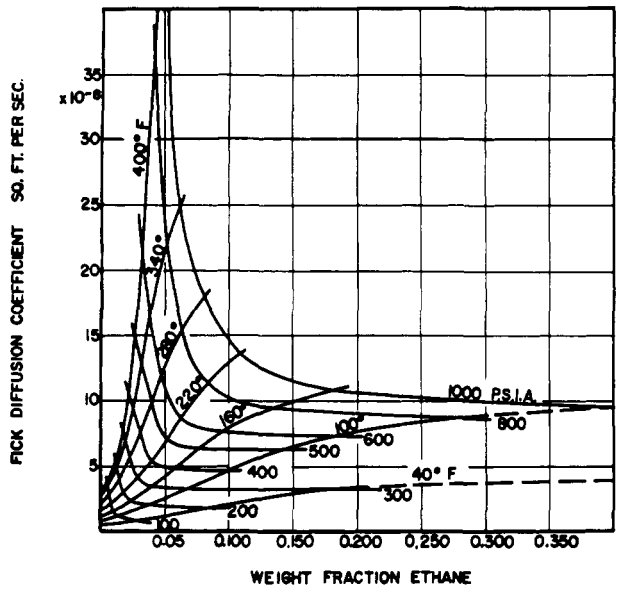

Figure 5. Effect of weight Fraction ethane upon Fick diffusion coefficient

obtain the same precision of measurement in the study with ethane as in corresponding studies with methane (*8–11*). Large changes in the Fick diffusion constant with state contributed materially to the difficulty.

The influence of the weight fraction ethane upon the Fick diffusion coefficient is shown on Figure 5. Marked increase in this coefficient at the higher pressures and temperatures is evident. Table IV records smoothed values of the Fick diffusion coefficient as a function of pressure and temperature in the ethane–white oil system.

Experimental data concerning the Fick diffusion coefficient of ethane in binary hydrocarbon systems are insufficient at this time to justify any attempt to relate the diffusion coefficient to the characteristics of the less volatile component. However, additional information upon the molecular transport characteristics of ethane should make this possible, as has been done for methane (*10*).

ACKNOWLEDGMENT

The assistance of John Lower in connection with the experimental work is acknowledged. Virginia Berry carried out the calculations associated with resolution of the data, and B. Lawson Miller contributed to the preparation of the manuscript.

NOMENCLATURE

$D_{F,k}$ = Fick diffusion coefficient of component k, sq. ft./sec.
m_k = weight of component k added per unit area of interface, lb./sq. ft.
$\underline{m}_k$ = total weight of component k crossing the interface, lb.
$\overline{V}_k$ = partial specific volume of component k, cu. ft./lb.
Δ = difference in
θ = time, sec.
σ_k = concentration of component k in the liquid phase, lb./cu. ft.

Superscript

* = average condition

Subscripts

e = conditions at equilibrium
g = gas phase
i = conditions at interface
j = component j, the stagnant component
k = component k, the diffusing component
l = liquid phase
0 = initial conditions

LITERATURE CITED

(1) Bertram, E.A., Lacey, W.N., *Ind. Eng. Chem.* **28**, 316 (1936).
(2) Bridgeman, O.C., *J. Am. Chem. Soc.* **49**, 1174 (1927).
(3) Hill, E.S., Lacey, W.N., *Ind. Eng. Chem.* **26**, 1324 (1934).
(4) *Ibid.*, p. 1327.
(5) Kirkwood, J.G., Crawford, B., Jr., *J. Phys. Chem.* **56**, 1048 (1952).
(6) Meyers, C.H., *Bur. Standards J. Research* **9**, 807 (1932).
(7) Pomeroy, R.D., Lacey, W.N., Scudder, N.F., Stapp, F.P., *Ind. Eng. Chem.* **25**, 1014 (1933).
(8) Reamer, H.H., Opfell, J.B., Sage, B.H., *Ibid.*, **48**, 275 (1956).
(9) Reamer, H.H., Sage, B.H., *A.I.Ch.E. Journal* **3**, 449 (1957).
(10) Reamer, H.H., Sage, B.H., J. CHEM. ENG. DATA **4**, 15 (1959).
(11) *Ibid.*, p. 296.
(12) Reamer, H.H., Sage, B.H., *Rev. Sci. Instr.* **29**, 709 (1958).
(13) Sage, B.H., Davies, J.A., Sherborne, J.E., Lacey, W.N., *Ind. Eng. Chem.* **28**, 1328 (1936).
(14) Sage, B.H., Hicks, B.L., Lacey, W.N., *Drilling and Production Practice* **1938**, 402.
(15) Schrage, R.W., "Theoretical Study of Interphase Mass Transfer," Columbia University Press, New York, 1953.

RECEIVED for review January 4, 1960. Accepted November 30, 1960. Contribution from Project 37, American Petroleum Institute, at California Institute of Technology.

Partial Volumetric Behavior in Hydrocarbon Systems

Ethane and *n*-Pentane in the Liquid Phase of the Ethane–*n*-Pentane System

H. H. REAMER, VIRGINIA BERRY, and B. H. SAGE
Chemical Engineering Laboratory, California Institute of Technology, Pasadena, Calif.

RECENTLY, the volumetric and phase behavior of the ethane–*n*-pentane system was investigated (*3*). In addition, the phase behavior of the methane-ethane–*n*-pentane system has been studied over a limited range of temperatures (*1*). On the basis of the foregoing data, with primary reference to the recent study of the volumetric behavior of the the ethane–*n*-pentane system (*3*), the values of the partial volumes of ethane and *n*-pentane were evaluated.

The partial molal volume (hereafter referred to as the partial volume) is defined by the equation,

$$\overline{V} = \left(\frac{\partial \underline{V}}{\partial \underline{m}_k}\right)_{T,P,m_j} \qquad (1)$$

Articles from these laboratories on partial volume have been published in *Drilling and Production Practice* pp. 402–20 (1939), and pp. 641–652 (1940); *California Oil World* **34**, 31 (1941); and in the *Journal of Chemical and Engineering Data* **4**, 98, 204 (1959).

Molal volumes of the ethane–*n*-pentane system (3) were smoothed with respect to pressure, temperature, and composition. From large-scale plots of the isobaric-isothermal variation in the molal volume with respect to composition, the partial volumes of ethane and *n*-pentane at mole fractions greater than 0.4 were determined by application of the following expression

$$\overline{V}_k = V + (1 - n_k)\left(\frac{\partial V}{\partial n_k}\right)_{T,P} \quad (2)$$

At mole fractions less than 0.4, the partial volumes were established from the relation

$$\overline{V}_k = \frac{V - n_j\overline{V}_j}{n_k} \quad (3)$$

Values of the partial volume of ethane and *n*-pentane obtained by the application of Equations 2 and 3 were smoothed with respect to pressure, temperature, and composition. After smoothing, the thermodynamic consistency was determined by use of the Gibbs-Duhem (2) equation, written for partial volumes as

$$n_k\left(\frac{\partial \overline{V}_k}{\partial n_k}\right)_{T,P} = n_j\left(\frac{\partial \overline{V}_j}{\partial n_j}\right)_{T,P} \quad (4)$$

An alternative method of calculating the partial volume, based on an integrated form of Equation 4, was used in a limited number of regions of composition, temperature, and pressure.

$$\overline{V}_k = V_k^\circ - \int_0^{1-n_k} \left(\frac{n_j}{n_k}\right)\left(\frac{\partial \overline{V}_j}{\partial n_j}\right)_{T,P} dn_j \quad (5)$$

As an example of the consistency of the partial volumes as calculated by the above-described methods, there are presented in Table I values of the partial volume of ethane and *n*-pentane as determined by application of Equations 2 and 3, and those obtained from Equation 5. The former values are identified as graphical, the latter, as integrated. The standard deviation between the values arrived at by direct graphical operations and those obtained by integration has been indicated for each state. For the system as a whole, the standard error of estimate was 0.002 cubic foot per pound mole, which corresponds to approximately 0.2% deviation. It is believed that the information presented in Table I is a reasonable evaluation of the thermodynamic consistency of the data presented.

The corresponding values of the partial molal volume of ethane and *n*-pentane (Tables II and III) do not include measurements in the gaseous region. The extent of the volumetric measurements in this region did not appear sufficient to justify attempts to evaluate the partial volume.

In Tables II and III the number of significant figures has been decreased from 4 to 3 at the smaller mole fractions of each of the components. This results from the inevitably larger uncertainties in the evaluation of the partial quantities in the regions of small mole fractions.

A large number of diagrams can be prepared from the information recorded in Tables II and III, but only a few illustrative examples are presented here. Figures 1 and 2 show a regular decrease in the partial volume as the mole fraction of each component is decreased. This behavior is typical of that encountered in hydrocarbon systems.

Figures 3 and 4, as would be expected, indicate a progressive decrease in the partial volume with an increase in pressure and a regular increase in the partial molal volume with an increase in temperature. Upon approach to the critical state of the mixture for a composition corresponding to 0.7 mole fraction of the component, there is a rapid change in the partial volume with change in state. The effect of pressure upon the partial molal volume of both components is small at the lower temperatures but increases significantly as the temperature is increased.

ACKNOWLEDGMENT

This work was carried out as a part of the activities of the American Petroleum Institute Research Project 37 located in the Chemical Engineering Laboratory at the California Institute of Technology. Janet Chapple assisted in carrying out many of the calculations reported here and B. Lawson Miller aided in the preparation of the manuscript.

(Nomenclature on page 188)

Table I. Thermodynamic Consistency of Partial Volumetric Data

Composition, Mole Fraction Ethane	Ethane		*n*-Pentane		Ethane		*n*-Pentane	
	Graphical	Integrated	Graphical	Integrated	Graphical	Integrated	Graphical	Integrated
	5000 P.S.I.A., 160° F.				10,000 P.S.I.A., 160° F.			
0.1	1.056[a]	1.051	1.872	1.872	0.980	0.975	1.786	1.786
0.2	1.082	1.077	1.867	1.867	0.983	0.984	1.785	1.784
0.3	1.110	1.104	1.860	1.859	0.990	0.993	1.782	1.782
0.4	1.134	1.129	1.850	1.846	1.004	1.003	1.779	1.777
0.5	1.153	1.150	1.835	1.829	1.017	1.013	1.773	1.769
0.6	1.169	1.167	1.811	1.804	1.027	1.023	1.761	1.757
0.7	1.182	1.181	1.777	1.771	1.036	1.033	1.743	1.740
0.8	1.192	1.190	1.740	1.735	1.043	1.041	1.721	1.720
0.9	1.197	1.196	1.704	1.698	1.048	1.047	1.700	1.697
σ		0.004[b]		0.005		0.003		0.002
	5000 P.S.I.A., 400° F.				5000 P.S.I.A., 400° F.			
0.1	1.533	1.534	2.222	2.222	1.222	1.223	2.022	2.023
0.2	1.552	1.552	2.218	2.218	1.231	1.231	2.020	2.020
0.3	1.576	1.575	2.209	2.209	1.244	1.245	2.015	2.015
0.4	1.607	1.608	2.191	2.191	1.261	1.260	2.008	2.008
0.5	1.649	1.648	2.159	2.158	1.276	1.275	1.998	1.996
0.6	1.690	1.690	2.110	2.107	1.288	1.289	1.979	1.977
0.7	1.731	1.730	2.033	2.034	1.298	1.300	1.951	1.950
0.8	1.766	1.763	1.948	1.947	1.306	1.308	1.920	1.918
0.9	1.783	1.781	1.849	1.851	1.312	1.313	1.876	1.878
σ		0.001		0.001		0.001		0.002

[a] Partial molal volume expressed in cubic feet per pound-mole.
[b] Standard error of estimate expressed in cubic foot per pound-mole.

Table II. Partial Molal Volume of Ethane in the Ethane–*n*-Pentane System

Pressure, P.S.I.A.	Mole Fraction Ethane 0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
					40° F.				
	(35.5)[a]	(69.0)	(103.4)	(138.4)	(175.7)	(212.9)	(252.0)	(293.8)	(340.0)
Bubble point	1.05[b]	1.07	1.09	1.106	1.128	1.152	1.173	1.191	1.198
200	1.04	1.06	1.08	1.103	1.126	...	...	...	...
400	1.04	1.06	1.08	1.095	1.116	1.140	1.162	1.183	1.195
600	1.03	1.05	1.07	1.088	1.107	1.129	1.149	1.168	1.180
800	1.02	1.04	1.06	1.080	1.100	1.119	1.137	1.154	1.165
1,000	1.02	1.04	1.05	1.073	1.092	1.109	1.126	1.142	1.152
1,250	1.01	1.03	1.05	1.065	1.082	1.098	1.114	1.128	1.137
1,500	1.00	1.02	1.04	1.057	1.074	1.089	1.103	1.115	1.124
1,750	1.00	1.01	1.03	1.049	1.065	1.080	1.093	1.104	1.112
2,000	0.99	1.01	1.02	1.042	1.059	1.072	1.084	1.094	1.101
2,250	0.98	1.00	1.02	1.035	1.051	1.064	1.076	1.085	1.091
2,500	0.98	0.99	1.01	1.029	1.045	1.057	1.068	1.077	1.083
2,750	0.97	0.99	1.01	1.022	1.037	1.050	1.060	1.069	1.074
3,000	0.96	0.98	1.00	1.016	1.031	1.043	1.053	1.061	1.067
3,500	0.96	0.97	0.99	1.005	1.019	1.030	1.039	1.048	1.053
4,000	0.94	0.96	0.98	0.993	1.006	1.017	1.027	1.035	1.041
4,500	0.94	0.95	0.97	0.983	0.995	1.006	1.017	1.024	1.030
5,000	0.93	0.94	0.96	0.974	0.986	0.997	1.007	1.015	1.020
6,000	0.91	0.93	0.94	0.958	0.971	0.981	0.990	0.997	1.001
7,000	0.90	0.92	0.93	0.945	0.957	0.967	0.975	0.981	0.985
8,000	0.88	0.90	0.92	0.932	0.945	0.954	0.961	0.966	0.970
9,000	0.86	0.89	0.90	0.920	0.933	0.942	0.949	0.953	0.957
10,000	0.85	0.87	0.89	0.909	0.922	0.930	0.937	0.942	0.945
					100° F.				
	(70.1)[a]	(127.9)	(187.7)	(250.0)	(315.3)	(384.0)	(459.9)	(549.0)	(662.1)
Bubble point	1.18[b]	1.21	1.23	1.266	1.306	1.359	1.446	1.652	2.176[c]
200	1.18	1.20	1.23	...	...	...	...	...	...
400	1.17	1.19	1.22	1.254	1.296	1.356	...	...	...
600	1.16	1.18	1.21	1.239	1.280	1.330	1.416	1.604	...
800	1.14	1.17	1.19	1.225	1.262	1.308	1.377	1.500	1.716
1,000	1.13	1.16	1.18	1.212	1.246	1.288	1.345	1.431	1.514
1,250	1.12	1.14	1.17	1.196	1.228	1.265	1.311	1.370	1.412
1,500	1.11	1.13	1.16	1.182	1.211	1.244	1.283	1.323	1.351
1,750	1.09	1.12	1.14	1.168	1.196	1.226	1.257	1.286	1.306
2,000	1.08	1.11	1.13	1.155	1.180	1.208	1.234	1.256	1.272
2,250	1.07	1.09	1.12	1.142	1.167	1.192	1.214	1.233	1.244
2,500	1.06	1.08	1.11	1.130	1.154	1.178	1.197	1.213	1.222
2,750	1.05	1.07	1.10	1.120	1.142	1.164	1.182	1.195	1.203
3,000	1.04	1.06	1.09	1.109	1.130	1.151	1.168	1.180	1.187
3,500	1.02	1.05	1.07	1.092	1.111	1.130	1.143	1.153	1.159
4,000	1.01	1.03	1.05	1.074	1.092	1.108	1.121	1.130	1.135
4,500	1.00	1.02	1.04	1.059	1.076	1.091	1.102	1.110	1.115
5,000	0.98	1.01	1.03	1.045	1.061	1.076	1.086	1.094	1.099
6,000	0.96	0.99	1.01	1.022	1.037	1.049	1.059	1.066	1.072
7,000	0.95	0.97	0.99	1.004	1.017	1.028	1.037	1.044	1.048
8,000	0.93	0.95	0.97	0.988	1.000	1.011	1.019	1.024	1.027
9,000	0.92	0.94	0.96	0.973	0.986	0.995	1.002	1.006	1.009
10,000	0.91	0.93	0.95	0.960	0.972	0.980	0.985	0.990	0.992
					160° F.				
	(121.1)[a]	(209.2)	(301.9)	(400.4)	(506.4)	(624.6)	(758.2)	(897.0)	(885.0)
Bubble point	1.29[b]	1.37	1.45	1.535	1.627	1.732	1.856	2.017	...
200	1.28	...	...	...	...	...	...	...	...
400	1.26	1.34	1.44	...	...	...	...	...	...
600	1.25	1.32	1.40	1.491	1.589	...	...	...	...
800	1.23	1.30	1.37	1.452	1.534	1.648	1.826	...	...
1,000	1.22	1.28	1.35	1.416	1.488	1.582	1.730	1.958	2.296
1,250	1.20	1.26	1.31	1.375	1.438	1.518	1.636	1.806	2.044
1,500	1.19	1.24	1.29	1.339	1.397	1.465	1.558	1.676	1.840
1,750	1.17	1.22	1.26	1.310	1.363	1.421	1.492	1.581	1.671
2,000	1.16	1.20	1.24	1.288	1.333	1.385	1.442	1.504	1.562
2,250	1.15	1.19	1.23	1.266	1.307	1.352	1.402	1.449	1.488
2,500	1.14	1.18	1.21	1.249	1.286	1.326	1.366	1.406	1.435
2,750	1.13	1.17	1.20	1.232	1.267	1.302	1.336	1.369	1.392
3,000	1.12	1.16	1.19	1.219	1.252	1.282	1.310	1.337	1.356
3,500	1.10	1.14	1.17	1.194	1.221	1.246	1.267	1.287	1.297
4,000	1.09	1.12	1.14	1.173	1.196	1.216	1.234	1.248	1.256
4,500	1.07	1.10	1.13	1.153	1.173	1.191	1.206	1.218	1.223
5,000	1.06	1.08	1.11	1.134	1.153	1.169	1.182	1.192	1.197
6,000	1.03	1.06	1.08	1.100	1.117	1.131	1.141	1.149	1.154
7,000	1.01	1.03	1.05	1.071	1.086	1.099	1.109	1.116	1.120
8,000	1.00	1.01	1.03	1.045	1.059	1.073	1.082	1.088	1.091
9,000	0.99	1.00	1.01	1.022	1.036	1.048	1.058	1.064	1.068
10,000	0.98	0.98	0.99	1.004	1.017	1.027	1.036	1.043	1.048

[a] Values of parentheses represent bubble-point pressures expressed in pounds per square inch.

[b] Partial molal volumes are expressed in cubic feet per pound-mole.

[c] Subject to greater uncertainty.

Table II. Continued

Pressure, P.S.I.A.	Mole Fraction Ethane 0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
				220° F.					
	(206.2)[a]	(324.5)	(445.5)	(574.4)	(716.7)	(864.8)	(984.7)	(862.5)	...
Bubble point	1.50[b]	1.64	1.79	1.974	2.213	2.639	...	...	...
400	1.47	1.62	...	...	...	...	...	...	...
600	1.45	1.58	1.74	1.961	...	...	...	...	...
800	1.43	1.54	1.68	1.860	2.150	...	...	...	...
1,000	1.41	1.51	1.63	1.777	2.004	2.398	3.12	...	...
1,250	1.39	1.47	1.57	1.688	1.843	2.094	2.487	3.14	...
1,500	1.37	1.44	1.52	1.606	1.720	1.880	2.116	2.477	2.839
1,750	1.35	1.41	1.47	1.540	1.625	1.735	1.907	2.132	2.363
2,000	1.34	1.38	1.44	1.487	1.554	1.637	1.759	1.934	2.091
2,250	1.32	1.36	1.40	1.443	1.498	1.568	1.664	1.790	1.895
2,500	1.31	1.34	1.37	1.409	1.454	1.513	1.598	1.694	1.761
2,750	1.29	1.32	1.35	1.390	1.418	1.472	1.543	1.619	1.664
3,000	1.28	1.30	1.32	1.353	1.389	1.438	1.500	1.557	1.591
3,500	1.25	1.27	1.29	1.312	1.342	1.381	1.423	1.461	1.488
4,000	1.23	1.24	1.26	1.278	1.304	1.335	1.366	1.394	1.413
4,500	1.21	1.22	1.23	1.249	1.273	1.299	1.324	1.345	1.358
5,000	1.18	1.19	1.21	1.226	1.244	1.268	1.289	1.307	1.315
6,000	1.14	1.15	1.17	1.184	1.202	1.219	1.232	1.243	1.249
7,000	1.11	1.11	1.13	1.147	1.160	1.176	1.189	1.198	1.204
8,000	1.08	1.09	1.10	1.114	1.126	1.142	1.154	1.162	1.168
9,000	1.07	1.07	1.08	1.090	1.100	1.114	1.123	1.132	1.136
10,000	1.06	1.06	1.06	1.072	1.077	1.088	1.094	1.103	1.110
				280° F.					
	(325.8)[a]	(471.0)	(626.6)	(802.4)	(928.0)	(935.3)	...	...	...
Bubble point	2.29[b]	2.56	3.00	3.76	...	...	...	...	...
400	2.22	...	...	...	...	...	...	...	...
600	2.03	2.27	...	...	...	...	...	...	...
800	1.92	2.09	2.42	...	...	...	...	...	...
1,000	1.83	1.99	2.21	2.688	3.71	...	...	...	...
1,250	1.75	1.86	2.02	2.338	2.959	3.90	...	...	...
1,500	1.68	1.76	1.89	2.088	2.470	2.961	3.49	3.81	3.92
1,750	1.62	1.68	1.77	1.916	2.152	2.439	2.777	3.07	3.24
2,000	1.57	1.62	1.69	1.800	1.954	2.142	2.359	2.567	2.727
2,500	1.52	1.56	1.62	1.709	1.824	1.962	2.126	2.291	2.417
2,250	1.48	1.52	1.57	1.642	1.732	1.838	1.961	2.092	2.194
2,750	1.46	1.49	1.53	1.586	1.660	1.749	1.849	1.952	2.022
3,000	1.43	1.46	1.49	1.536	1.599	1.676	1.762	1.846	1.898
3,500	1.40	1.42	1.43	1.464	1.511	1.566	1.630	1.694	1.724
4,000	1.36	1.37	1.39	1.407	1.444	1.489	1.539	1.583	1.608
4,500	1.33	1.34	1.35	1.362	1.392	1.429	1.471	1.503	1.520
5,000	1.30	1.30	1.31	1.328	1.348	1.380	1.415	1.440	1.456
6,000	1.25	1.25	1.26	1.270	1.290	1.313	1.334	1.349	1.359
7,000	1.20	1.20	1.21	1.224	1.239	1.259	1.275	1.288	1.295
8,000	1.16	1.17	1.17	1.187	1.197	1.212	1.228	1.241	1.246
9,000	1.13	1.14	1.15	1.156	1.164	1.176	1.192	1.203	1.206
10,000	1.12	1.12	1.12	1.124	1.131	1.144	1.156	1.167	1.173
				340° F.					
	(488.5)[a]	(670.3)	(749.0)	...	...	...	...	...	...
Bubble point	5.17[b]	5.95	7.81	...	...	...	...	...	...
600	4.28	...	...	...	...	...	...	...	...
800	3.08	4.46	7.36	...	...	...	...	...	...
1,000	2.63	3.31	4.44	...	...	...	...	...	...
1,250	2.30	2.61	3.22	4.11	...	...	...	...	...
1,500	2.11	2.29	2.64	3.17	3.83	4.32	4.57	...	...
1,750	1.98	2.10	2.34	2.659	3.07	3.44	3.71	3.87	3.92
2,000	1.89	1.97	2.14	2.353	2.623	2.921	3.16	3.31	3.38
2,250	1.81	1.87	1.99	2.152	2.340	2.567	2.770	2.894	2.959
2,500	1.75	1.80	1.88	2.004	2.146	2.307	2.472	2.591	2.658
2,750	1.70	1.73	1.80	1.892	2.004	2.127	2.258	2.368	2.431
3,000	1.65	1.68	1.73	1.806	1.898	2.000	2.106	2.201	2.252
3,500	1.57	1.59	1.62	1.677	1.746	1.823	1.904	1.966	1.996
4,000	1.50	1.52	1.54	1.585	1.636	1.698	1.754	1.804	1.826
4,500	1.44	1.46	1.48	1.515	1.558	1.604	1.648	1.686	1.705
5,000	1.40	1.41	1.43	1.461	1.498	1.534	1.566	1.596	1.614
6,000	1.32	1.34	1.35	1.380	1.408	1.432	1.453	1.471	1.483
7,000	1.28	1.28	1.30	1.316	1.339	1.360	1.375	1.390	1.398
8,000	1.24	1.24	1.25	1.269	1.287	1.303	1.314	1.325	1.331
9,000	1.20	1.21	1.22	1.228	1.240	1.254	1.265	1.275	1.282
10,000	1.18	1.18	1.18	1.192	1.202	1.210	1.222	1.235	1.243

[a] Values of parentheses represent bubble-point pressures expressed in pounds per square inch.

[b] Partial molal volumes are expressed in cubic feet per pound-mole.
[c] Subject to greater uncertainty.

(Table II continued on next page)

Table II. Continued

Pressure, P.S.I.A.	Mole Fraction Ethane 0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
					400° F.				
800	14.6	16.7	...	...	...	...	...	...	...
1,000	5.92	7.67	8.82	9.20	...	...	...	...	...
1,250	3.68	4.59	5.56	6.42	6.80	6.94	...	...	...
1,500	2.95	3.43	4.03	4.69	5.12	5.28	5.34	5.36	5.36
1,750	2.60	2.84	3.21	3.70	4.17	4.44	4.53	4.55	4.54
2,000	2.37	2.52	2.78	3.14	3.48	3.72	3.86	3.91	3.92
2,250	2.21	2.32	2.51	2.752	2.999	3.23	3.38	3.45	3.46
2,500	2.09	2.18	2.31	2.480	2.675	2.855	2.997	3.08	3.11
2,750	1.99	2.06	2.15	2.285	2.432	2.588	2.718	2.793	2.825
3,000	1.92	1.97	2.03	2.135	2.258	2.383	2.496	2.572	2.605
3,500	1.78	1.81	1.86	1.933	2.019	2.106	2.188	2.252	2.284
4,000	1.68	1.71	1.74	1.793	1.856	1.920	1.985	2.035	2.062
4,500	1.60	1.62	1.65	1.692	1.741	1.795	1.844	1.881	1.903
5,000	1.53	1.55	1.58	1.607	1.649	1.690	1.731	1.766	1.783
6,000	1.43	1.45	1.47	1.493	1.521	1.552	1.581	1.604	1.614
7,000	1.36	1.37	1.39	1.414	1.436	1.458	1.480	1.496	1.504
8,000	1.30	1.32	1.34	1.355	1.372	1.388	1.402	1.416	1.424
9,000	1.26	1.27	1.29	1.304	1.320	1.335	1.348	1.358	1.362
10,000	1.22	1.23	1.24	1.261	1.276	1.288	1.298	1.306	1.312
					460° F.				
1,000	11.0	14.3	...	...	...	...	...	...	...
1,250	6.34	7.40	7.94	8.12	7.99	7.62	...	...	...
1,500	4.46	5.06	5.64	5.92	5.98	5.98	5.98	5.98	5.98
1,750	3.49	3.92	4.49	4.93	5.05	5.07	5.07	5.08	5.08
2,000	2.97	3.29	3.69	4.14	4.37	4.42	4.42	4.42	4.42
2,250	2.65	2.86	3.13	3.49	3.78	3.88	3.90	3.90	3.90
2,500	2.42	2.59	2.79	3.06	3.29	3.43	3.50	3.51	3.51
2,750	2.25	2.38	2.57	2.772	2.950	3.08	3.16	3.19	3.20
3,000	2.11	2.22	2.38	2.546	2.696	2.815	2.889	2.927	2.942
3,500	1.92	2.00	2.12	2.244	2.352	2.442	2.506	2.543	2.560
4,000	1.80	1.86	1.94	2.034	2.127	2.200	2.245	2.276	2.295
4,500	1.71	1.76	1.82	1.891	1.958	2.013	2.055	2.088	2.105
5,000	1.64	1.68	1.72	1.782	1.837	1.880	1.914	1.941	1.960
6,000	1.51	1.54	1.58	1.632	1.673	1.702	1.723	1.739	1.748
7,000	1.42	1.45	1.49	1.518	1.552	1.578	1.595	1.606	1.615
8,000	1.36	1.38	1.41	1.439	1.462	1.486	1.502	1.515	1.521
9,000	1.32	1.33	1.36	1.382	1.405	1.421	1.431	1.440	1.444
10,000	1.27	1.28	1.30	1.326	1.344	1.360	1.372	1.385	1.385

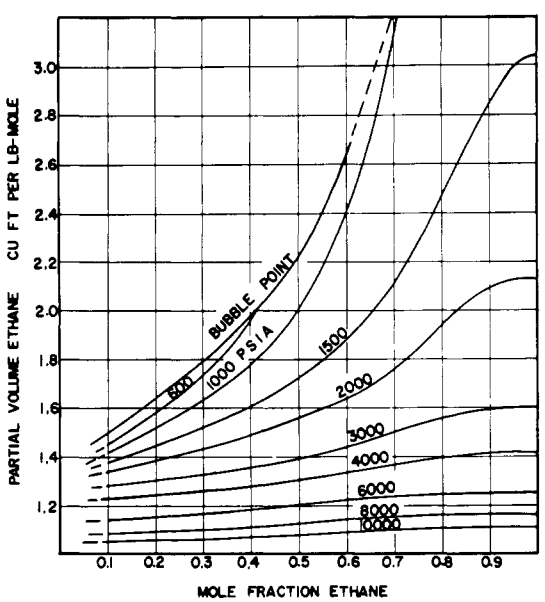

Figure 1. Influence of composition on the partial molal volume of ethane at 220° F.

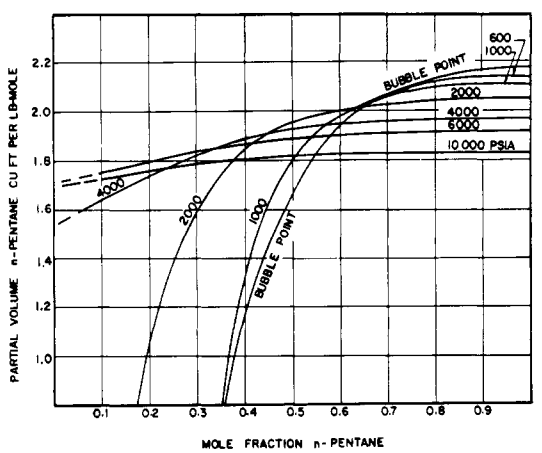

Figure 2. Influence of composition on the partial molal volume of *n*-pentane at 220° F.

NOMENCLATURE

m_k = lb. moles of component k
n_k = mole fraction of component k
V = molal volume, cu. ft./lb. mole
$\overline{V}$ = partial molal volume, partial volume, cu. ft./lb. mole
$\underline{V}$ = total volume, cu. ft.
σ = standard error of estimate, cu. ft./lb. mole

Subscripts

j, k = components j and k
m_i = change in state during which the weight of all components other than k remains constant
P = pressure, p.s.i.a.
T = thermodynamic temperature, ° R.

Superscript

° = pure component

Table III. Partial Molal Volume of *n*-Pentane in the Ethane–*n*-Pentane System

Pressure, P.S.I.A.	Mole Fraction *n*-Pentane 0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
					40° F.				
	(340.0)[a]	(293.8)	(252.0)	(212.9)	(175.7)	(138.4)	(103.4)	(69.0)	(35.5)
Bubble point	1.55[b]	1.61	1.67	1.716	1.748	1.771	1.786	1.794	1.797
200	...	...	...	...	1.748	1.771	1.786	1.793	1.795
400	1.56	1.62	1.68	1.720	1.750	1.770	1.783	1.790	1.793
600	1.57	1.64	1.69	1.724	1.751	1.769	1.781	1.788	1.790
800	1.58	1.65	1.70	1.728	1.752	1.768	1.778	1.785	1.788
1,000	1.59	1.65	1.70	1.729	1.752	1.766	1.777	1.783	1.785
1,250	1.60	1.66	1.70	1.730	1.750	1.764	1.774	1.780	1.782
1,500	1.61	1.66	1.70	1.729	1.748	1.762	1.771	1.776	1.779
1,750	1.61	1.66	1.70	1.728	1.747	1.759	1.768	1.774	1.776
2,000	1.62	1.66	1.70	1.727	1.745	1.757	1.765	1.771	1.773
2,250	1.62	1.66	1.70	1.725	1.743	1.755	1.762	1.768	1.770
2,500	1.62	1.66	1.70	1.724	1.741	1.752	1.760	1.765	1.767
2,750	1.62	1.66	1.70	1.722	1.739	1.750	1.757	1.763	1.764
3,000	1.62	1.66	1.69	1.720	1.737	1.748	1.755	1.760	1.762
3,500	1.62	1.66	1.69	1.716	1.733	1.743	1.750	1.755	1.756
4,000	1.62	1.66	1.69	1.712	1.728	1.738	1.745	1.750	1.751
4,500	1.62	1.66	1.68	1.707	1.723	1.733	1.740	1.744	1.746
5,000	1.62	1.65	1.68	1.702	1.718	1.728	1.735	1.739	1.740
6,000	1.62	1.65	1.67	1.693	1.707	1.717	1.724	1.728	1.730
7,000	1.62	1.64	1.66	1.683	1.697	1.706	1.713	1.718	1.720
8,000	1.61	1.64	1.66	1.672	1.685	1.695	1.702	1.707	1.710
9,000	1.61	1.63	1.65	1.661	1.675	1.684	1.692	1.697	1.700
10,000	1.60	1.62	1.64	1.650	1.662	1.673	1.682	1.687	1.691
					100° F.				
	(662.1)[a]	(549.0)	(459.9)	(384.0)	(315.3)	(250.0)	(187.7)	(127.9)	(70.1)
Bubble point	−0.20[b,c]	0.85	1.55	1.740	1.817	1.856	1.879	1.894	1.900
200	...	...	...	...	...	...	1.878	1.892	1.897
400	...	...	...	1.741	1.820	1.855	1.874	1.886	1.892
600	...	0.97	1.57	1.748	1.821	1.853	1.870	1.881	1.887
800	−0.34[c]	1.22	1.60	1.752	1.820	1.850	1.866	1.876	1.883
1,000	0.87	1.37	1.63	1.756	1.818	1.847	1.862	1.872	1.879
1,250	1.25	1.48	1.66	1.761	1.816	1.843	1.858	1.868	1.873
1,500	1.42	1.56	1.68	1.764	1.813	1.839	1.854	1.864	1.869
1,750	1.52	1.62	1.70	1.766	1.812	1.835	1.850	1.859	1.864
2,000	1.58	1.65	1.71	1.769	1.808	1.832	1.846	1.854	1.860
2,250	1.62	1.67	1.72	1.770	1.805	1.828	1.842	1.850	1.854
2,500	1.64	1.69	1.73	1.772	1.802	1.824	1.838	1.845	1.850
2,750	1.65	1.70	1.74	1.772	1.800	1.820	1.833	1.841	1.844
3,000	1.66	1.70	1.74	1.772	1.798	1.817	1.829	1.836	1.840
3,500	1.67	1.71	1.74	1.770	1.793	1.810	1.821	1.828	1.832
4,000	1.67	1.71	1.74	1.767	1.788	1.803	1.812	1.819	1.823
4,500	1.67	1.70	1.73	1.762	1.782	1.796	1.804	1.811	1.816
5,000	1.67	1.70	1.73	1.758	1.777	1.789	1.796	1.803	1.807
6,000	1.67	1.70	1.73	1.749	1.765	1.774	1.781	1.787	1.792
7,000	1.66	1.69	1.72	1.737	1.751	1.760	1.766	1.772	1.777
8,000	1.66	1.69	1.71	1.724	1.738	1.746	1.753	1.758	1.763
9,000	1.66	1.68	1.70	1.712	1.724	1.733	1.740	1.744	1.749
10,000	1.65	1.67	1.69	1.700	1.712	1.721	1.727	1.732	1.736
					160° F.				
	(885.0)[a]	(897.0)	(758.2)	(624.6)	(506.4)	(400.4)	(301.9)	(209.2)	(121.1)
Bubble point	...	...	1.32[b]	1.668	1.819	1.902	1.957	1.992	2.015
200	...	...	...	...	...	...	...	...	2.013
400	...	...	...	...	...	...	1.957	1.988	2.006
600	...	...	...	...	1.831	1.911	1.956	1.983	1.999
800	...	...	1.34	1.706	1.848	1.915	1.954	1.976	1.990
1,000	−1.00[c]	0.80[c]	1.42	1.736	1.860	1.919	1.951	1.970	1.983
1,250	−0.62[c]	0.93	1.51	1.760	1.868	1.918	1.946	1.963	1.974
1,500	0.07[c]	1.13	1.58	1.779	1.873	1.918	1.942	1.957	1.965
1,750	0.78[c]	1.30	1.62	1.790	1.874	1.915	1.936	1.950	1.957
2,000	1.14	1.43	1.66	1.799	1.873	1.911	1.930	1.942	1.949
2,250	1.32	1.51	1.68	1.803	1.871	1.907	1.925	1.935	1.941
2,500	1.42	1.56	1.70	1.806	1.868	1.902	1.919	1.928	1.934
2,750	1.49	1.60	1.72	1.808	1.865	1.897	1.914	1.922	1.926
3,000	1.54	1.64	1.73	1.810	1.862	1.892	1.907	1.915	1.920
3,500	1.62	1.68	1.75	1.812	1.855	1.881	1.895	1.902	1.906
4,000	1.66	1.71	1.76	1.813	1.848	1.870	1.882	1.890	1.894
4,500	1.69	1.73	1.77	1.813	1.841	1.860	1.871	1.878	1.883
5,000	1.70	1.74	1.78	1.811	1.835	1.850	1.860	1.867	1.872
6,000	1.72	1.75	1.78	1.804	1.821	1.832	1.842	1.848	1.852
7,000	1.72	1.75	1.77	1.792	1.808	1.818	1.824	1.830	1.835
8,000	1.71	1.74	1.76	1.782	1.795	1.804	1.810	1.815	1.818
9,000	1.71	1.73	1.75	1.771	1.784	1.791	1.796	1.800	1.802
10,000	1.70	1.72	1.74	1.761	1.773	1.779	1.782	1.785	1.786

[a] Values in parentheses represent bubble-point pressures expressed in pounds per square inch.

[b] Partial molal volumes are expressed in cubic feet per pound mole.

[c] Subject to greater uncertainty.

(Table III continued on next page)

Table III. Continued

Pressure, P.S.I.A.	Mole Fraction *n*-Pentane 0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
				220° F.					
	...	(862.5)[a]	(984.7)	(864.8)	(716.7)	(574.4)	(445.5)	(324.5)	(206.2)
Bubble point	...	...	...	1.185[b]	1.658	1.930	2.064	2.132	2.168
400	...	...	...	...	...	...	...	2.127	2.153
600	...	...	...	...	...	1.936	2.065	2.118	2.153
800	...	...	...	...	1.720	1.961	2.062	2.108	2.124
1,000	...	...	−0.04[c]	1.312	1.800	1.977	2.059	2.097	2.112
1,250	−4.74[c]	−1.24[c]	0.77	1.574	1.875	1.992	2.053	2.083	2.097
1,500	−2.58[c]	0.13[c]	1.27	1.735	1.922	2.000	2.046	2.070	2.081
1,750	−0.78[c]	0.75	1.48	1.807	1.943	2.005	2.037	2.056	2.067
2,000	0.17[c]	1.04	1.59	1.839	1.954	2.004	2.029	2.045	2.054
2,250	0.74[c]	1.28	1.66	1.861	1.958	2.000	2.021	2.034	2.041
2,500	1.05	1.41	1.70	1.873	1.958	1.995	2.012	2.023	2.029
2,750	1.25	1.51	1.74	1.882	1.956	1.988	2.004	2.012	2.018
3,000	1.39	1.58	1.76	1.886	1.951	1.981	1.995	2.002	2.007
3,500	1.55	1.69	1.80	1.889	1.942	1.967	1.978	1.985	1.989
4,000	1.64	1.74	1.83	1.890	1.930	1.952	1.963	1.968	1.972
4,500	1.70	1.77	1.84	1.886	1.919	1.938	1.949	1.954	1.957
5,000	1.73	1.79	1.84	1.882	1.908	1.926	1.936	1.940	1.944
6,000	1.76	1.80	1.84	1.869	1.890	1.905	1.912	1.917	1.920
7,000	1.76	1.80	1.83	1.855	1.872	1.885	1.892	1.896	1.898
8,000	1.75	1.79	1.82	1.838	1.854	1.865	1.871	1.876	1.878
9,000	1.74	1.77	1.80	1.823	1.836	1.846	1.851	1.855	1.857
10,000	1.73	1.76	1.79	1.806	1.819	1.826	1.830	1.833	1.835
				280° F.					
	...	...	...	(935.3)[a]	(928.0)	(802.4)	(626.6)	(47.10)	(325.8)
Bubble point	...	...	...	...	1.145[b]	1.788	2.140	2.292	2.367
400	...	...	...	...	...	...	...	...	2.358
600	...	...	...	...	...	...	...	2.287	2.333
800	...	...	...	...	...	...	2.159	2.276	2.305
1,000	...	...	...	...	1.049[c]	1.905	2.174	2.256	2.279
1,250	...	...	...	0.300[c]	1.473	1.997	2.176	2.232	2.250
1,500	−1.42[c]	−0.87[c]	0.11[c]	1.174	1.732	2.050	2.169	2.211	2.225
1,750	−0.85[c]	0.01[c]	0.92[c]	1.538	1.880	2.075	2.158	2.190	2.202
2,000	−0.24[c]	0.70[c]	1.32[c]	1.738	1.958	2.085	2.145	2.172	2.181
2,250	0.27[c]	1.00[c]	1.52	1.832	1.996	2.087	2.132	2.154	2.162
2,500	0.68[c]	1.24	1.64	1.880	2.014	2.087	2.120	2.138	2.144
2,750	1.01[c]	1.41	1.71	1.908	2.024	2.080	2.108	2.123	2.128
3,000	1.21	1.52	1.76	1.928	2.025	2.075	2.097	2.108	2.112
3,500	1.47	1.66	1.83	1.954	2.023	2.061	2.076	2.083	2.085
4,000	1.60	1.73	1.86	1.964	2.016	2.044	2.056	2.060	2.062
4,500	1.68	1.78	1.88	1.963	2.004	2.027	2.036	2.040	2.041
5,000	1.73	1.82	1.90	1.957	1.992	2.011	2.019	2.022	2.024
6,000	1.79	1.85	1.90	1.942	1.968	1.981	1.988	1.992	1.993
7,000	1.81	1.86	1.98	1.925	1.945	1.956	1.961	1.964	1.966
8,000	1.81	1.85	1.88	1.906	1.923	1.933	1.937	1.940	1.942
9,000	1.80	1.83	1.86	1.886	1.902	1.909	1.913	1.916	1.917
10,000	1.78	1.81	1.84	1.866	1.879	1.886	1.890	1.891	1.892
				340° F.					
	...	...	...	...	...	...	(749.0)[a]	(670.3)	(488.5)
Bubble point	...	...	...	...	...	...	1.162[b]	1.932	2.523
600	...	...	...	...	...	...	...	...	2.544
800	...	...	...	...	...	...	1.588	2.274	2.550
1,000	...	...	...	...	...	...	2.012	2.372	2.504
1,250	...	...	...	...	...	1.687	2.187	2.398	2.452
1,500	0.02[c]	0.17[c]	0.44[c]	0.850[c]	1.424	1.956	2.255	2.371	2.405
1,750	0.10[c]	0.42[c]	0.80[c]	1.319	1.754	2.086	2.261	2.339	2.366
2,000	0.42[c]	0.68[c]	1.13	1.565	1.919	2.142	2.257	2.312	2.332
2,250	0.62[c]	0.97[c]	1.36	1.755	2.014	2.164	2.250	2.289	2.304
2,500	0.78[c]	1.17	1.55	1.869	2.060	2.172	2.240	2.268	2.278
2,750	0.97[c]	1.33	1.67	1.933	2.084	2.174	2.228	2.249	2.255
3,000	1.17	1.47	1.76	1.966	2.094	2.170	2.215	2.231	2.234
3,500	1.45	1.66	1.85	2.001	2.098	2.155	2.185	2.195	2.199
4,000	1.62	1.76	1.90	2.016	2.090	2.136	2.157	2.165	2.168
4,500	1.71	1.83	1.94	2.020	2.076	2.114	2.132	2.139	2.142
5,000	1.78	1.87	1.95	2.017	2.064	2.094	2.109	2.116	2.118
6,000	1.83	1.90	1.96	2.003	2.036	2.056	2.068	2.074	2.076
7,000	1.85	1.91	1.95	1.984	2.009	2.024	2.034	2.040	2.041
8,000	1.85	1.98	1.93	1.963	1.985	1.996	2.004	2.008	2.008
9,000	1.84	1.88	1.92	1.942	1.962	1.972	1.976	1.979	1.980
10,000	1.83	1.86	1.90	1.922	1.938	1.948	1.952	1.953	1.954

[a] Values in parentheses represent bubble-point pressures expressed in pounds per square inch.

[b] Partial molal volumes are expressed in cubic feet per pound mole.

[c] Subject to greater uncertainty.

Table III. Continued

Pressure, P.S.I.A.	Mole Fraction *n*-Pentane 0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
					400° F.				
800	...	...	...	...	...	...	...	2.213	2.156
1,000	...	...	...	...	...	2.077	2.080	2.404	2.776
1,250	...	...	...	1.653	1.657	1.854	2.219	2.548	2.740
1,500	1.43	1.41	1.41	1.472	1.699	2.024	2.369	2.564	2.652
1,750	1.26	1.28	1.35	1.510	1.802	2.145	2.419	2.547	2.588
2,000	1.20	1.27	1.40	1.645	1.950	2.221	2.415	2.506	2.533
2,250	1.23	1.33	1.52	1.798	2.073	2.273	2.403	2.465	2.487
2,500	1.28	1.42	1.64	1.910	2.137	2.296	2.387	2.434	2.448
2,750	1.34	1.51	1.75	1.989	2.176	2.299	2.369	2.404	2.414
3,000	1.41	1.59	1.83	2.042	2.188	2.292	2.352	2.376	2.385
3,500	1.57	1.73	1.93	2.089	2.193	2.268	2.312	2.328	2.333
4,000	1.72	1.84	1.99	2.108	2.188	2.242	2.273	2.286	2.290
4,500	1.80	1.91	2.02	2.113	2.175	2.215	2.240	2.250	2.254
5,000	1.85	1.95	2.03	2.110	2.159	2.191	2.209	2.218	2.222
6,000	1.90	1.97	2.03	2.087	2.123	2.144	2.158	2.165	2.168
7,000	1.92	1.97	2.02	2.059	2.088	2.103	2.114	2.121	2.124
8,000	1.92	1.96	2.00	2.031	2.056	2.069	2.076	2.080	2.084
9,000	1.91	1.94	1.98	2.003	2.024	2.037	2.043	2.049	2.050
10,000	1.88	1.92	1.95	1.979	1.998	2.008	2.015	2.020	2.022
					460° F.				
1,000	...	...	...	...	...	...	...	3.15	3.51
1,250	...	...	...	...	...	...	...	3.08	3.25
1,500	2.52	2.52	2.53	2.530	2.544	2.587	2.741	2.936	3.04
1,750	2.27	2.27	2.28	2.294	2.329	2.412	2.632	2.832	2.920
2,000	2.14	2.14	2.14	2.150	2.210	2.390	2.622	2.761	2.820
2,250	2.02	2.03	2.04	2.084	2.190	2.414	2.608	2.700	2.738
2,500	1.93	1.94	1.97	2.084	2.258	2.431	2.573	2.642	2.674
2,750	1.87	1.90	1.97	2.120	2.284	2.425	2.535	2.594	2.620
3,000	1.84	1.90	2.00	2.152	2.292	2.412	2.502	2.553	2.575
3,500	1.84	1.94	2.06	2.186	2.292	2.382	2.444	2.485	2.502
4,000	1.86	1.98	2.10	2.197	2.281	2.348	2.396	2.427	2.440
4,500	1.91	2.02	2.12	2.197	2.266	2.316	2.353	2.375	2.386
5,000	1.95	2.04	2.12	2.191	2.245	2.287	2.316	2.333	2.340
6,000	2.00	2.06	2.12	2.165	2.201	2.230	2.251	2.264	2.269
7,000	2.01	2.05	2.09	2.132	2.160	2.180	2.195	2.208	2.215
8,000	1.99	2.03	2.07	2.100	2.122	2.140	2.154	2.162	2.157
9,000	1.98	2.01	2.04	2.070	2.089	2.106	2.118	2.125	2.127
10,000	1.96	1.99	2.02	2.038	2.056	2.071	2.084	2.091	2.093

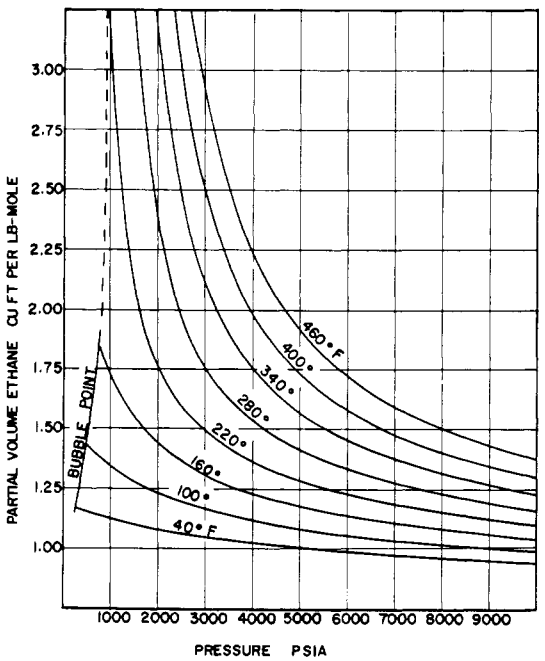

Figure 3. Effect of pressure and temperature on the partial molal volume of ethane for a mixture containing 0.7 mole fraction ethane

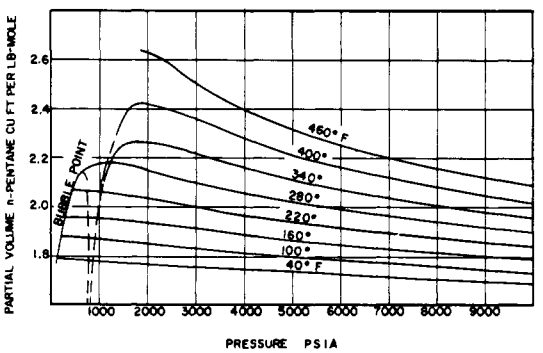

Figure 4. Effect of pressure and temperature on the partial molal volume of *n*-pentane for a mixture containing 0.7 mole fraction *n*-pentane

LITERATURE CITED

(1) Billman, G.W., Sage, B.H., Lacey, W.N., *Trans. Am. Inst. Mining Met. Engrs.* **174**, 13 (1948).
(2) Gibbs, J., "Collected Works," Vol. **I**, Longmans, Green, New York, 1931.
(3) Reamer, H.H., Sage, B.H., Lacey, W.N., *J. Chem. Eng. Data* **5**, 44 (1960).

RECEIVED for review February 1, 1960. Accepted December 21, 1960.