P (psia)	Vol. (ml.)	time (sec)	Flow rate (ml./sec)	Average flow rate	Permeability (cm ³ (STP).cm/cm ² .sec.cmHg)	Average Permeability	STDEV of Permeability
N ₂	50	0.1	1408.53	7.100E-05	7.102E-05	2.206E-11	2.207E-11	3.731E-14
			1405.44	7.115E-05		2.211E-11		
			1410.12	7.092E-05		2.203E-11		
C ₃ H ₆	52	0.1	3386.49	2.953E-05	2.884E-05	8.822E-12	8.616E-12	2.912E-13
			3552.33	2.815E-05		8.410E-12		
C ₃ H ₈	48	0.1	4456.25	2.244E-05	2.185E-05	7.263E-12	7.071E-12	2.706E-13
			4704.13	2.126E-05		6.880E-12		

$$\frac{C_3H_6}{C_3H_8} \text{ selectivity} = 1.22$$

Table C4 10%wt Modified NaX-Ultem MMM

Membrane thickness 0.00405 cm

Gas	P (psia)	Vol. (ml.)	time (sec)	Flow rate (ml./sec)	Average flow rate	Permeability (cm ³ (STP).cm/cm ² .sec.cmHg)	Average Permeability	STDEV of Permeability
N ₂	50	0.1	1215.23	8.229E-05	8.220E-05	2.718E-11	2.715E-11	3.802E-14
			1218.45	8.207E-05		2.711E-11		
			1215.87	8.225E-05		2.716E-11		
C ₃ H ₆	52	0.1	2423.25	4.127E-05	3.998E-05	1.311E-11	1.270E-11	4.606E-13
			2603.56	3.841E-05		1.220E-11		
			2483.36	4.027E-05		1.279E-11		
C ₃ H ₈	50	0.1	10940.78	9.140E-06	8.985E-06	3.019E-12	2.968E-12	7.244E-14
			11325.12	8.830E-06		2.916E-12		

$$\frac{C_3H_6}{C_3H_8} \text{ selectivity} = 4.28$$

Table C5 20%wt Modified NaX-Ultem MMM

Membrane thickness 0.00441 cm

Gas	P (psia)	Vol. (ml.)	time (sec)	Flow rate (ml./sec)	Average flow rate	Permeability (cm ³ (STP).cm/cm ² .sec.cmHg)	Average Permeability	STDEV of Permeability
N ₂	52	0.1	892.13	1.121E-04	1.120E-04	3.876E-11	3.872E-11	4.906E-14
			894.26	1.118E-04		3.867E-11		
			892.53	1.120E-04		3.874E-11		
C ₃ H ₆	50	0.1	1812.23	5.518E-05	5.642E-05	1.984E-11	2.029E-11	9.668E-13
			1832.12	5.458E-05		1.963E-11		
			1680.44	5.951E-05		2.140E-11		
C ₃ H ₈	52	0.1	7920.23	1.263E-05	1.243E-05	4.366E-12	4.299E-12	9.525E-14
			8172.38	1.224E-05		4.231E-12		

$$\frac{C_3H_6}{C_3H_8} \text{ selectivity} = 4.72$$

Table C6 30%wt Modified NaX-Ultem MMM

Membrane thickness 0.00425 cm

Gas	P (psia)	Vol. (ml.)	time (sec)	Flow rate (ml./sec)	Average flow rate	Permeability (cm ³ (STP).cm/cm ² .sec.cmHg)	Average Permeability	STDEV of Permeability
N ₂	52	0.1	730.41	1.369E-04	1.368E-04	4.563E-11	4.558E-11	6.135E-14
			732.31	1.366E-04		4.551E-11		
			730.91	1.368E-04		4.559E-11		
C ₃ H ₆	50	0.1	1532.11	6.527E-05	6.422E-05	2.262E-11	2.226E-11	8.989E-13
			1512.45	6.612E-05		2.292E-11		
			1632.33	6.126E-05		2.123E-11		
C ₃ H ₈	50	0.1	7015.63	1.425E-05	1.416E-05	4.940E-12	4.907E-12	4.739E-14
			7112.12	1.406E-05		4.873E-12		

$$\frac{C_3H_6}{C_3H_8} \text{ selectivity} = 4.54$$

Table C7 10%wt Modified AgX-Ultem MMM

Membrane thickness 0.00415 cm

Gas	P (psia)	Vol. (ml.)	time (sec)	Flow rate (ml./sec)	Average flow rate	Permeability (cm ³ (STP).cm/cm ² .sec.cmHg)	Average Permeability	STDEV of Permeability
N ₂	52	0.1	1216.94	8.217E-05	8.021E-05	2.674E-11	2.610E-11	9.041E-13
			1278.05	7.824E-05		2.546E-11		
			1274.32	7.847E-05		2.554E-11		
C ₃ H ₆	50	0.1	4500.32	2.222E-05	2.285E-05	7.520E-12	7.734E-12	3.028E-13
			4257.86	2.349E-05		7.948E-12		
C ₃ H ₈	52	0.1	10505.48	9.519E-06	9.692E-06	3.098E-12	3.154E-12	7.964E-14
			10136.92	9.865E-06		3.210E-12		

$$\frac{C_3H_6}{C_3H_8} \text{ selectivity} = 2.45$$

Table C8 20%wt Modified AgX-Ultem MMM

Membrane thickness 0.0027 cm

Gas	P (psia)	Vol. (ml.)	time (sec)	Flow rate (ml./sec)	Average flow rate	Permeability (cm ³ (STP).cm/cm ² .sec.cmHg)	Average Permeability	STDEV of Permeability
N ₂	51	0.1	724.12	1.381E-04	1.345E-04	2.981E-11	2.903E-11	1.371E-12
			786.55	1.271E-04		2.744E-11		
			723.69	1.382E-04		2.983E-11		
C ₃ H ₆	50	0.1	2424.36	4.125E-05	4.041E-05	9.082E-12	8.898E-12	3.591E-13
			2595.26	3.853E-05		8.484E-12		
			2412.32	4.145E-05		9.127E-12		
C ₃ H ₈	50	0.1	7179.65	1.393E-05	1.434E-05	3.067E-12	3.157E-12	1.277E-13
			6780.48	1.475E-05		3.247E-12		

$$\frac{C_3H_6}{C_3H_8} \text{ selectivity} = 2.82$$

Table C9 30%wt Modified AgX-Ultem MMM

Membrane thickness 0.0030 cm

Gas	P (psia)	Vol. (ml.)	time (sec)	Flow rate (ml./sec)	Average flow rate	Permeability (cm ³ (STP).cm/cm ² .sec.cmHg)	Average Permeability	STDEV of Permeability
N ₂	50	0.1	640.40	1.562E-04	1.475E-04	3.820E-11	3.607E-11	3.376E-12
			646.56	1.547E-04		3.784E-11		
			760.23	1.315E-04		3.218E-11		
C ₃ H ₆	50	0.1	2452.34	4.078E-05	3.998E-05	9.976E-12	9.782E-12	3.265E-13
			2601.32	3.844E-05		9.405E-12		
			2455.23	4.073E-05		9.964E-12		
C ₃ H ₈	52	0.1	6920.66	1.445E-05	1.415E-05	3.399E-12	3.329E-12	9.897E-14
			7217.86	1.385E-05		3.259E-12		

$$\frac{C_3H_6}{C_3H_8} \text{ selectivity} = 2.94$$

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