THERMODYNAMIC PROPERTIES

EXPLANATION OF TABLES

The following subsection presents information on the thermodynamic properties of a number of fluids. In some cases transport properties are also included.

Notation

c_p = specific heat
e = specific internal energy
h = enthalpy
k = thermal conductivity
p = pressure
s = specific entropy
t = temperature
T = absolute temperature
u = specific internal energy
μ = viscosity
v = specific volume
f = subscript denoting saturated liquid
g = subscript denoting saturated vapor

UNITS CONVERSIONS

For this subsection, the following units conversions are applicable:

c_p, specific heat: To convert kilojoules per kilogram-kelvin to British thermal units per pound–degree Fahrenheit, multiply by 0.23885.

e, internal energy: To convert kilojoules per kilogram to British thermal units per pound, multiply by 0.42992.

g, gravity acceleration: To convert meters per second squared to feet per second squared, multiply by 3.2808.

h, enthalpy: To convert kilojoules per kilogram to British thermal units per pound, multiply by 0.42992.

k, thermal conductivity: To convert watts per meter-kelvin to British thermal unit–feet per hour–square foot–degree Fahrenheit, multiply by 0.57779.

p, pressure: To convert bars to kilopascals, multiply by 1×10^2; to convert bars to pounds-force per square inch, multiply by 14.504; and to convert millimeters of mercury to pounds-force per square inch, multiply by 0.01934.

s, entropy: to convert kilojoules per kilogram-kelvin to British thermal units per pound–degree Rankine, multiply by 0.23885.

t, temperature: $°F = \frac{9}{5}\ °C + 32$.

T, absolute temperature: $°R = \frac{9}{5}\ K$.

u, internal energy: to convert kilojoules per kilogram to British thermal units per pound, multiply by 0.42992.

μ, viscosity: to convert pascal-seconds to pound-force–seconds per square foot, multiply by 0.020885; to convert pascal-seconds to c_p, multiply by 1000.

v, specific volume: to convert cubic meters per kilogram to cubic feet per pound, multiply by 16.018.

ρ, density: to convert kilograms per cubic meter to pounds per cubic foot, multiply by 0.062428.

ADDITIONAL REFERENCES

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TABLE 2-226 Thermophysical Properties of Saturated Acetone

Temperature, K	Pressure, bar	v_f, m^3/kg	v_g, m^3/kg	h_f, kJ/kg	h_g, kJ/kg	s_f, kJ/kg·K	s_g, kJ/kg·K	c_{pf}, kJ/kg·K	μ_f, 10^{-6} Pa·s	k_f, W/m·K	Pr
300	0.318	0.001 261	1.415	−67	466	−0.213	1.561				
310	0.482	0.001 285	0.942	−46	476	−0.144	1.540				
320	0.710	0.001 309	0.645	−22	490	−0.068	1.531				
329.3[b]	1.013	0.001 333	0.456	0	506	0	1.537	2.29	232	0.141	3.77
330	1.040	0.001 335	0.448	2	506	0.003	1.521	2.29	231	0.141	3.75
340	1.52	0.001 359	0.311	25	509	0.075	1.514	2.33	212	0.137	3.61
350	2.04	0.001 383	0.237	51	529	0.150	1.516	2.38	200	0.132	3.61
360	2.74	0.001 408	0.179	78	543			2.43	187	0.128	3.55
370	3.60	0.001 435	0.138	103	554			2.48	176	0.124	3.52
380	4.52	0.001 464	0.110	127	566			2.53	165	0.119	3.51
390	5.87	0.001 495	0.0854	151	577			2.59	153	0.115	3.45
400	7.31	0.001 528	0.0684	184	588			2.65	141	0.111	3.37
410	8.94	0.001 564	0.0556	207	598			2.73	130	0.107	3.32
420	10.82	0.001 604	0.0454	231	608			2.82	119	0.103	3.26
430	13.64	0.001 647	0.0356	256	618			2.92	109	0.099	3.21
440	16.37	0.001 695	0.0292	281	625			3.03	99	0.095	3.16
450	19.42	0.001 748	0.0240	308	632			3.15	90	0.092	3.08
460	22.79	0.001 81	0.0199	337	637			3.29	80	0.088	2.99
470	27.52	0.001 88	0.0159	365	641			3.45	71	0.083	2.95
480	32.52	0.001 98	0.0130	396	638			3.76	64	0.077	3.13
490	37.73	0.002 15	0.0091								
500	43.08	0.002 46	0.0063								
508.2[c]	47.61	0.003 67	0.0037								

b = normal boiling point; *c* = critical point

P, v, h, and *s* interpolated and converted from *Heat Exchanger Design Handbook,* vol. 5, Hemisphere, Washington, DC, 1983 and reproduced in Beaton, C. F. and G. F. Hewitt, *Physical Property Data for the Design Engineer,* Hemisphere, New York, 1989 (394 pp.). Other values compiled by P. E. Liley

An enthalpy-pressure diagram to 1000 psia, 250–500 °F appears in *J. Chem. Eng. Data* **7,** 1 (1962): 75–78.

TABLE 2-227 Saturated Acetylene*

Temperature, K	Pressure, bar	v_{cond}, m^3/kg	v_g, m^3/kg	h_{cond}, kJ/kg	h_g, kJ/kg	s_{cond}, kJ/(kg·K)	s_g, kJ/(kg·K)
162.0	0.101		5.081	158	983	2.967	8.062
169.3	0.203		2.644	173	994	3.039	7.889
173.9	0.304		1.805	182	999	3.095	7.797
180.0	0.507		1.116	194	1007	3.161	7.672
184.3	0.709		0.810	203	1011	3.216	7.596
189.1	1.013		0.5780	214	1015	3.272	7.511
192.4[t]	1.283		0.4617	221	1018	3.312	7.455
		———		———		———	
192.4[t]	1.283	0.00164	0.4617	378	1018	4.127	7.455
200.9	2.027	0.00165	0.3011	411	1027	4.296	7.362
209.4	3.040	0.00169	0.2074	445	1035	4.461	7.280
221.5	5.066	0.00174	0.1264	493	1046	4.684	7.180
230.4	7.093	0.00179	0.0907	528	1052	4.837	7.111
240.7	10.13	0.00186	0.0635	565	1058	4.990	7.037
253.2	15.20	0.00195	0.0420	602	1061	5.133	6.947
263.0	20.27	0.00204	0.0309	628	1061	5.231	6.878
271.6	25.33	0.00213	0.0240	654	1060	5.326	6.822
278.9	30.40	0.00223	0.0193	680	1057	5.414	6.767
284.9	35.46	0.00232	0.0159	704	1051	5.494	6.716
290.4	40.53	0.00242	0.0133	727	1041	5.576	6.658
300.0	50.66	0.00270	0.0093	778	1017	5.737	6.534
307.8	60.80	0.00335	0.0061	850	968	5.965	6.351
308.7[c]	62.47	0.00434	0.0043	908	908	6.158	6.158

*Values recalculated into SI units from those of Din. *Thermodynamic Functions of Gases,* vol. 2, Butterworth, London, 1956. Above the solid line the condensed phase is solid; below the line it is liquid. *t* = triple point; *c* = critical point.

TABLE 2-228 Saturated Air*

T, K	P_f, bar	P_g, bar	v_f, m^3/kg	v_g, m^3/kg	h_f, kJ/kg	h_g, kJ/kg	s_f, kJ/(kg·K)	s_g, kJ/(kg·K)	c_{pf}, kJ/(kg·K)	μ_f, 10^{-4} Pa·s	k_f, W/(m·K)
60			1.040.–3	5.55	–159.2	59.7	2.528	6.255		3.25	0.180
62			1.050.–3	3.73	–155.2	61.7	2.585	6.164		2.98	0.176
64	0.123	0.071	1.060.–3	2.57	–151.4	63.6	2.641	6.080		2.75	0.173
66	0.174	0.104	1.070.–3	1.82	–147.8	65.5	2.696	6.002		2.54	0.169
68	0.239	0.147	1.080.–3	1.313	–144.2	67.4	2.747	5.929		2.36	0.166
70	0.323	0.205	1.089.–3	0.968	–140.6	69.2	2.797	5.862	1.817	2.21	0.163
72	0.429	0.280	1.101.–3	0.728	–137.1	71.0	2.847	5.799	1.827	2.07	0.160
74	0.560	0.376	1.113.–3	0.556	–133.5	72.8	2.895	5.740	1.838	1.95	0.156
76	0.721	0.495	1.125.–3	0.431	–129.9	74.5	2.941	5.685	1.849	1.84	0.152
78	0.915	0.644	1.136.–3	0.339	–126.3	76.2	2.988	5.634	1.861	1.74	0.148
80	1.146	0.825	1.146.–3	0.270	–122.6	77.8	3.034	5.585	1.873	1.65	0.145
82	1.420	1.043	1.160.–3	0.217	–118.8	79.4	3.079	5.540	1.885	1.58	0.142
84	1.741	1.305	1.173.–3	0.177	–115.0	80.9	3.123	5.496	1.898	1.51	0.139
86	2.114	1.614	1.187.–3	0.145	–111.2	82.3	3.167	5.454	1.912	1.44	0.135
88	2.544	1.976	1.201.–3	0.120	–107.4	83.6	3.209	5.414	1.927	1.38	0.132
90	3.036	2.397	1.216.–3	0.1002	–103.5	84.8	3.251	5.376	1.944	1.32	0.128
92	3.596	2.884	1.231.–3	0.0843	–99.5	85.9	3.293	5.340	1.962	1.27	0.125
94	4.229	3.441	1.247.–3	0.0713	–95.5	87.0	3.335	5.304	1.982	1.23	0.121
96	4.940	4.075	1.265.–3	0.0607	–91.5	87.9	3.376	5.270	2.003	1.18	0.117
98	5.736	4.792	1.283.–3	0.0520	–87.5	88.7	3.416	5.236	2.027	1.14	0.114
100	6.621	5.599	1.302.–3	0.0447	–83.3	89.3	3.456	5.204	2.053	1.10	0.110
105	9.265	8.056	1.355.–3	0.0312	–72.8	90.2	3.553	5.124	2.137	1.02	0.102
110	12.59	11.22	1.418.–3	0.0222	–61.9	90.1	3.649	5.045	2.264	0.95	0.093
115	16.68	15.21	1.495.–3	0.0159	–50.3	88.4	3.747	4.964	2.477	0.87	0.084
120	21.61	20.14	1.596.–3	0.0115	–37.5	84.8	3.850	4.877	2.916	0.75	0.076
125	27.43	26.14	1.757.–3	0.0081	–22.0	78.2	3.969	4.776	4.585	0.42	0.067
130	34.16	33.32	2.075.–3	0.0054	0.4	66.1	4.136	4.644			
132.55^c		37.69	3.196.–3	0.0032	37.4	37.4	4.410	4.410	∞		∞

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*Liquid properties extracted or converted from Vasserman and Rabinovich, *Thermophysical Properties of Liquid Air and Its Components,* Moscow, 1968, and NBS-NSF transl. TT 69-55092, 1970. Copyrighted material. Reproduced by permission. Vapor properties extracted or converted from Vasserman, Kazavchinskii, and Rabinovich, *Thermophysical Properties of Air and Its Components,* Nauka, Moscow, 1966, and NBS-NSF transl. TT 70-50095, 1971. Copyrighted material. Reproduced by permission. Note that on pages 150–151 of the TT 69-55092 publication certain values of TT 70-50095 were adjusted. As a complete retabulation was not given, the tables here are based upon the two separate publications, as indicated. See also Table 2-235 for the argon-oxygen-nitrogen equilibrium data. c = critical point. The notation 1.040.–3 signifies 1.040×10^{-3}.

TABLE 2-229 Thermophysical Properties of Compressed Air*

Pressure, bar	Temperature, K												
	80	90	100	120	140	160	180	200	220	240	260	280	300
1 v		0.251	0.281	0.340	0.399	0.457	0.515	0.537	0.631	0.688	0.746	0.803	0.861
h		87.9	98.3	118.8	139.1	159.3	179.5	199.7	219.8	239.9	260.0	280.2	300.3
s	Mix	5.650	5.759	5.946	6.103	6.238	6.357	6.463	6.559	6.647	6.727	6.802	6.871
C_p		1.044	1.032	1.020	1.014	1.010	1.008	1.007	1.006	1.006	1.006	1.006	1.007
μ		0.064	0.071	0.085	0.097	0.109	0.121	0.133	0.144	0.154	0.165	0.175	0.185
k		0.0084	0.0093	0.0112	0.0129	0.0147	0.0164	0.0181	0.0198	0.0214	0.0231	0.0247	0.0263
5 v	0.00115	0.00122	0.0509	0.0646	0.0773	0.0895	0.102	0.114	0.125	0.137	0.149	0.160	0.172
h	–122.3	–103.3	90.6	113.6	135.3	156.4	177.1	197.7	218.1	238.5	258.8	279.1	299.4
s	3.031	3.250	5.246	5.455	5.623	5.763	5.885	5.994	6.092	6.180	6.262	6.337	6.406
C_p	1.868	1.941	1.212	1.107	1.065	1.045	1.033	1.025	1.020	1.017	1.015	1.013	1.013
μ	1.794	1.163	0.077	0.087	0.098	0.110	0.122	0.134	0.145	0.155	0.165	0.175	0.185
k	0.146	0.128	0.0103	0.0119	0.0135	0.0151	0.0168	0.0185	0.0201	0.0217	0.0234	0.0250	0.0265
10 v	0.00115	0.00121	0.00130	0.0298	0.0370	0.0436	0.0499	0.0561	0.0621	0.0681	0.0741	0.0800	0.0859
h	–122.0	–103.1	–83.2	106.2	130.2	152.5	174.1	195.2	216.1	236.7	257.3	277.8	298.3
s	3.028	3.246	3.452	5.214	5.398	5.548	5.675	5.786	5.885	5.975	6.058	6.134	6.204
C_p	1.863	1.932	2.041	1.270	1.146	1.093	1.065	1.049	1.038	1.031	1.026	1.023	1.201
μ	1.816	1.177	0.838	0.089	0.101	0.112	0.124	0.135	0.146	0.156	0.166	0.176	0.186
k	0.146	0.128	0.111	0.0126	0.0141	0.0157	0.0173	0.0189	0.0205	0.0221	0.0237	0.0253	0.0268
20 v	0.00114	0.00121	0.00129	0.0116	0.0167	0.0206	0.0241	0.0274	0.0306	0.0337	0.0368	0.0398	0.0428
h	–121.3	–102.5	–82.9	85.2	118.5	144.3	167.7	190.1	211.9	233.2	254.3	275.2	296.0
s	3.022	3.239	3.442	4.882	5.140	5.312	5.450	5.568	5.672	5.765	5.849	5.927	5.998
C_p	1.853	1.916	2.010	2.237	1.390	1.215	1.141	1.101	1.076	1.061	1.050	1.042	1.037
μ	1.859	1.205	0.857	0.098	0.106	0.116	0.127	0.137	0.148	0.158	0.168	0.178	0.187
k	0.147	0.130	0.112	0.0152	0.0157	0.0169	0.0182	0.0197	0.0212	0.0228	0.0243	0.0258	0.0273
40 v	0.00114	0.00120	0.00128	0.00153	0.0058	0.0090	0.0114	0.0131	0.0148	0.0165	0.0182	0.0198	0.0214
h	–120.0	–101.4	–82.2	–39.8	83.6	125.3	154.3	179.7	203.5	226.3	248.5	270.2	291.7
s	3.011	3.225	3.424	3.807	4.745	5.025	5.196	5.330	5.444	5.543	5.632	5.712	5.786
C_p	1.834	1.886	1.958	2.432	3.193	1.610	1.335	1.221	1.159	1.122	1.097	1.081	1.068
μ	1.943	1.261	0.896	0.516	0.132	0.129	0.135	0.144	0.154	0.163	0.172	0.182	0.191
k	0.149	0.132	0.115	0.0814	0.0460	0.0201	0.0206	0.0217	0.0229	0.0242	0.0256	0.0270	0.0284
60 v	0.00113	0.00119	0.00126	0.00147	0.00222	0.00505	0.00687	0.00833	0.00963	0.0108	0.0120	0.0131	0.0142
h	–118.6	–100.3	–81.4	–40.8	22.8	90.0	132.6	163.9	191.1	216.1	240.0	263.1	285.6
s	3.000	3.211	3.407	3.773	4.260	4.798	5.020	5.174	5.298	5.404	5.497	5.581	5.657
C_p	1.818	1.860	1.915	2.205	4.808	2.338	1.594	1.361	1.249	1.186	1.146	1.119	1.100
μ	2.028	1.318	0.936	0.559	0.277	0.153	0.149	0.154	0.161	0.169	0.178	0.186	0.195
k	0.150	0.134	0.117	0.0861	0.0480	0.0360	0.0238	0.0240	0.0248	0.0258	0.0270	0.0283	0.0296
80 v	0.00113	0.00119	0.00126	0.00145	0.00188	0.00327	0.00480	0.00601	0.00706	0.00803	0.00894	0.00981	0.0107
h	–117.2	–99.1	–80.4	–41.3	9.0	78.4	125.3	158.7	187.1	212.9	237.3	260.8	283.7
s	2.989	3.198	3.391	3.745	4.138	4.597	4.875	5.051	5.186	5.299	5.396	5.484	5.562
C_p	1.802	1.838	1.881	2.078	2.992	3.029	1.887	1.510	1.342	1.250	1.194	1.156	1.130
μ	2.12	1.38	0.977	0.597	0.356	0.194	0.167	0.166	0.170	0.177	0.184	0.191	0.200
k	0.152	0.134	0.120	0.0901	0.0599	0.0420	0.0278	0.0268	0.0269	0.0276	0.0286	0.0296	0.0308
100 v	0.00112	0.00118	0.00125	0.00142	0.00174	0.00252	0.00366	0.00467	0.00556	0.00637	0.00713	0.00785	0.00855
h	–115.8	–97.8	–79.4	–41.3	3.9	61.7	111.8	148.8	179.4	206.7	232.2	256.4	279.9
s	2.978	3.186	3.376	3.721	4.076	4.457	4.753	4.949	5.095	5.214	5.315	5.406	5.486
C_p	1.789	1.818	1.852	1.992	2.506	2.874	2.114	1.650	1.431	1.311	1.239	1.191	1.158
μ	2.21	1.44	1.02	0.631	0.405	0.249	0.193	0.181	0.181	0.185	0.191	0.198	0.205
k	0.154	0.137	0.122	0.0936	0.0669	0.0500	0.0327	0.0299	0.0293	0.0295	0.0302	0.0311	0.0320
150 v	0.00111	0.00116	0.00122	0.00137	0.00158	0.00194	0.00247	0.00309	0.00369	0.00425	0.00478	0.00529	0.00578
h	–112.2	–94.5	–76.6	–40.1	0.5	45.2	89.5	129.2	163.2	193.4	221.0	247.0	271.8
s	2.954	3.157	3.342	3.673	3.988	4.287	4.548	4.757	4.919	5.051	5.161	5.257	5.343
C_p	1.789	1.818	1.852	1.992	2.506	2.874	2.114	1.650	1.431	1.311	1.239	1.267	1.220
μ	2.44	1.60	1.13	0.709	0.490	0.349	0.266	0.229	0.215	0.211	0.212	0.215	0.220
k	0.157	1.142	0.127	0.101	0.0785	0.0588	0.0455	0.0389	0.0360	0.0348	0.0346	0.0349	0.0354
200 v	0.00110	0.00115	0.00120	0.00133	0.00150	0.00174	0.00206	0.00245	0.00287	0.00328	0.00368	0.00407	0.00446
h	–108.5	–91.2	–73.6	–38.0	0.2	40.2	79.8	117.6	152.2	183.6	212.5	239.6	265.5
s	2.930	3.130	3.312	3.634	3.931	4.198	4.432	4.631	4.796	4.932	5.048	5.149	5.238
C_p	1.733	1.747	1.761	1.809	1.905	1.988	1.953	1.814	1.643	1.501	1.396	1.321	1.266
μ	2.70	1.78	1.25	0.782	0.561	0.420	0.331	0.279	0.253	0.241	0.236	0.235	0.237
k	0.161	0.146	0.132	0.107	0.0868	0.0691	0.0559	0.0476	0.0429	0.0405	0.0393	0.0389	0.0389
250 v	0.00109	0.00114	0.00119	0.00130	0.00144	0.00162	0.00186	0.00214	0.00244	0.00276	0.00307	0.00338	0.00368
h	–104.8	–87.6	–70.3	–35.4	1.3	38.9	75.8	111.7	145.6	177.1	206.6	234.3	260.8
s	2.909	3.106	3.285	3.601	3.886	4.138	4.355	4.544	4.706	4.843	4.961	5.064	5.155
C_p	1.712	1.722	1.733	1.767	1.824	1.854	1.831	1.748	1.635	1.522	1.427	1.353	1.297
μ	2.96	1.97	1.39	0.855	0.625	0.476	0.385	0.327	0.292	0.272	0.262	0.257	0.256
k	0.165	0.150	0.137	0.113	0.0935	0.0769	0.0641	0.0552	0.0495	0.0460	0.0441	0.0430	0.0426

*For sources, units, and remarks, see Table 2-228. v = specific volume, m^3/kg; h = specific enthalpy, kJ/kg; s = specific entropy, kJ/(kg·K); c_p = specific heat at constant pressure, kJ/(kg·K); μ = viscosity, 10^{-4} Pa·s; and k = thermal conductivity, W/(m·K). For specific heat ratio, see Table 2-200; for Prandtl number, see Table 2-369.

Temperature, K												
350	400	450	500	600	800	1000	1200	1400	1600	1800	2000	2500
1.005	1.148	1.292	1.436	1.723	2.297	2.872	3.446	4.020	4.594	5.168	5.743	7.200
350.7	401.2	452.1	503.4	607.5	822.5	1046.8	1278	1515	1764	2017	2279	3011
7.026	7.161	7.282	7.389	7.579	7.888	8.138	8.349	8.531	8.695	8.844	8.983	9.308
1.009	1.014	1.021	1.030	1.051	1.099	1.141	1.175	1.207	1.248	1.286	1.337	1.665
0.208	0.230	0.251	0.270	0.306	0.370	0.424	0.473	0.527	0.584	0.637	0.689	0.818
0.0301	0.0336	0.0371	0.0404	0.0466	0.0577	0.0681	0.0783	0.0927	0.106	0.120	0.137	0.222
0.201	0.230	0.259	0.288	0.345	0.460	0.575	0.690	0.805	0.920	1.034	1.149	1.438
350.0	400.8	451.8	503.2	607.4	822.6	1046.9	1279	1516	1764	2017	2278	2981
6.563	6.698	6.818	6.927	7.116	7.426	7.676	7.887	8.069	8.233	8.382	8.520	8.832
1.014	1.017	1.024	1.032	1.053	1.100	1.142	1.175	1.208	1.248	1.285	1.326	1.516
0.208	0.230	0.251	0.270	0.306	0.370	0.425	0.473	0.527	0.584	0.637	0.689	0.818
0.0303	0.0338	0.0372	0.0405	0.0467	0.0578	0.0681	0.0783	0.0927	0.106	0.120	0.136	0.195
0.101	0.115	0.130	0.144	0.173	0.231	0.288	0.345	0.403	0.460	0.518	0.575	0.720
349.2	400.2	451.4	502.9	607.3	822.7	1047.2	1279	1516	1765	2018	2279	2974
6.361	6.497	6.618	6.727	6.917	7.226	7.477	7.688	7.870	8.034	8.183	8.321	8.630
1.019	1.021	1.027	1.034	1.055	1.100	1.142	1.175	1.208	1.248	1.284	1.324	1.481
0.209	0.231	0.252	0.271	0.306	0.370	0.425	0.473	0.527	0.584	0.637	0.689	0.817
0.0305	0.0340	0.0374	0.0407	0.0469	0.0579	0.0682	0.0784	0.0927	0.106	0.120	0.135	0.187
0.0503	0.0577	0.0650	0.0723	0.0868	0.116	0.145	0.173	0.202	0.231	0.260	0.288	0.360
347.7	399.1	450.7	502.4	607.2	823.0	1047.7	1280	1517	1766	2019	2279	2970
6.158	6.295	6.417	6.526	6.716	7.027	0.277	7.489	7.671	7.835	7.984	8.121	8.428
1.030	1.029	1.033	1.039	1.057	1.102	1.143	1.176	1.209	1.249	1.284	1.322	1.456
0.210	0.232	0.253	0.272	0.307	0.371	0.425	0.474	0.527	0.584	0.637	0.689	0.817
0.0309	0.0344	0.0377	0.0410	0.0471	0.0581	0.0685	0.0787	0.0928	0.106	0.120	0.135	0.181
0.0252	0.0290	0.0327	0.0364	0.0438	0.0583	0.0728	0.0872	0.102	0.116	0.130	0.145	0.181
344.6	397.0	449.2	501.5	606.9	823.7	1048.8	1281	1519	1768	2021	2281	2969
5.950	6.090	6.212	6.323	6.515	6.826	7.077	7.289	7.473	7.636	7.785	7.922	8.229
1.051	1.044	1.044	1.049	1.063	0.105	1.145	1.177	1.210	1.249	1.284	1.322	1.438
0.213	0.235	0.255	0.274	0.309	0.372	0.426	0.474	0.527	0.584	0.637	0.689	0.817
0.0318	0.0351	0.0384	0.0416	0.0476	0.0584	0.0687	0.0789	0.0928	0.106	0.120	0.135	0.177
0.0169	0.0194	0.0220	0.0245	0.0294	0.0392	0.0489	0.0585	0.0681	0.0776	0.0872	0.0968	0.1207
340.4	394.0	447.1	500.6	606.8	824.3	1050.0	1283	1521	1770	2023	2284	2969
5.824	5.967	6.091	6.202	6.396	6.708	6.960	7.172	7.355	7.520	7.669	7.806	8.112
1.072	1.059	1.055	1.057	1.069	1.108	1.147	1.178	1.210	1.249	1.286	1.322	1.430
0.217	0.237	0.257	0.275	0.310	0.373	0.427	0.475	0.527	0.584	0.637	0.689	0.817
0.0328	0.0359	0.0391	0.0422	0.0481	0.0588	0.0690	0.0790	0.0929	0.106	0.120	0.134	0.176
0.0127	0.0147	0.0166	0.0185	0.0223	0.0296	0.0369	0.0442	0.0513	0.0585	0.0657	0.0729	0.0908
339.0	393.1	446.5	499.8	606.7	825.1	1051.1	1284	1522	1772	2025	2285	2971
5.733	5.878	6.004	6.116	6.311	6.624	6.877	7.089	7.273	7.437	7.586	7.723	8.029
1.091	1.073	1.066	1.065	1.075	1.111	1.149	1.180	1.210	1.249	1.286	1.322	1.426
0.220	0.240	0.259	0.278	0.312	0.374	0.428	0.475	0.527	0.584	0.637	0.689	0.817
0.0337	0.0368	0.0398	0.0428	0.0486	0.0592	0.0693	0.0793	0.0929	0.106	0.120	0.134	0.175
0.0102	0.0118	0.0134	0.0149	0.0180	0.0239	0.0298	0.0356	0.0413	0.0470	0.0528	0.0584	0.0729
336.5	391.3	445.3	499.0	606.6	825.8	1052.4	1286	1524	1774	2027	2288	2972
5.661	5.807	5.935	6.048	6.244	6.559	6.812	7.024	7.208	7.373	7.522	7.659	7.964
1.110	1.087	1.076	1.073	1.080	1.114	1.151	1.181	1.211	1.250	1.288	1.323	1.423
0.224	0.243	0.262	0.280	0.314	0.375	0.429	0.477	0.527	0.584	0.637	0.689	0.817
0.0347	0.0376	0.0405	0.0434	0.0491	0.0595	0.0696	0.0795	0.0930	0.106	0.120	0.134	0.175
0.00695	0.00806	0.00914	0.0102	0.0123	0.0163	0.0202	0.0241	0.0279	0.0317	0.0356	0.0394	0.0490
330.9	387.5	442.9	497.5	606.6	827.8	1055.5	1290	1529	1779	2033	2294	2977
5.525	5.677	5.807	5.922	6.121	6.439	6.693	6.906	7.092	7.256	7.405	7.543	7.848
1.151	1.117	1.099	1.092	1.093	1.121	1.155	1.184	1.213	1.252	1.290	1.325	1.418
0.235	0.252	0.270	0.286	0.318	0.379	0.431	0.478	0.527	0.584	0.637	0.689	
0.0374	0.0398	0.0424	0.0451	0.0504	0.0605	0.0703	0.0801	0.0932	0.106	0.120	0.133	
0.00534	0.00620	0.00702	0.00783	0.00940	0.0125	0.0154	0.0184	0.0212	0.0241	0.0269	0.0298	0.0370
326.5	384.5	440.9	496.6	607.0	829.9	1058.7	1294	1533	1783	2038	2299	2982
5.426	5.581	5.715	5.831	6.033	6.353	6.608	6.822	7.009	7.173	7.323	7.460	7.765
1.184	1.141	1.119	1.108	1.104	1.128	1.160	1.187	1.214	1.254	1.292	1.326	1.415
0.248	0.262	0.278	0.293	0.324	0.382	0.434	0.481	0.528	0.585	0.638		
0.0400	0.0420	0.0423	0.0467	0.0517	0.0614	0.0711	0.0808	0.0934	0.106	0.120		
0.00440	0.00509	0.00576	0.00642	0.00770	0.0102	0.0126	0.0149	0.0172	0.0195	0.0218	0.0241	0.0298
323.2	382.3	439.6	496.0	607.6	832.2	1062.0	1298	1538	1789	2043	2304	2988
5.348	5.506	5.641	5.760	5.963	6.286	6.542	6.757	6.944	7.108	7.258	7.396	7.701
1.208	1.161	1.135	1.121	1.115	1.135	1.164	1.190	1.216	1.256	1.294	1.328	1.414
0.262	0.273	0.286	0.301	0.329	0.386	0.437	0.483	0.528	0.585			
0.0429	0.0443	0.0462	0.0484	0.0531	0.0624	0.0718	0.0814	0.0937	0.106			

TABLE 2-229 Thermophysical Properties of Compressed Air (*Concluded*)

Pressure, bar	Temperature, K												
	80	90	100	120	140	160	180	200	220	240	260	280	300
300 v	0.00108	0.00112	0.00117	0.00127	0.00139	0.00155	0.00173	0.00195	0.00219	0.00243	0.00269	0.00294	0.00318
h	−101.0	−84.0	−67.0	−32.4	3.1	39.2	74.5	109.0	142.0	173.2	202.7	230.8	257.7
s	2.888	3.083	3.260	3.572	3.849	4.090	4.298	4.480	4.637	4.773	4.891	4.995	5.088
C_p	1.694	1.703	1.713	1.740	1.769	1.777	1.751	1.689	1.607	1.518	1.438	1.370	1.316
μ	3.24	2.18	1.53	0.932	0.687	0.529	0.433	0.370	0.329	0.303	0.288	0.280	0.276
k	0.168	0.154	0.141	0.118	0.0996	0.0836	0.0710	0.0619	0.0555	0.0514	0.0487	0.0471	0.0462
400 v		0.00110	0.00114	0.00123	0.00133	0.00145	0.00158	0.00173	0.00189	0.00206	0.00224	0.00242	0.00260
h		−76.6	−59.8	−25.9	8.3	42.4	75.8	108.5	140.1	170.5	199.7	227.8	254.8
s		3.042	3.216	3.523	3.788	4.016	4.214	4.386	4.537	4.669	4.786	4.890	4.983
C_p		1.674	1.686	1.704	1.702	1.685	1.654	1.607	1.550	1.490	1.431	1.378	1.331
μ		2.63	1.86	1.10	0.802	0.631	0.500	0.446	0.397	0.364	0.341	0.325	0.316
k		0.161	0.149	0.127	0.110	0.0946	0.0823	0.0729	0.0660	0.0610	0.0574	0.0550	0.0533
500 v		0.00109	0.00112	0.00120	0.00128	0.00138	0.00148	0.00160	0.00173	0.00186	0.00199	0.00213	0.00227
h		−69.0	−52.3	−18.7	14.4	47.4	79.8	111.4	142.0	171.7	200.5	228.4	255.4
s		3.005	3.177	3.482	3.743	3.966	4.151	4.317	4.463	4.593	4.708	4.811	4.905
C_p		1.655	1.670	1.686	1.667	1.644	1.598	1.557	1.509	1.461	1.415	1.371	1.331
μ		3.13	2.24	1.31	0.924	0.710	0.0560	0.512	0.459	0.420	0.391	0.370	0.356
k		0.167	0.156	0.135	0.119	0.104	0.0916	0.0822	0.0749	0.0694	0.0653	0.0622	0.0599
600 v								0.00151	0.00161	0.00172	0.00183	0.00194	0.00205
h								116.0	146.1	175.3	203.6	231.2	258.1
s								2.263	4.406	4.533	4.646	4.749	4.842
C_p								1.525	1.480	1.438	1.398	1.361	1.327
μ									0.516	0.472	0.439	0.414	0.396
k								0.0903	0.0828	0.0769	0.0724	0.0689	0.0662
800 v									0.00147	0.00155	0.00163	0.00171	0.00179
h									157.4	185.9	213.7	240.3	267.3
s									4.318	4.442	4.553	4.653	4.745
C_p									1.445	1.406	1.372	1.342	1.314
μ											0.529	0.497	0.473
k									0.0964	0.0901	0.0850	0.0809	0.0776
1000 v											0.00151	0.00157	0.00163
h											226.4	253.2	279.5
s											4.482	4.582	4.672
C_p											1.355	1.327	1.303
μ													0.546
k											0.0961	0.0916	0.0878

Temperature, K												
350	400	450	500	600	800	1000	1200	1400	1600	1800	2000	2500
0.00379	0.00437	0.00493	0.00548	0.00656	0.00864	0.0107	0.0126	0.0145	0.0164	0.0183	0.0202	0.0250
320.9	380.9	438.9	495.9	608.5	834.5	1065.3	1302	1542	1794	2049	2310	2993
5.283	5.443	5.580	5.700	5.906	6.230	6.488	6.703	6.891	7.056	7.206	7.344	7.648
1.226	1.176	1.148	1.133	1.124	1.140	1.168	1.193	1.217	1.257	1.298	1.330	1.413
0.276	0.284	0.296	0.308	0.335	0.390	0.440	0.485	0.529				
0.0457	0.0466	0.0481	0.0501	0.0544	0.0634	0.0726	0.0820	0.0940				
0.00304	0.00348	0.00390	0.00432	0.00514	0.00673	0.00826	0.00977	0.0111	0.0126	0.0140	0.0155	0.0190
319.1	380.0	439.0	496.8	611.0	839.4	1072.0	1310	1552	1804	2059	2321	3004
5.181	5.344	5.483	5.605	5.813	6.142	6.401	6.618	6.808	6.972	7.123	7.261	7.566
1.246	1.195	1.166	1.149	1.138	1.151	1.176	1.199	1.222	1.258	1.301	1.333	1.412
0.307	0.308	0.315	0.325	0.348	0.398	0.446	0.490					
0.0513	0.0512	0.0521	0.0535	0.0571	0.0653	0.0740	0.0832					
0.00262	0.00296	0.00330	0.00364	0.00430	0.00558	0.00683	0.00804	0.00911	0.0103	0.0114	0.0126	0.0154
319.9	381.3	440.8	499.1	614.3	844.6	1078.8	1318	1561	1814	2070	2332	3015
5.103	5.267	5.408	5.531	5.741	6.072	6.333	6.550	6.743	6.907	7.058	7.196	7.501
1.255	1.206	1.176	1.159	1.148	1.159	1.183	1.205	1.226	1.265	1.306	1.337	1.412
0.338	0.333	0.336	0.343	0.361	0.407	0.452	0.495					
0.0568	0.0557	0.0560	0.0569	0.0598	0.0672	0.0755	0.0844					
0.00234	0.00262	0.00290	0.00318	0.00374	0.00481	0.00586	0.00689	0.00776	0.00873	0.00970	0.0107	0.0130
322.6	384.2	444.0	502.6	618.5	850.1	1085.5	1326	1570	1824	2080	2343	3026
5.041	5.205	5.346	5.470	5.681	6.014	6.277	6.495	6.690	6.854	7.005	7.144	7.449
1.258	1.211	1.182	1.166	1.154	1.166	1.189	1.210	1.231	1.267	1.310	1.341	1.412
0.370	0.359	0.358	0.361	0.375	0.416	0.459	0.501					
0.0620	0.0602	0.0598	0.0603	0.0625	0.0691	0.0770	0.0857					
0.00200	0.00221	0.00242	0.00263	0.00304	0.00385	0.00465	0.00544	0.00608	0.00681	0.00754	0.00826	0.0101
331.6	393.8	453.4	512.3	625.8	862.0	1099.3	1341	1588	1844	2101	2365	3049
4.943	5.108	5.250	5.374	5.586	5.922	6.136	6.407	6.605	6.769	6.921	7.060	7.366
1.257	1.216	1.188	1.172	1.161	1.175	1.198	1.219	1.240	1.275	1.318	1.347	1.412
0.432	0.411	0.402	0.399	0.405	0.436	0.474	0.512					
0.0718	0.0688	0.0673	0.0669	0.0679	0.0730	0.0800	0.0881					
0.00180	0.00196	0.00213	0.00230	0.00262	0.00328	0.00392	0.00455	0.00507	0.00565	0.00624	0.00681	0.00825
343.4	405.1	465.3	524.4	641.2	875.1	1113.3	1356	1606	1863	2121	2386	3071
4.869	5.034	5.176	5.300	5.513	5.850	6.115	6.337	6.539	6.703	6.856	6.995	7.302
1.254	1.217	1.192	1.175	1.164	1.179	1.204	1.225	1.248	1.283	1.325	1.354	1.413
0.494	0.463	0.446	0.438	0.435	0.456	0.489	0.524					
0.0810	0.0768	0.0744	0.0733	0.0732	0.0768	0.0830	0.0906					

TABLE 2-230 Enthalpy and Psi Functions for Ideal-Gas Air*

T, K	h, kJ/kg	Ψ	T, K	h, kJ/kg	Ψ	T, K	h, kJ/kg	Ψ
200	200.0	−0.473	650	659.8	1.339	1200	1278	2.376
210	210.0	−0.400	660	670.5	1.364	1220	1301	2.406
220	220.0	−0.329	670	681.1	1.388	1240	1325	2.435
230	230.1	−0.262	680	691.8	1.412	1260	1349	2.463
240	240.1	−0.197	690	702.5	1.436	1280	1372	2.491
250	250.1	−0.135	700	713.3	1.459	1300	1396	2.519
260	260.1	−0.076	710	724.0	1.482	1320	1420	2.547
270	270.1	−0.018	720	734.8	1.505	1340	1444	2.574
280	280.1	0.037	730	745.6	1.528	1360	1467	2.601
290	290.2	0.090	740	756.4	1.550	1380	1491	2.627
300	300.2	0.142	750	767.3	1.572	1400	1515	2.653
310	310.3	0.191	760	778.2	1.594	1420	1539	2.679
320	320.3	0.240	770	789.1	1.615	1440	1563	2.705
330	330.4	0.286	780	800.0	1.637	1460	1587	2.730
340	340.4	0.332	790	811.0	1.658	1480	1612	2.755
350	350.5	0.376	800	821.9	1.679	1500	1636	2.779
360	360.6	0.419	810	832.9	1.699	1520	1660	2.803
370	370.7	0.461	820	844.0	1.720	1540	1684	2.827
380	380.8	0.502	830	855.0	1.740	1560	1709	2.851
390	390.9	0.541	840	866.1	1.760	1580	1738	2.875
400	401.0	0.580	850	877.2	1.780	1600	1758	2.898
410	411.2	0.618	860	888.3	1.800	1620	1782	2.921
420	421.3	0.655	870	899.4	1.819	1640	1806	2.944
430	431.5	0.691	880	910.6	1.838	1660	1831	2.966
440	441.7	0.727	890	921.8	1.857	1680	1855	2.988
450	451.8	0.761	900	933.0	1.876	1700	1880	3.010
460	462.1	0.795	910	944.2	1.895	1720	1905	3.032
470	472.3	0.829	920	955.4	1.914	1740	1929	3.054
480	482.5	0.861	930	966.7	1.932	1760	1954	3.075
490	492.8	0.893	940	978.0	1.950	1780	1979	3.096
500	503.1	0.925	950	989.3	1.969	1800	2003	3.117
510	513.4	0.956	960	1000.6	1.987	1820	2028	3.138
520	523.7	0.986	970	1011.9	2.004	1840	2053	3.158
530	534.0	1.016	980	1023.3	2.022	1860	2078	3.178
540	544.4	1.045	990	1034.7	2.039	1880	2102	3.198
550	554.8	1.074	1000	1046.1	2.057	1900	2127	3.218
560	565.2	1.102	1020	1068.9	2.091	1920	2152	3.238
570	575.6	1.130	1040	1091.9	2.125	1940	2177	3.258
580	586.1	1.158	1060	1114.9	2.158	1960	2202	3.277
590	596.5	1.185	1080	1138.0	2.190	1980	2227	3.296
600	607.0	1.211	1100	1161.1	2.223	2000	2252	3.215
610	617.5	1.238	1120	1184.3	2.254	2050	2315	3.362
620	628.1	1.264	1140	1207.6	2.285	2100	2377	3.408
630	638.6	1.289	1160	1230.9	2.316	2150	2440	3.453
640	649.2	1.314	1180	1254.3	2.346	2200	2504	3.496

*Values rounded off from Chappell and Cockshutt, Nat. Res. Counc. Can. Rep. NRC LR 759 (NRC No. 14300), 1974. This source tabulates values of seven thermodynamic functions at 1-K increments from 200 to 2200 K in SI units and at other increments for two other unit systems. An earlier report (NRC LR 381, 1963) gives a more detailed description of an earlier fitting from 200 to 1400 K. In the above table h = specific enthalpy, kJ/kg, and $\Psi_2 - \Psi_1 = \log_{10} (P_2/P_1)_s$ for an isentrope. In terms of the Keenan and Kaye function ϕ, $\Psi = (\log_{10} e/R) \cdot \phi$.

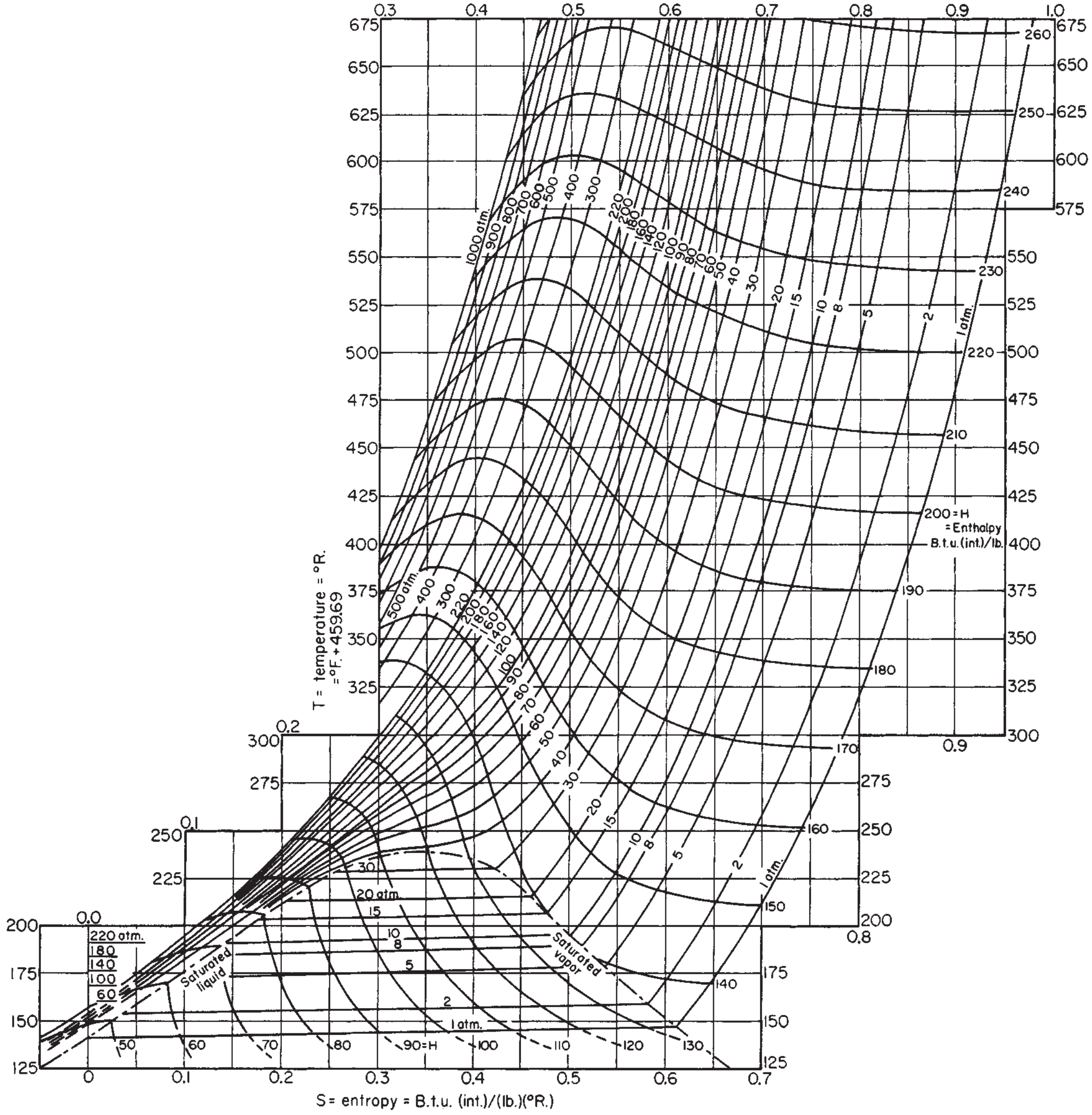

FIG. 2-5 Temperature-entropy diagram for air. [*Landsbaum, Dadds, Stevens, et al.,* Am. Inst. Chem. Eng. J., ***1****(3), 303 (1955). Reproduced by permission of the authors and of the editor, American Institute of Chemical Engineers.*]

TABLE 2-231 Air

Other tables include Stewart, R. B., S. G. Penoncello, et al., University of Idaho CATS report, 85-5, 1985 (0.1–700 bar, 85–750 K), and a revision is in process of publication. Tables including reactions with hydrocarbons include Gordon, S., NASA Techn. Paper 1907, 4 vols., 1982. See also Gupta, R. N., K-P. Lee, et al., NASA RP 1232, 1990 (89 pp.) and RP 1260, 1991 (75 pp.). Analytic expressions for high temperatures were given by Matsuzaki, R., *Jap. J. Appl. Phys.*, **21,** 7 (1982): 1009–1013 and Japanese National Aerospace Laboratory report NAL TR 671, 1981 (45 pp.). Functions from 1500 to 15000 K were tabulated by Hilsenrath, J. and M. Klein, AEDC-TR-65-58 = AD 612 301, 1965 (333 pp.). Tables from 10000 to 10,000,000 K were authored by Gilmore, F. R., Lockheed rept. 3-27-67-1, vol 1., 1967 (340 pp.), also published as *Radiative Properties of Air,* IFI/Plenum, New York, 1969 (648 pp.). Saturation and superheat tables and a chart to 7000 psia, 660°R appear in Stewart, R. B., R. T. Jacobsen, et al., *Thermodynamic Properties of Refrigerants,* ASHRAE, Atlanta, GA, 1986 (521 pp.). For specific heat, thermal conductivity, and viscosity see *Thermophysical Properties of Refrigerants,* ASHRAE, 1993.

AIR, MOIST

An ASHRAE publication, *Thermodynamic Properties of Dry Air and Water and S. I. Psychrometric Charts,* 1983 (360 pp.), extensively reviews moist air properties. Gandiduson, P., *Chem. Eng.*, Oct. 29, 1984 gives on page 118 a nomograph from 50 to 120°F, while equations in SI units were given by Nelson, B., *Chem. Eng. Progr.* **76,** 5 (May 1980): 83–85. Liley, P. E., *2000 Solved Problems in M.E. Thermodynamics,* McGraw-Hill, New York, 1989, gives four simple equations with which most calculations can be made. Devres, Y.O., *Appl. Energy* **48** (1994): 1–18 gives equations with which three known properties can be used to determine four others. Klappert, M. T. and G. F. Schilling, Rand RM-4244-PR = AD 604 856, 1984 (40 pp.) gives tables from 100 to 270 K, while programs from −60 to 2°F are given by Sando, F. A., *ASHRAE Trans.,* **96,** 2 (1990): 299–308.

Viscosity references include Kestin, J. and J. H. Whitelaw, *Int. J. Ht. Mass Transf.* **7,** 11 (1964): 1245–1255; Studnokov, E. L., *Inz.-Fiz. Zhur.* **19,** 2 (1970): 338–340; Hochramer, D. and F. Munczak, *Setzb. Ost. Acad. Wiss II* **175,** 10 (1966): 540–550. For thermal conductivity see, for instance, Mason, E. A. and L. Monchick, *Humidity and Moisture Control in Science and Industry,* Reinhold, New York, 1965 (257–272).

TABLE 2-232 Saturated Ammonia*

T, K	P, bar	v_f, m^3/kg	v_g, m^3/kg	h_f, kJ/kg	h_g, kJ/kg	s_f, kJ/(kg·K)	s_g, kJ/(kg·K)	c_{pf}, kJ/(kg·K)	μ_f, 10^{-4} Pa·s	k_f, W/(m·K)
195.5^t	0.0608	1.327.–3	15.648	−1110.1	380.1	4.203	11.827	4.73	4.25	0.715
200	0.0865	1.372.–3	11.237	−1088.8	388.5	4.311	11.698	4.61	4.07	0.709
210	0.1775	1.394.–3	5.729	−1044.1	406.7	4.529	11.438	4.38	3.69	0.685
220	0.3381	1.417.–3	3.135	−1000.6	424.1	4.731	11.207	4.35	3.34	0.661
230	0.6044	1.442.–3	1.822	−957.0	440.7	4.925	11.002	4.38	3.02	0.638
240	1.0226	1.468.–3	1.115	−912.9	456.2	5.113	10.817	4.43	2.73	0.615
250	1.6496	1.495.–3	0.712	−868.2	470.6	5.294	10.650	4.48	2.45	0.592
260	2.5529	1.524.–3	0.472	−823.1	483.8	5.471	10.498	4.54	2.20	0.569
270	3.8100	1.551.–3	0.324	−777.3	495.6	5.643	10.358	4.60	1.97	0.546
280	5.5077	1.589.–3	0.228	−730.9	506.0	5.811	10.228	4.66	1.76	0.523
290	7.741	1.626.–3	0.165	−683.8	514.7	5.975	10.108	4.73	1.58	0.500
300	10.61	1.666.–3	0.121	−636.0	521.5	6.135	9.994	4.82	1.41	0.477
310	14.24	1.710.–3	0.091	−587.2	526.1	6.293	9.885	4.91	1.26	0.454
320	18.72	1.760.–3	0.069	−537.5	528.2	6.448	9.779	5.02	1.13	0.431
330	24.20	1.815.–3	0.053	−486.7	527.5	6.602	9.675	5.17	1.02	0.408
340	30.79	1.878.–3	0.0410	−434.3	523.3	6.755	9.571	5.37	0.92	0.385
350	38.64	1.952.–3	0.0319	−380.0	515.1	6.908	9.465	5.64	0.83	0.361
360	47.90	2.039.–3	0.0249	−323.2	501.8	7.063	9.354	6.04	0.75	0.337
370	58.74	2.148.–3	0.0194	−262.6	481.9	7.222	9.235	6.68	0.69	0.313
380	71.35	2.291.–3	0.0149	−196.5	452.7	7.391	9.100	7.80	0.61	0.286
390	85.98	2.499.–3	0.0113	−120.9	408.1	7.578	8.935	10.3	0.50	0.254
400	103.0	2.882.–3	0.0077	−23.5	329.0	7.813	8.694	21.	0.39	0.21
405.4^c	113.0	4.255.–3	0.0043	142.7	142.7	8.216	8.216	∞	0.25	∞

**P, v, h,* and *s* values condensed from *ASHRAE Handbook, 1981: Fundamentals.* Copyright 1981 by the American Society of Heating, Refrigerating and Air Conditioning Engineers, Inc., and reproduced by permission of the copyright owner. c_p, μ, and k values are interpolated and converted from *Thermophysical Properties of Refrigerants,* ASHRAE, New York, 1976. t = triple point; c = critical point. The notation 1.327.–3 signifies 1.327×10^{-3}. At 195.5 K, the viscosity of the saturated liquid is 4.25×10^{-4} Pa·s.

Most recent tabulations of ammonia properties are based upon the extensive tabulation to 5000 bar, 750 K of Haar, L. and J. S. Gallagher, *J. Phys. Chem. Ref. Data,* **7,** 3 (1978): 635–792, which does, however, neglect dissociation. For tables to 70,000 psia, 920°F, see Stewart, R. B., R. T. Jacobsen, et al., *Thermodynamic Properties of Refrigerants,* ASHRAE, Atlanta, GA, 1986 (521 pp.). A chart in fps units corresponding with these tables appears on page 17.34 of the ASHRAE 1989 *Fundamentals Handbook.*

Simmons, A. L., C. E. Miller III, et al., *Tables and Charts of Equilibrium Thermodynamic Properties of Ammonia for Temperatures from 500 to 50000 K,* NASA SP 3099, 1976 (255 pp.), tabulates ρ, h, s, c_p, c_v, Z, and so on, from 0.01 to 400 bar and also 18 species of decomposition products.

The 1993 ASHRAE *Handbook—Fundamentals* (SI ed.) gives material for integral degrees Celsius with temperatures on the ITS 90 scale for saturation temperatures from −77.66 to 132.22 °C. The same diagram reproduced here appears in that source.

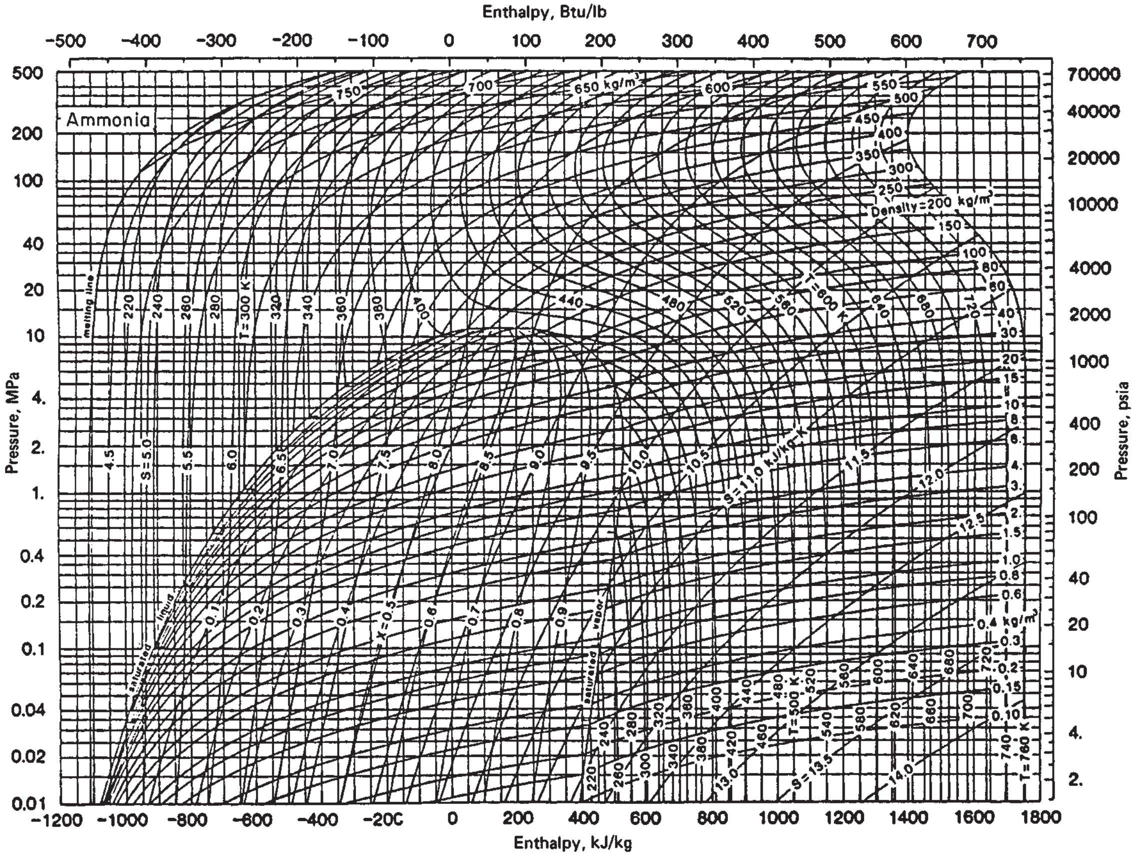

FIG. 2-6 Enthalpy–log-pressure diagram for ammonia. 1 MPa = 10 bar. (*Copyright 1981 by the American Society of Heating, Refrigerating and Air-Conditioning Engineers and reproduced by permission of the copyright owner.*)

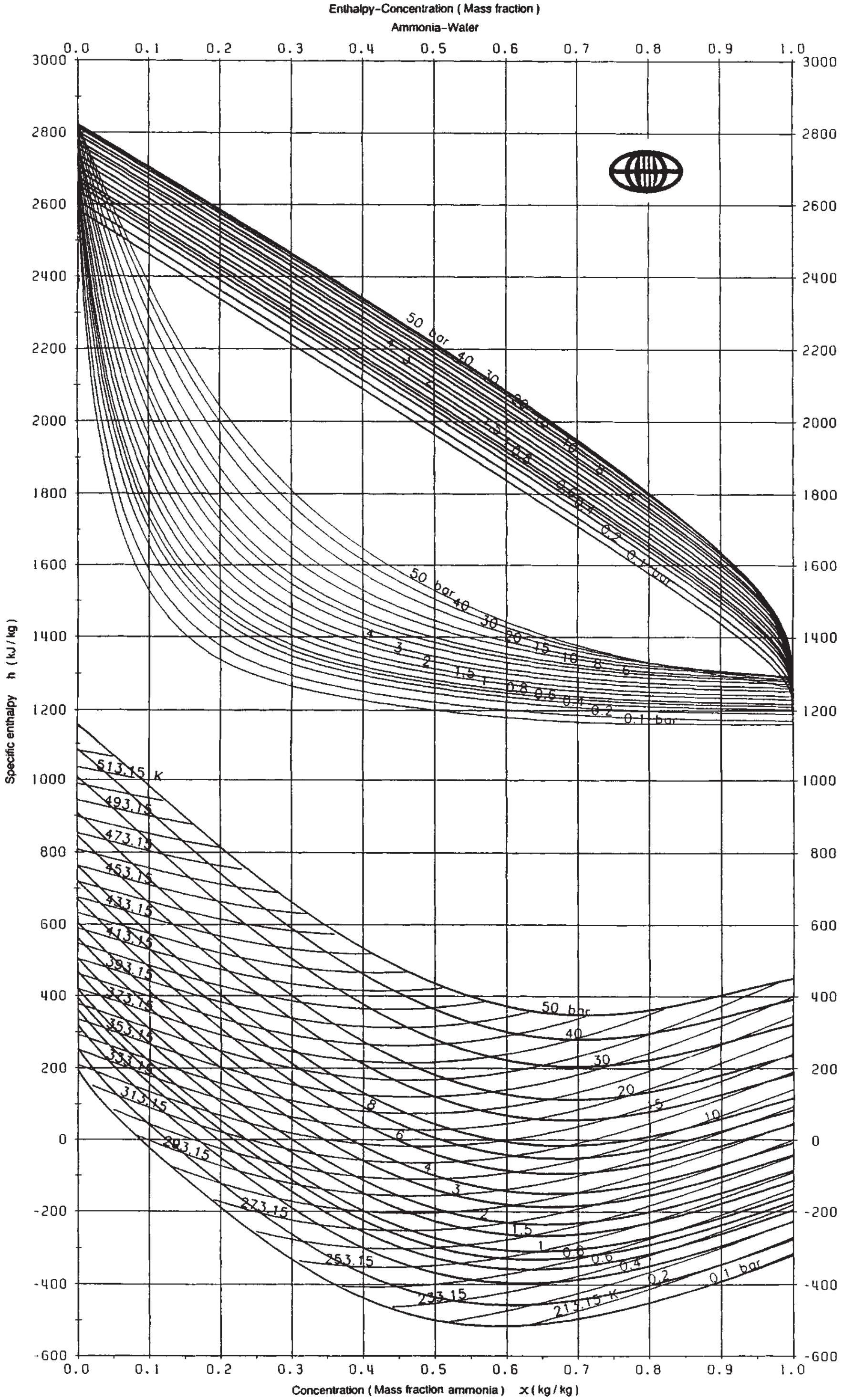

FIG. 2-7 Enthalpy-concentration diagram for aqueous ammonia. From *Thermodynamic and Physical Properties* NH_3–H_2O, Int. Inst. Refrigeration, Paris, France, 1994 (88 pp.). Reproduced by permission. In order to determine equilibrium compositions, draw a vertical from any liquid composition on any boiling line (the lowest plots) to intersect the appropriate auxiliarly curve (the intermediate curves). A horizontal then drawn from this point to the appropriate dew line (the upper curves) will establish the vapor composition. The Int. Inst. Refrigeration publication also gives extensive *P-v-x* tables from −50 to 316°C. Other sources include Park, Y. M. and Sonntag, R. E., *ASHRAE Trans.*, **96,** 1 (1990): 150–159 (*x, h, s,* tables, 360 to 640 K); Ibrahim, O. M. and S. A. Klein, *ASHRAE Trans.*, **99,** 1 (1993): 1495–1502 (Eqs., 0.2 to 110 bar, 293 to 413 K); Smolen, T. M., D. B. Manley, et al., *J. Chem. Eng. Data,* **36** (1991): 202–208 (*p-x* correlation, 0.9 to 450 psia, 293–413 K); Ruiter, J. P., *Int. J. Refrig.,* **13** (1990): 223–236 gives ten subroutines for computer calculations.

TABLE 2-233 Saturated Argon (R740)*

T, K	P, bar	v_f, m^3/kg	v_g, m^3/kg	h_f, kJ/kg	h_g, kJ/kg	s_f, kJ/(kg·K)	s_g, kJ/(kg·K)	c_{pf}, kJ/(kg·K)	μ_f, 10^{-4} Pa·s	k_f, W/(m·K)
10		5.646.–4		0.20		0.0266		0.083		
20		5.666.–4		2.20		0.1559		0.306		
30		5.707.–4		6.12		0.3129		0.466		
40		5.763.–4		11.30		0.4610		0.560		
50		5.831.–4		17.26		0.5937		0.627		
60		5.912.–4		23.85		0.7138		0.687		
70	0.082	6.008.–4	2.1800	31.08	229.08	0.8250	3.415	0.752		
80	0.406	6.125.–4	0.3918	39.07	232.88	0.9316	3.364	0.836		
83.8^t	0.687	6.178.–4	0.2434	42.34	235.06	0.9720	3.280	0.877		
83.8^t	0.687	7.068.–4	0.2434	71.88	235.06	1.333	3.280	1.050	2.93	0.134
85	0.790	7.107.–4	0.2145	73.16	235.55	1.348	3.258	1.058	2.81	0.132
87.3	1.013	7.174.–4	0.1710	75.61	236.39	1.375	3.216	1.073	2.60	0.128
90	1.338	7.269.–4	0.1327	78.55	237.37	1.403	3.168	1.091	2.40	0.124
95	2.137	7.440.–4	0.0864	84.15	238.91	1.462	3.091	1.124	2.08	0.116
100	3.247	7.628.–4	0.0588	89.85	240.20	1.520	3.023	1.158	1.82	0.109
110	6.665	8.064.–4	0.0299	101.83	241.66	1.632	2.903	1.229	1.46	0.096
115	9.107	8.322.–4	0.0221	108.11	241.78	1.685	2.848	1.274	1.32	0.090
120	12.13	8.618.–4	0.0166	114.62	241.33	1.738	2.794	1.336	1.21	0.084
125	15.81	8.965.–4	0.0126	121.50	240.30	1.792	2.743	1.427	1.12	0.078
130	20.23	9.620.–4	0.0096	128.79	238.41	1.846	2.690	1.550	1.01	0.072
135	25.49	9.906.–4	0.0074	136.76	234.60	1.902	2.633	1.752	0.89	0.066
140	31.68	1.061.–3	0.0056	145.58	230.74	1.961	2.570		0.75	0.060
145	38.93	1.172.–3	0.0041	155.73	223.09	2.026	2.490		0.60	0.054
150	47.39	1.468.–3	0.0026	174.64	204.35	2.133	2.331		0.45	
150.9	48.98	1.867.–3	0.0019	189.94	189.94	2.201	2.201		0.28	∞

*Values extracted and in some cases rounded off from those cited in Rabinovich (ed.), *Thermophysical Properties of Neon, Argon, Krypton and Xenon,* Standards Press, Moscow, 1976. This source contains values for the compressed state for pressures up to 1000 bar, etc. t = triple point. Above the solid line the condensed phase is solid; below it, it is liquid. The notation 5.646.–4 signifies 5.646 × 10^{-4}. At 83.8 K, the viscosity of the saturated liquid is 2.93 × 10^{-4} Pa·s = 0.000293 Ns/m^2. This book was published in English translation by Hemisphere, New York, 1988 (604 pp.).

TABLE 2-234 Thermodynamic Properties of Compressed Argon*

T, K		Pressure, bar										
		1	100	200	300	400	500	600	700	800	900	1000
	v	0.2035	7.420.–4	7.255.–4	7.120.–4	7.006.–4	6.907.–4	6.819.–4	6.050.–4	6.009.–4	5.976.–4	5.935.–4
100	h	243.4	93.6	97.9	102.5	107.2	112.0	116.8	91.1	96.1	101.0	106.0
	s	3.299	1.494	1.464	1.438	1.414	1.393	1.372	1.037	1.026	1.016	1.007
	v	0.4151	2.96.–3	1.430.–5	1.159.–3	1.045.–3	9.778.–4	9.312.–4	8.962.–4	8.683.–4	8.454.–4	8.260.–4
200	h	296.4	250.2	217.1	209.1	207.9	209.2	211.9	215.1	218.9	223.0	227.4
	s	3.667	2.538	2.276	2.173	2.112	2.068	2.033	2.004	1.979	1.957	1.936
	v	0.6241	5.96.–3	2.976.–3	2.071.–3	1.666.–3	1.443.–3	1.304.–3	1.207.–3	1.136.–3	1.081.–3	1.037.–3
300	h	348.6	330.9	316.3	306.6	301.4	299.3	299.2	300.5	302.7	305.6	310.0
	s	3.879	2.872	2.686	2.572	2.493	2.435	2.389	2.352	2.320	2.293	2.269
	v	0.8326	8.37.–3	4.279.–3	2.957.–3	2.322.–3	1.955.–3	1.719.–3	1.557.–3	1.435.–3	1.344.–3	1.271.–3
400	h	400.7	391.3	383.6	378.4	375.2	373.8	373.8	374.8	376.6	379.2	382.0
	s	4.028	3.048	2.881	2.780	2.707	2.651	2.603	2.565	2.533	2.505	3.480
	v	1.0409	1.062.–2	5.464.–3	3.772.–3	2.940.–3	2.448.–3	2.124.–3	1.899.–3	1.730.–3	1.607.–3	1.506.–3
500	h	452.8	447.7	444.3	442.0	440.9	440.6	441.4	422.9	444.7	447.1	449.9
	s	4.145	3.174	3.018	2.924	2.854	2.801	2.755	2.718	2.685	2.658	2.633
	v	1.2489	1.280.–2	6.589.–3	4.539.–3	3.525.–3	2.922.–3	2.522.–3	2.238.–3	2.023.–3	1.866.–3	1.736.–3
600	h	504.9	502.4	501.6	501.4	501.8	503.0	504.6	506.6	508.7	511.2	513.9
	s	4.240	3.274	3.122	3.031	2.966	2.914	2.870	2.834	2.801	2.774	2.750
	v	1.4569	1.495.–2	7.686.–3	5.281.–3	4.088.–3	3.377.–3	2.906.–3	2.570.–3	2.317.–3	2.123.–3	1.966.–3
700	h	556.9	556.5	556.9	558.0	559.8	561.8	564.2	566.9	569.6	527.5	575.3
	s	4.320	3.356	3.207	3.118	3.054	3.005	2.963	2.928	2.897	2.870	2.845
	v	1.6659	1.708.–2	8.768.–3	6.011.–3	4.640.–3	3.822.–3	3.280.–3	2.893.–3	2.603.–3	2.376.–3	2.196.–3
800	h	609.9	609.8	611.0	612.9	615.2	618.1	621.2	624.5	627.8	631.3	634.8
	s	4.389	3.427	3.279	3.191	3.129	3.081	3.039	3.005	2.975	2.948	2.924
	v	1.8739	1.920.–2	9.841.–3	6.732.–3	5.183.–3	4.259.–3	3.646.–3	3.209.–3	2.881.–3	2.626.–3	2.423.–3
900	h	661.0	662.7	664.6	667.2	670.1	673.3	676.8	680.7	684.4	688.3	692.3
	s	4.451	3.490	3.342	3.255	3.193	3.145	3.105	3.071	3.042	3.016	2.992
	v	2.0819	2.131.–2	1.091.–2	7.448.–3	5.723.–3	4.692.–3	4.008.–3	3.520.–3	3.156.–3	2.872.–3	2.645.–3
1000	h	713.1	715.4	717.9	720.9	724.3	727.8	731.5	735.6	739.8	744.1	748.5
	s	4.506	3.545	3.398	3.312	3.250	3.203	3.163	3.129	3.100	3.074	3.051

*Values extracted and in some cases rounded off from those cited in Rabinovich (ed.), *Thermophysical Properties of Neon, Argon, Krypton and Xenon,* Standards Press, Moscow, 1976. v = specific volume, m^3/kg; h = specific enthalpy, kJ/kg; s = specific entropy, kJ/(kg·K). This source contains an exhaustive tabulation of values. The notation 7.420.–4 signifies 7.420 × 10^{-4}. This book was published in English translation by Hemisphere, New York, 1988 (604 pp.). The 1993 ASHRAE *Handbook—Fundamentals* (SI ed.) has a thermodynamic chart for pressures from 1 to 2000 bar, temperatures from 90 to 700 K. Saturation and superheat tables and a chart to 50,000 psia, 1220 °R appear in Stewart, R. B., R. T. Jacobsen, et al., *Thermodynamic Properties of Refrigerants,* ASHRAE, Atlanta, GA, 1986 (521 pp.). For specific heat, thermal conductivity, and viscosity see *Thermophysical Properties of Refrigerants,* ASHRAE, 1993.

Extensive tables for 10 properties from 0.9–100 bar, 86–400 K are given by Jacques, A., Fermi Accelerator Lab., Batavia, IL, rept TM 1517, 1988 (201 pp.). In Hilsenrath, J., C. G. Messina, et al., AEDC-TR-66-248 = AD 644 081, 1966 (121 pp.), thermodynamic properties and chemical composition from 2400 to 35,000 K are tabulated. See also Drellishak, K. S. et al., AEDC-TDR-63-146, 1963; AEDC-TDR-64-12 = AD 427839, 1964.

TABLE 2-235 Liquid-Vapor Equilibrium Data for the Argon-Nitrogen-Oxygen System*

Liquid mole fraction		Vapor mole fraction			Temperature,°R	Relative volatility			Pressure activity coefficient			Enthalpy, Btu/(lb·mol)		Heat capacity, Btu/(lb·mol·°R)	
$N_2/N_2 + O_2$	Ar	N_2	Ar	O_2		N_2/Ar	N_2/O_2	Ar/O_2	N_2	Ar	O_2	Liquid	Vapor	Liquid	Vapor
Pressure, 1 atm															
0.	0.	0.	0.	1.0000	162.4	2.575	4.010	1.557	1.118	1.165	0.999	−1841.	1093.	13.2	7.406
0.	0.01	0.	0.0154	0.9845	162.3	2.581	4.007	1.553	1.117	1.161	1.000	−1844.	1087.	13.1	7.374
0.	0.02	0.	0.0306	0.9694	162.2	2.586	4.004	1.548	1.115	1.158	1.000	−1847.	1082.	13.1	7.342
0.	0.03	0.	0.0456	0.9544	162.1	2.592	4.001	1.544	1.113	1.155	1.000	−1850.	1076.	13.1	7.311
0.	0.04	0.	0.0603	0.9397	162.0	2.597	3.998	1.540	1.112	1.151	1.001	−1852.	1071.	13.0	7.281
0.	0.05	0.	0.0748	0.9253	161.9	2.602	3.995	1.535	1.110	1.148	1.001	−1855.	1066.	13.0	7.251
0.	0.07	0.	0.1031	0.8970	161.7	2.613	3.989	1.526	1.107	1.142	1.002	−1860.	1056.	12.9	7.192
0.	0.10	0.	0.1439	0.8561	161.5	2.629	3.979	1.513	1.103	1.132	1.003	−1868.	1041.	12.9	7.107
0.	0.20	0.	0.2687	0.7313	160.7	2.682	3.941	1.469	1.091	1.104	1.010	−1893.	997.	12.6	6.847
0.	0.40	0.	0.4796	0.5204	159.4	2.786	3.852	1.382	1.076	1.058	1.034	−1938.	924.	11.9	6.406
0.	0.60	0.	0.6605	0.3395	158.5	2.888	3.746	1.297	1.075	1.026	1.072	−1978.	862.	11.3	6.026
0.	0.80	0.	0.8293	0.1707	157.7	2.991	3.632	1.214	1.087	1.008	1.127	−2015.	807.	10.7	5.669
0.	0.90	0.	0.9136	0.0865	157.5	3.042	3.572	1.174	1.099	1.003	1.162	−2032.	779.	10.4	5.491
0.10	0.	0.3135	0.	0.6865	157.7	2.621	4.111	1.568	1.103	1.168	1.012	−1834.	1060.	13.2	7.410
0.10	0.01	0.3095	0.0119	0.6786	157.6	2.626	4.106	1.563	1.102	1.164	1.012	−1837.	1057.	13.1	7.386
0.10	0.02	0.3056	0.0237	0.6707	157.6	2.631	4.100	1.558	1.100	1.161	1.012	−1839.	1053.	13.1	7.361
0.10	0.03	0.3017	0.0354	0.6630	157.6	2.636	4.095	1.554	1.099	1.157	1.013	−1842.	1049.	13.1	7.337
0.10	0.04	0.2978	0.0470	0.6553	157.6	2.641	4.090	1.549	1.098	1.154	1.013	−1844.	1045.	13.1	7.313
0.10	0.05	0.2939	0.0585	0.6476	157.5	2.645	4.085	1.544	1.096	1.151	1.013	−1846.	1042.	13.0	7.289
0.10	0.07	0.2863	0.0812	0.6325	157.5	2.655	4.074	1.534	1.094	1.144	1.014	−1851.	1034.	13.0	7.242
0.10	0.10	0.2752	0.1145	0.6103	157.4	2.669	4.058	1.520	1.090	1.135	1.015	−1858.	1024.	12.9	7.173
0.10	0.20	0.2399	0.2207	0.5394	157.2	2.717	4.003	1.473	1.080	1.106	1.022	−1882.	990.	12.5	6.951
0.10	0.40	0.1759	0.4170	0.4072	157.0	2.812	3.887	1.382	1.070	1.061	1.045	−1926.	928.	11.9	6.540
0.10	0.60	0.1169	0.6036	0.2795	156.9	2.906	3.766	1.296	1.072	1.029	1.082	−1969.	871.	11.3	6.147
0.10	0.80	0.0595	0.7933	0.1471	156.9	3.001	3.640	1.213	1.086	1.009	1.134	−2009.	813.	10.7	5.746
0.10	0.90	0.0303	0.8937	0.0762	157.1	3.048	3.576	1.173	1.099	1.004	1.166	−2029.	783.	10.4	5.534
0.20	0.	0.5095	0.	0.4905	154.0	2.641	4.155	1.573	1.085	1.171	1.026	−1814.	1035.	13.2	7.422
0.20	0.01	0.5042	0.0096	0.4861	154.0	2.646	4.149	1.568	1.084	1.168	1.026	−1816.	1032.	13.2	7.402
0.20	0.02	0.4990	0.0192	0.4818	154.0	2.651	4.143	1.563	1.083	1.164	1.026	−1819.	1029.	13.1	7.382
0.20	0.03	0.4938	0.0288	0.4775	154.1	2.655	4.137	1.558	1.082	1.161	1.027	−1821.	1027.	13.1	7.362
0.20	0.04	0.4886	0.0383	0.4731	154.1	2.660	4.131	1.553	1.081	1.158	1.027	−1824.	1024.	13.1	7.342
0.20	0.05	0.4834	0.0477	0.4688	154.1	2.665	4.125	1.548	1.080	1.154	1.027	−1826.	1021.	13.0	7.322
0.20	0.07	0.4732	0.0666	0.4602	154.1	2.674	4.112	1.538	1.078	1.148	1.028	−1831.	1016.	13.0	7.283
0.20	0.10	0.4580	0.0946	0.4474	154.2	2.688	4.094	1.523	1.075	1.139	1.030	−1839.	1008.	12.9	7.224
0.20	0.20	0.4083	0.1866	0.4051	154.3	2.735	4.032	1.474	1.068	1.110	1.036	−1863.	981.	12.6	7.031
0.20	0.40	0.3123	0.3680	0.3197	154.8	2.829	3.907	1.381	1.062	1.064	1.058	−1911.	930.	11.9	6.648
0.20	0.60	0.2162	0.5550	0.2288	155.4	2.921	3.779	1.294	1.068	1.032	1.093	−1958.	877.	11.3	6.252
0.20	0.80	0.1144	0.7602	0.1254	156.2	3.009	3.647	1.212	1.086	1.011	1.140	−2004.	819.	10.7	5.817
0.20	0.90	0.0593	0.8744	0.0663	156.7	3.052	3.580	1.173	1.099	1.006	1.169	−2026.	787.	10.4	5.574
0.40	0.	0.7333	0.	0.2667	148.7	2.629	4.124	1.569	1.050	1.187	1.065	−1748.	997.	13.3	7.452
0.40	0.01	0.7279	0.0070	0.2651	148.8	2.634	4.119	1.564	1.049	1.183	1.065	−1751.	996.	13.3	7.437
0.40	0.02	0.7226	0.0140	0.2635	148.8	2.640	4.114	1.558	1.049	1.179	1.065	−1754.	994.	13.2	7.422
0.40	0.03	0.7172	0.0210	0.2619	148.9	2.645	4.108	1.553	1.048	1.176	1.066	−1757.	992.	13.2	7.407
0.40	0.04	0.7118	0.0280	0.2602	148.9	2.650	4.103	1.548	1.048	1.172	1.066	−1760.	991.	13.2	7.392
0.40	0.05	0.7064	0.0350	0.2586	149.0	2.656	4.098	1.543	1.047	1.169	1.066	−1763.	989.	13.1	7.377
0.40	0.07	0.6956	0.0491	0.2553	149.1	2.667	4.087	1.533	1.047	1.162	1.066	−1770.	986.	13.1	7.347
0.40	0.10	0.6794	0.0703	0.2503	149.3	2.683	4.072	1.517	1.046	1.152	1.067	−1779.	981.	13.0	7.301
0.40	0.20	0.6244	0.1426	0.2331	149.9	2.737	4.018	1.468	1.044	1.122	1.071	−1810.	964.	12.6	7.145
0.40	0.40	0.5075	0.2977	0.1948	151.2	2.841	3.907	1.375	1.048	1.074	1.088	−1871.	928.	11.9	6.811
0.40	0.60	0.3743	0.4776	0.1482	152.8	2.939	3.788	1.289	1.062	1.039	1.116	−1932.	885.	11.3	6.423
0.40	0.80	0.2121	0.7010	0.0870	154.8	3.025	3.657	1.209	1.084	1.016	1.154	−1991.	829.	10.7	5.944
0.40	0.90	0.1141	0.8382	0.0477	155.9	3.063	3.586	1.171	1.099	1.008	1.177	−2020.	794.	10.4	5.651
0.60	0.	0.8569	0.	0.1431	144.9	2.575	3.993	1.551	1.024	1.218	1.126	−1663.	970.	13.6	7.483
0.60	0.01	0.8521	0.0056	0.1424	145.0	2.582	3.991	1.546	1.024	1.214	1.125	−1667.	969.	13.5	7.471
0.60	0.02	0.8472	0.0111	0.1416	145.1	2.589	3.988	1.541	1.024	1.210	1.125	−1672.	968.	13.5	7.459
0.60	0.03	0.8424	0.0167	0.1409	145.1	2.595	3.985	1.536	1.024	1.206	1.124	−1676.	967.	13.4	7.446
0.60	0.04	0.8375	0.0224	0.1402	145.2	2.602	3.983	1.531	1.024	1.202	1.124	−1680.	966.	13.4	7.434
0.60	0.05	0.8326	0.0280	0.1395	145.3	2.609	3.980	1.526	1.023	1.198	1.123	−1684.	965.	13.4	7.421
0.60	0.07	0.8227	0.0394	0.1380	145.5	2.622	3.975	1.516	1.023	1.190	1.122	−1692.	963.	13.3	7.396
0.60	0.10	0.8076	0.0566	0.1357	145.7	2.642	3.966	1.501	1.023	1.179	1.121	−1704.	960.	13.2	7.357
0.60	0.20	0.7557	0.1163	0.1280	146.5	2.707	3.937	1.454	1.025	1.145	1.120	−1744.	948.	12.8	7.224
0.60	0.40	0.6391	0.2507	0.1102	148.4	2.833	3.867	1.365	1.036	1.090	1.126	−1824.	923.	12.0	6.926
0.60	0.60	0.4938	0.4191	0.0871	150.6	2.945	3.777	1.283	1.056	1.049	1.143	−1903.	888.	11.3	6.556
0.60	0.80	0.2961	0.6500	0.0539	153.5	3.037	3.662	1.206	1.083	1.021	1.169	−1978.	837.	10.7	6.055
0.60	0.90	0.1647	0.8047	0.0306	155.2	3.071	3.592	1.170	1.098	1.010	1.185	−2014.	801.	10.4	5.723
0.80	0.	0.9384	0.	0.0616	142.0	2.501	3.811	1.524	1.013	1.273	1.214	−1570.	949.	14.0	7.514
0.80	0.01	0.9340	0.0047	0.0613	142.0	2.509	3.811	1.519	1.013	1.268	1.212	−1575.	948.	13.9	7.503
0.80	0.02	0.9296	0.0094	0.0610	142.1	2.517	3.812	1.515	1.013	1.263	1.210	−1580.	947.	13.9	7.492
0.80	0.03	0.9252	0.0142	0.0607	142.2	2.525	3.812	1.510	1.013	1.257	1.209	−1585.	947.	13.8	7.481
0.80	0.04	0.9207	0.0189	0.0604	142.3	2.533	3.813	1.506	1.013	1.258	1.207	−1590.	946.	13.8	7.470
0.80	0.05	0.9162	0.0237	0.0601	142.4	2.540	3.813	1.501	1.013	1.247	1.205	−1595.	945.	13.7	7.459
0.80	0.07	0.9071	0.0334	0.0595	142.6	2.556	3.814	1.492	1.012	1.238	1.202	−1606.	944.	13.6	7.437
0.80	0.10	0.8934	0.0481	0.0586	142.8	2.580	3.814	1.478	1.013	1.224	1.197	−1621.	942.	13.5	7.403
0.80	0.20	0.8452	0.0994	0.0554	143.8	2.658	3.814	1.435	1.015	1.181	1.185	−1671.	934.	13.0	7.284
0.80	0.40	0.7339	0.2177	0.0483	146.0	2.809	3.797	1.352	1.028	1.112	1.173	−1772.	916.	12.2	7.013
0.80	0.60	0.5869	0.3740	0.0391	148.7	2.943	3.751	1.275	1.051	1.062	1.173	−1870.	889.	11.4	6.662
0.80	0.80	0.3690	0.6059	0.0252	152.2	3.045	3.662	1.202	1.082	1.026	1.184	−1964.	843.	10.7	6.153
0.80	0.90	0.2117	0.7736	0.0147	154.5	3.078	3.595	1.168	1.098	1.013	1.193	−2007.	806.	10.3	5.790

*Calculated values, from Wilson, Silverberg, and Zellner, USAF Aero Propulsion Laboratory. Rep. APL TDR 64-64 (AD 603 151), 1964. Relative volatility = $\alpha_{i-j} = (y_i/x_i)(x_j/y_j)$, where x = liquid composition, y = vapor composition. Pressure activity coefficient = y_iP/x_ip^0, where p^0 = vapor pressure. These data were confirmed by the analyses of Bender, *Cryogenics,* **13,** 11 (1973); and by Elshayal and Lu, *J. Chem. Eng. Data,* **16,** 31 (1971). See also Armstrong, G. T., J. M. Goldstein, et al., *J. Res. N.B.S.*, **55,** 5 (1955): 265–277; Bender, E., *Cryogenics*, **13,** 1 (1973): 11–18; Elshayal, I. M. and B. C-y Lu, *J. Chem. Eng. Data*, **16,** 1 (1971): 31–37; Funada, I., S. Yoshimura, et al., *Advan. Cryog. Engng.*, **7** (1982): 893–901; and Hwang, S-C., *Fluid Phase Equila.*, **37** (1987): 153–167.

TABLE 2-235 Liquid-Vapor Equilibrium Data for the Argon-Nitrogen-Oxygen System (*Continued*)

Liquid mole fraction		Vapor mole fraction			Temperature,°R	Relative volatility			Pressure activity coefficient			Enthalpy, Btu/(lb·mol)		Heat capacity, Btu/(lb·mol·°R)	
$N_2/N_2 + O_2$	Ar	N_2	Ar	O_2		N_2/Ar	N_2/O_2	Ar/O_2	N_2	Ar	O_2	Liquid	Vapor	Liquid	Vapor
Pressure, 1 atm (*Cont.*)															
0.90	0.	0.9709	0.	0.0291	140.6	2.459	3.710	1.509	1.015	1.311	1.271	−1522.	939.	14.2	7.530
0.90	0.01	0.9667	0.0044	0.0289	140.7	2.468	3.712	1.504	1.014	1.305	1.268	−1527.	938.	14.2	7.519
0.90	0.02	0.9624	0.0088	0.0288	140.8	2.476	3.714	1.500	1.014	1.299	1.265	−1533.	938.	14.1	7.509
0.90	0.03	0.9581	0.0133	0.0286	140.9	2.485	3.716	1.496	1.013	1.293	1.263	−1538.	937.	14.1	7.498
0.90	0.04	0.9538	0.0177	0.0285	141.0	2.493	3.718	1.491	1.013	1.287	1.260	−1544.	937.	14.0	7.488
0.90	0.05	0.9494	0.0222	0.0284	141.1	2.502	3.720	1.487	1.013	1.281	1.257	−1550.	936.	14.0	7.477
0.90	0.07	0.9407	0.0312	0.0281	141.3	2.519	3.724	1.478	1.013	1.270	1.252	−1561.	935.	13.8	7.456
0.90	0.10	0.9274	0.0450	0.0276	141.6	2.545	3.729	1.465	1.012	1.254	1.245	−1578.	934.	13.7	7.423
0.90	0.20	0.8808	0.0931	0.0261	142.6	2.629	3.743	1.424	1.014	1.204	1.226	−1633.	928.	13.2	7.310
0.90	0.40	0.7723	0.2048	0.0229	144.9	2.793	3.755	1.344	1.026	1.126	1.200	−1745.	912.	12.3	7.050
0.90	0.60	0.6262	0.3552	0.0186	147.8	2.938	3.733	1.270	1.050	1.069	1.190	−1853.	889.	11.4	6.708
0.90	0.80	0.4018	0.5860	0.0122	151.7	3.048	3.660	1.201	1.081	1.029	1.192	−1956.	846.	10.7	6.197
0.90	0.90	0.2339	0.7589	0.0072	154.2	3.082	3.597	1.167	1.098	1.014	1.197	−2004.	809.	10.3	5.822
0.97	0.	0.9916	0.	0.0084	139.8	2.429	3.638	1.498	1.018	1.342	1.316	−1488.	933.	14.4	7.541
0.97	0.01	0.9874	0.0042	0.0084	139.9	2.438	3.641	1.494	1.018	1.335	1.313	−1494.	932.	14.4	7.531
0.97	0.02	0.9832	0.0085	0.0083	140.0	2.447	3.644	1.489	1.017	1.329	1.309	−1500.	932.	14.3	7.520
0.97	0.03	0.9790	0.0127	0.0083	140.1	2.456	3.647	1.485	1.017	1.322	1.306	−1505.	931.	14.2	7.510
0.97	0.04	0.9748	0.0170	0.0083	140.2	2.465	3.650	1.481	1.016	1.315	1.302	−1511.	931.	14.2	7.500
0.97	0.05	0.9705	0.0213	0.0082	140.3	2.474	3.653	1.477	1.016	1.309	1.299	−1517.	930.	14.1	7.489
0.97	0.07	0.9619	0.0300	0.0081	140.5	2.492	3.658	1.468	1.015	1.296	1.293	−1529.	929.	14.0	7.469
0.97	0.10	0.9488	0.0432	0.0080	140.8	2.519	3.667	1.456	1.014	1.278	1.284	−1547.	928.	13.9	7.437
0.97	0.20	0.9032	0.0893	0.0076	141.8	2.608	3.691	1.415	1.014	1.224	1.257	−1606.	923.	13.3	7.327
0.97	0.40	0.7965	0.1969	0.0066	144.2	2.780	3.722	1.339	1.025	1.137	1.220	−1725.	910.	12.3	7.073
0.97	0.60	0.6513	0.3433	0.0054	147.2	2.934	3.718	1.267	1.049	1.075	1.202	−1841.	889.	11.4	6.737
0.97	0.80	0.4236	0.5728	0.0036	151.3	3.050	3.658	1.199	1.081	1.031	1.198	−1951.	847.	10.7	6.226
0.97	0.90	0.2489	0.7489	0.0021	153.9	3.084	3.597	1.167	1.098	1.015	1.200	−2002.	810.	10.3	5.844
1.00	0.	1.0000	0.	0.	139.4	2.416	3.607	1.493	1.021	1.357	1.338	−1473.	930.	14.5	7.546
1.00	0.01	0.9959	0.0041	0.0000	139.5	2.425	3.611	1.489	1.020	1.350	1.334	−1479.	929.	14.4	7.535
1.00	0.02	0.9917	0.0083	0.0000	139.6	2.434	3.614	1.485	1.019	1.343	1.330	−1485.	929.	14.4	7.525
1.00	0.03	0.9875	0.0125	0.0000	139.7	2.443	3.617	1.480	1.019	1.336	1.326	−1491.	929.	14.3	7.515
1.00	0.04	0.9833	0.0167	0.0000	139.8	2.452	3.621	1.476	1.018	1.329	1.322	−1497.	928.	14.3	7.505
1.00	0.05	0.9791	0.0209	0.0000	139.9	2.462	3.624	1.472	1.018	1.322	1.318	−1503.	928.	14.2	7.495
1.00	0.07	0.9705	0.0295	0.0000	140.1	2.480	3.630	1.464	1.017	1.309	1.311	−1516.	927.	14.1	7.474
1.00	0.10	0.9576	0.0424	0.0000	140.4	2.507	3.640	1.452	1.016	1.290	1.301	−1534.	926.	13.9	7.443
1.00	0.20	0.9122	0.0878	0.0000	141.5	2.598	3.668	1.412	1.015	1.232	1.271	−1595.	921.	13.4	7.333
1.00	0.40	0.8063	0.1937	0.0000	143.9	2.774	3.708	1.337	1.025	1.142	1.230	−1716.	909.	12.4	7.082
1.00	0.60	0.6616	0.3384	0.	147.0	2.932	3.712	1.266	1.048	1.077	1.208	−1836.	888.	11.4	6.749
1.00	0.80	0.4327	0.5674	0.	151.1	3.050	3.657	1.199	1.080	1.032	1.201	−1949.	848.	10.7	6.838
1.00	0.90	0.2553	0.7447	0.	153.8	3.085	3.598	1.166	1.098	1.016	1.201	−2001.	811.	10.3	5.853
Pressure, 4 atm															
0.	0.	0.	0.	1.0000	190.6	2.020	2.776	1.375	0.987	1.111	1.000	−1466.	1224.	13.4	8.122
0.	0.01	0.	0.0137	0.9863	190.5	2.023	2.775	1.372	0.986	1.109	1.001	−1470.	1218.	13.4	8.094
0.	0.02	0.	0.0272	0.9728	190.4	2.026	2.773	1.369	0.985	1.106	1.001	−1473.	1212.	13.4	8.065
0.	0.03	0.	0.0405	0.9595	190.3	2.030	2.772	1.366	0.985	1.104	1.002	−1477.	1207.	13.4	8.037
0.	0.04	0.	0.0537	0.9463	190.2	2.033	2.770	1.362	0.984	1.102	1.002	−1480.	1201.	13.4	8.010
0.	0.05	0.	0.0668	0.9332	190.1	2.037	2.768	1.359	0.983	1.100	1.003	−1484.	1196.	13.3	7.982
0.	0.07	0.	0.0924	0.9076	189.9	2.043	2.765	1.353	0.982	1.096	1.004	−1490.	1185.	13.3	7.929
0.	0.10	0.	0.1299	0.8701	189.6	2.053	2.759	1.344	0.980	1.089	1.005	−1500.	1169.	13.3	7.850
0.	0.20	0.	0.2471	0.7529	188.8	2.086	2.738	1.313	0.974	1.070	1.013	−1533.	1121.	13.1	7.605
0.	0.40	0.	0.4548	0.5452	187.5	2.148	2.688	1.251	0.967	1.038	1.034	−1593.	1037.	12.7	7.166
0.	0.60	0.	0.6410	0.3590	186.5	2.207	2.627	1.190	0.967	1.016	1.066	−1647.	964.	12.3	6.771
0.	0.80	0.	0.8190	0.1811	185.8	2.264	2.560	1.131	0.976	1.003	1.110	−1698.	896.	11.9	6.389
0.	0.90	0.	0.9084	0.0916	185.5	2.292	2.524	1.101	0.983	1.000	1.137	−1723.	862.	11.8	6.196
0.10	0.	0.2393	0.	0.7607	186.2	2.063	2.831	1.372	0.994	1.120	1.020	−1452.	1193.	13.7	8.150
0.10	0.01	0.2363	0.0116	0.7521	186.1	2.066	2.828	1.369	0.994	1.117	1.021	−1455.	1188.	13.6	8.126
0.10	0.02	0.2334	0.0230	0.7436	186.1	2.069	2.825	1.365	0.993	1.115	1.021	−1459.	1184.	13.6	8.102
0.10	0.03	0.2305	0.0344	0.7351	186.0	2.072	2.822	1.362	0.992	1.113	1.021	−1462.	1180.	13.6	8.078
0.10	0.04	0.2277	0.0457	0.7267	186.0	2.075	2.820	1.359	0.991	1.110	1.022	−1465.	1175.	13.6	8.054
0.10	0.05	0.2248	0.0569	0.7183	186.0	2.078	2.817	1.356	0.990	1.108	1.022	−1469.	1171.	13.5	8.031
0.10	0.07	0.2192	0.0792	0.7017	185.9	2.083	2.811	1.349	0.988	1.104	1.023	−1475.	1163.	13.5	7.984
0.10	0.10	0.2109	0.1120	0.6772	185.8	2.092	2.802	1.340	0.986	1.097	1.024	−1485.	1150.	13.4	7.915
0.10	0.20	0.1843	0.2174	0.5983	185.5	2.119	2.772	1.308	0.979	1.077	1.030	−1517.	1110.	13.2	7.691
0.10	0.40	0.1353	0.4150	0.4497	185.2	2.173	2.707	1.246	0.971	1.044	1.049	−1578.	1037.	12.8	7.269
0.10	0.60	0.0896	0.6045	0.3058	185.0	2.224	2.638	1.186	0.971	1.020	1.078	−1637.	968.	12.4	6.860
0.10	0.80	0.0452	0.7961	0.1588	185.1	2.273	2.564	1.128	0.978	1.006	1.117	−1693.	900.	12.0	6.444
0.10	0.90	0.0229	0.8957	0.0814	185.2	2.296	2.526	1.100	0.985	1.002	1.141	−1720.	865.	11.8	6.226
0.20	0.	0.4170	0.	0.5831	182.4	2.094	2.861	1.366	0.997	1.128	1.041	−1431.	1166.	13.8	8.189
0.20	0.01	0.4126	0.0099	0.5776	182.4	2.097	2.857	1.363	0.996	1.125	1.041	−1434.	1162.	13.8	8.167
0.20	0.02	0.4082	0.0198	0.5721	182.4	2.100	2.854	1.359	0.995	1.123	1.042	−1438.	1159.	13.8	8.146
0.20	0.03	0.4038	0.0297	0.5666	182.4	2.102	2.851	1.356	0.994	1.120	1.042	−1441.	1155.	13.8	8.125
0.20	0.04	0.3994	0.0395	0.5611	182.4	2.105	2.847	1.353	0.993	1.118	1.042	−1445.	1152.	13.7	8.104
0.20	0.05	0.3951	0.0493	0.5557	182.4	2.107	2.844	1.349	0.992	1.116	1.042	−1448.	1149.	13.7	8.083
0.20	0.07	0.3864	0.0688	0.5448	182.4	2.112	2.837	1.343	0.990	1.111	1.043	−1455.	1142.	13.7	8.041
0.20	0.10	0.3735	0.0979	0.5286	182.5	2.120	2.827	1.333	0.988	1.104	1.044	−1465.	1132.	13.6	7.978
0.20	0.20	0.3316	0.1932	0.4752	182.6	2.145	2.792	1.301	0.982	1.083	1.049	−1498.	1099.	13.3	7.771
0.20	0.40	0.2506	0.3808	0.3686	183.0	2.194	2.720	1.240	0.974	1.049	1.065	−1562.	1035.	12.9	7.363
0.20	0.60	0.1706	0.5714	0.2580	183.6	2.239	2.645	1.181	0.974	1.024	1.090	−1625.	971.	12.4	6.944
0.20	0.80	0.0883	0.7742	0.1376	184.3	2.281	2.568	1.126	0.980	1.008	1.124	−1687.	904.	12.0	6.497
0.20	0.90	0.0452	0.8834	0.0715	184.8	2.301	2.528	1.099	0.986	1.003	1.145	−1717.	867.	11.8	6.255

TABLE 2-235 Liquid-Vapor Equilibrium Data for the Argon-Nitrogen-Oxygen System (*Concluded*)

Liquid mole fraction		Vapor mole fraction			Temperature,°R	Relative volatility			Pressure activity coefficient			Enthalpy, Btu/(lb·mol)		Heat capacity, Btu/(lb·mol·°R)	
$N_2/N_2 + O_2$	Ar	N_2	Ar	O_2		N_2/Ar	N_2/O_2	Ar/O_2	N_2	Ar	O_2	Liquid	Vapor	Liquid	Vapor
Pressure, 4 atm (*Cont.*)															
0.40	0.	0.6560	0.	0.3441	176.3	2.124	2.859	1.346	0.992	1.146	1.090	−1372.	1121.	14.1	8.277
0.40	0.01	0.6506	0.0077	0.3417	176.4	2.127	2.856	1.343	0.991	1.143	1.090	−1376.	1119.	14.0	8.260
0.40	0.02	0.6453	0.0155	0.3393	176.4	2.129	2.853	1.340	0.991	1.140	1.090	−1380.	1117.	14.0	8.242
0.40	0.03	0.6400	0.0232	0.3369	176.5	2.132	2.850	1.337	0.990	1.138	1.090	−1384.	1115.	14.0	8.224
0.40	0.04	0.6347	0.0310	0.3345	176.6	2.135	2.846	1.333	0.990	1.135	1.090	−1387.	1112.	13.9	8.206
0.40	0.05	0.6293	0.0387	0.3320	176.6	2.137	2.843	1.330	0.989	1.133	1.090	−1391.	1110.	13.9	8.188
0.40	0.07	0.6186	0.0543	0.3271	176.8	2.143	2.837	1.324	0.988	1.128	1.090	−1399.	1106.	13.9	8.153
0.40	0.10	0.6025	0.0778	0.3197	177.0	2.151	2.827	1.315	0.986	1.120	1.090	−1410.	1099.	13.8	8.098
0.40	0.20	0.5482	0.1575	0.2943	177.7	2.176	2.794	1.284	0.982	1.098	1.091	−1449.	1077.	13.5	7.915
0.40	0.40	0.4348	0.3259	0.2393	179.2	2.223	2.725	1.226	0.978	1.061	1.100	−1525.	1029.	13.0	7.527
0.40	0.60	0.3104	0.5141	0.1756	180.9	2.264	2.652	1.171	0.979	1.033	1.116	−1600.	975.	12.5	7.095
0.40	0.80	0.1684	0.7334	0.0982	182.9	2.297	2.573	1.120	0.985	1.013	1.139	−1674.	910.	12.0	6.597
0.40	0.90	0.0882	0.8595	0.0523	184.1	2.309	2.531	1.096	0.989	1.006	1.153	−1710.	872.	11.8	6.312
0.60	0.	0.8076	0.	0.1924	171.7	2.120	2.798	1.320	0.986	1.173	1.154	−1296.	1086.	14.2	8.369
0.60	0.01	0.8023	0.0064	0.1913	171.8	2.123	2.796	1.317	0.986	1.170	1.153	−1301.	1084.	14.2	8.354
0.60	0.02	0.7971	0.0127	0.1902	171.9	2.127	2.794	1.314	0.985	1.167	1.152	−1305.	1083.	14.1	8.338
0.60	0.03	0.7918	0.0192	0.1891	172.0	2.130	2.792	1.311	0.985	1.164	1.152	−1310.	1082.	14.1	8.322
0.60	0.04	0.7865	0.0256	0.1879	172.1	2.133	2.790	1.308	0.985	1.161	1.151	−1315.	1080.	14.1	8.306
0.60	0.05	0.7812	0.0321	0.1868	172.2	2.137	2.788	1.305	0.984	1.159	1.150	−1319.	1079.	14.0	8.289
0.60	0.07	0.7704	0.0451	0.1845	172.4	2.143	2.784	1.299	0.984	1.153	1.149	−1329.	1076.	14.0	8.257
0.60	0.10	0.7542	0.0649	0.1810	172.6	2.153	2.778	1.290	0.983	1.144	1.148	−1343.	1072.	13.9	8.208
0.60	0.20	0.6980	0.1332	0.1688	173.7	2.184	2.757	1.262	0.981	1.119	1.143	−1389.	1056.	13.6	8.038
0.60	0.40	0.5739	0.2848	0.1413	175.9	2.239	2.708	1.209	0.980	1.076	1.141	−1482.	1021.	13.0	7.666
0.60	0.60	0.4261	0.4667	0.1073	178.5	2.283	2.648	1.160	0.984	1.043	1.145	−1573.	976.	12.5	7.228
0.60	0.80	0.2413	0.6963	0.0625	181.6	2.311	2.576	1.115	0.989	1.019	1.155	−1661.	916.	12.0	6.690
0.60	0.90	0.1293	0.8367	0.0340	183.4	2.317	2.533	1.093	0.992	1.009	1.161	−1704.	876.	11.8	6.367
0.80	0.	0.9152	0.	0.0848	168.0	2.095	2.699	1.288	0.986	1.216	1.239	−1209.	1057.	14.3	8.462
0.80	0.01	0.9102	0.0055	0.0843	168.1	2.099	2.699	1.286	0.986	1.212	1.237	−1215.	1056.	14.2	8.447
0.80	0.02	0.9052	0.0110	0.0839	168.2	2.103	2.699	1.283	0.986	1.209	1.235	−1220.	1055.	14.2	8.432
0.80	0.03	0.9001	0.0165	0.0834	168.3	2.107	2.698	1.280	0.985	1.205	1.234	−1226.	1054.	14.2	8.417
0.80	0.04	0.8950	0.0221	0.0829	168.4	2.112	2.698	1.278	0.985	1.201	1.232	−1232.	1053.	14.1	8.402
0.80	0.05	0.8899	0.0277	0.0825	168.5	2.116	2.698	1.275	0.984	1.198	1.230	−1237.	1052.	14.1	8.387
0.80	0.07	0.8795	0.0390	0.0815	168.7	2.124	2.698	1.270	0.984	1.190	1.227	−1249.	1050.	14.0	8.356
0.80	0.10	0.8638	0.0562	0.0801	169.1	2.136	2.697	1.263	0.983	1.180	1.222	−1266.	1047.	14.0	8.309
0.80	0.20	0.8087	0.1162	0.0751	170.3	2.175	2.693	1.238	0.981	1.148	1.208	−1322.	1037.	13.7	8.148
0.80	0.40	0.6826	0.2535	0.0638	173.1	2.244	2.674	1.192	0.983	1.095	1.188	−1434.	1012.	13.1	7.786
0.80	0.60	0.5231	0.4274	0.0496	176.4	2.295	2.636	1.149	0.988	1.055	1.176	−1543.	976.	12.5	7.347
0.80	0.80	0.3077	0.6624	0.0299	180.3	2.323	2.576	1.109	0.993	1.024	1.171	−1647.	920.	12.0	6.777
0.80	0.90	0.1684	0.8150	0.0166	182.7	2.325	2.535	1.090	0.994	1.012	1.169	−1698.	880.	11.8	6.420
0.90	0.	0.9596	0.	0.0404	166.3	2.077	2.641	1.271	0.990	1.245	1.292	−1163.	1044.	14.3	8.509
0.90	0.01	0.9547	0.0051	0.0402	166.4	2.081	2.641	1.269	0.990	1.241	1.289	−1169.	1043.	14.3	8.494
0.90	0.02	0.9497	0.0103	0.0399	166.5	2.086	2.642	1.267	0.989	1.236	1.287	−1175.	1042.	14.2	8.479
0.90	0.03	0.9448	0.0155	0.0397	166.7	2.091	2.643	1.264	0.989	1.232	1.284	−1181.	1042.	14.2	8.464
0.90	0.04	0.9397	0.0208	0.0395	166.8	2.095	2.644	1.262	0.988	1.228	1.281	−1188.	1041.	14.2	8.449
0.90	0.05	0.9347	0.0260	0.0393	166.9	2.100	2.645	1.260	0.988	1.224	1.279	−1194.	1040.	14.1	8.434
0.90	0.07	0.9245	0.0367	0.0388	167.2	2.109	2.646	1.255	0.987	1.215	1.274	−1206.	1039.	14.1	8.404
0.90	0.10	0.9090	0.0529	0.0381	167.5	2.122	2.649	1.248	0.986	1.203	1.267	−1225.	1036.	14.0	8.358
0.90	0.20	0.8546	0.1096	0.0358	168.8	2.166	2.653	1.225	0.984	1.167	1.246	−1287.	1028.	13.7	8.198
0.90	0.40	0.7287	0.2407	0.0305	171.8	2.242	2.651	1.182	0.985	1.107	1.215	−1409.	1007.	13.1	7.840
0.90	0.60	0.5659	0.4102	0.0239	175.3	2.299	2.627	1.143	0.990	1.062	1.193	−1527.	975.	12.5	7.400
0.90	0.80	0.3387	0.6467	0.0146	179.7	2.328	2.575	1.106	0.995	1.027	1.179	−1640.	922.	12.0	6.818
0.90	0.90	0.1873	0.8045	0.0082	182.4	2.329	2.536	1.089	0.995	1.013	1.173	−1694.	882.	11.8	6.446
0.97	0.	0.9882	0.	0.0118	165.2	2.062	2.598	1.260	0.995	1.269	1.334	−1130.	1035.	14.3	8.541
0.97	0.01	0.9834	0.0050	0.0117	165.3	2.067	2.599	1.257	0.994	1.264	1.330	−1136.	1035.	14.3	8.527
0.97	0.02	0.9784	0.0099	0.0116	165.5	2.072	2.601	1.255	0.994	1.259	1.327	−1143.	1034.	14.2	8.512
0.97	0.03	0.9735	0.0149	0.0116	165.6	2.077	2.602	1.253	0.993	1.254	1.324	−1149.	1033.	14.2	8.497
0.97	0.04	0.9685	0.0200	0.0115	165.7	2.082	2.604	1.251	0.992	1.250	1.321	−1156.	1033.	14.2	8.482
0.97	0.05	0.9635	0.0250	0.0114	165.8	2.087	2.605	1.248	0.992	1.245	1.317	−1163.	1032.	14.2	8.467
0.97	0.07	0.9534	0.0353	0.0113	166.1	2.097	2.608	1.244	0.991	1.236	1.311	−1176.	1031.	14.1	8.437
0.97	0.10	0.9380	0.0509	0.0111	166.5	2.111	2.612	1.237	0.989	1.222	1.302	−1195.	1029.	14.0	8.391
0.97	0.10	0.9380	0.0509	0.0111	166.5	2.111	2.612	1.237	0.989	1.222	1.302	−1195.	1029.	14.0	8.391
0.97	0.20	0.8840	0.1056	0.0104	167.9	2.158	2.624	1.216	0.987	1.182	1.276	−1261.	1022.	13.7	8.233
0.97	0.40	0.7584	0.2327	0.0089	170.9	2.240	2.633	1.176	0.986	1.116	1.235	−1390.	1003.	13.1	7.877
0.97	0.60	0.5940	0.3990	0.0070	174.6	2.302	2.620	1.138	0.991	1.067	1.206	−1516.	974.	12.5	7.436
0.97	0.80	0.3597	0.6361	0.0043	179.3	2.332	2.574	1.104	0.996	1.030	1.185	−1635.	923.	12.0	6.846
0.97	0.90	0.2003	0.7972	0.0024	182.1	2.331	2.537	1.088	0.996	1.014	1.176	−1692.	883.	11.8	6.464
1.00	0.	1.0000	0.	0.	164.7	2.057	2.580	1.254	0.997	1.280	1.352	−1115.	1032.	14.3	8.555
1.00	0.01	0.9951	0.0049	0.0000	164.9	2.061	2.581	1.252	0.997	1.275	1.349	−1122.	1031.	14.3	8.541
1.00	0.02	0.9902	0.0098	0.0000	165.0	2.066	2.583	1.250	0.996	1.270	1.346	−1129.	1031.	14.3	8.526
1.00	0.03	0.9853	0.0147	0.0000	165.1	2.071	2.584	1.248	0.995	1.265	1.342	−1136.	1030.	14.2	8.511
1.00	0.04	0.9803	0.0197	0.0000	165.3	2.076	2.586	1.246	0.995	1.260	1.338	−1142.	1029.	14.2	8.496
1.00	0.05	0.9753	0.0247	0.0000	165.4	2.081	2.588	1.243	0.994	1.255	1.335	−1149.	1029.	14.2	8.481
1.00	0.07	0.9653	0.0347	0.0000	165.7	2.091	2.591	1.239	0.993	1.245	1.328	−1163.	1028.	14.1	8.451
1.00	0.10	0.9499	0.0501	0.0000	166.1	2.106	2.596	1.233	0.991	1.231	1.319	−1183.	1026.	14.0	8.405
1.00	0.20	0.8960	0.1040	0.0000	167.4	2.154	2.610	1.212	0.988	1.189	1.289	−1250.	1019.	13.7	8.247
1.00	0.40	0.7706	0.2294	0.0000	170.6	2.239	2.626	1.173	0.987	1.120	1.244	−1382.	1002.	13.1	7.892
1.00	0.60	0.6055	0.3945	0.	174.4	2.303	2.617	1.136	0.992	1.069	1.211	−1511.	973.	12.5	7.451
1.00	0.80	0.3684	0.6316	0.	179.1	2.333	2.574	1.103	0.996	1.030	1.188	−1633.	923.	12.0	6.858
1.00	0.90	0.2058	0.7942	0.	182.0	2.332	2.537	1.088	0.996	1.015	1.177	−1691.	884.	11.8	6.471

TABLE 2-236 Thermodynamic Properties of the International Standard Atmosphere*

Z, m	*T*, K	*P*, bar	ρ, kg/m^3	*g*, m/s^2	*M*	*a*, m/s	μ, Pa·s	*k*, W/(m·K)	λ, m	*H*, m
0	288.15	1.01325	1.2250	9.80665	28.964	340.29	1.79.–5	2.54.–5	6.63.–8	0
1,000	281.65	0.89876	1.1117	9.8036	28.964	336.43	1.76.–5	2.49.–5	7.31.–8	1,000
2,000	275.15	0.79501	1.0066	9.8005	28.964	332.53	1.73.–5	2.43.–5	8.07.–8	2,999
3,000	268.66	0.70121	0.90925	9.7974	28.964	328.58	1.69.–5	2.38.–5	8.94.–8	2,999
4,000	262.17	0.61660	0.81935	9.7943	28.964	324.59	1.66.–5	2.33.–5	9.92.–8	3,997
5,000	255.68	0.54048	0.73643	9.7912	28.964	320.55	1.63.–5	2.28.–5	1.10.–7	4,996
6,000	249.19	0.47217	0.66011	9.7882	28.964	316.45	1.59.–5	2.22.–5	1.23.–7	5,994
7,000	242.70	0.41105	0.59002	9.7851	28.964	312.31	1.56.–5	2.17.–5	1.38.–7	6,992
8,000	236.22	0.35651	0.52579	9.7820	28.964	308.11	1.53.–5	2.12.–5	1.55.–7	7,990
9,000	229.73	0.30800	0.46706	9.7789	28.964	303.85	1.49.–5	2.06.–5	1.74.–7	8,987
10,000	223.25	0.26499	0.41351	9.7759	28.964	299.53	1.46.–5	2.01.–5	1.97.–7	9,984
15,000	216.65	0.12111	0.19476	9.7605	28.964	295.07	1.42.–5	1.95.–5	4.17.–7	14,965
20,000	216.65	0.05529	0.08891	9.7452	28.964	295.07	1.42.–5	1.95.–5	9.14.–7	19,937
25,000	221.55	0.02549	0.04008	9.7300	28.964	298.39	1.45.–5	1.99.–5	2.03.–6	24,902
30,000	226.51	0.01197	0.01841	9.7147	28.964	301.71	1.48.–5	2.04.–5	4.42.–6	29,859
40,000	250.35	2.87.–3	4.00.–3	9.6844	28.964	317.19	1.60.–5	2.23.–5	2.03.–5	39,750
50,000	270.65	8.00.–4	1.03.–3	9.6542	28.964	329.80	1.70.–5	2.40.–5	7.91.–5	49,610
60,000	247.02	2.20.–4	3.10.–4	9.6241	28.964	315.07	1.58.–5	2.21.–5	2.62.–4	59,439
70,000	219.59	5.22.–5	8.28.–5	9.5942	28.964	297.06	1.44.–5	1.98.–5	9.81.–4	69,238
80,000	198.64	1.05.–5	1.85.–5	9.5644	28.964	282.54	1.32.–5	1.80.–5	4.40.–3	79,006
90,000	186.87	1.84.–6	3.43.–6	9.5348	28.95				2.37.–2	88,744
100,000	195.08	3.20.–7	5.60.–7	9.5052	28.40				0.142	98,451
150,000	634.39	4.54.–9	2.08.–9	9.3597	24.10				33	146,542
200,000	854.56	8.47.–10	2.54.–10	9.2175	21.30				240	193,899
250,000	941.33	2.48.–10	6.07.–11	9.0785	19.19				890	240,540
300,000	976.01	8.77.–11	1.92.–11	8.9427	17.73				2600	286,480
400,000	995.83	1.45.–11	2.80.–12	8.6799	15.98				1.6.+4	376,320
500,000	999.24	3.02.–12	5.22.–13	8.4286	14.33				7.7.+4	463,540
600,000	999.85	8.21.–13	1.14.–13	8.1880	11.51				2.8.+5	548,252
800,000	999.99	1.70.–13	1.14.–14	7.7368	5.54				1.4.+6	710,574
1,000,000	1000.00	7.51.–14	3.56.–15	7.3218	3.94				3.1.+6	864,071

*Extracted from *U.S. Standard Atmosphere, 1976, National Oceanic and Atmospheric Administration,* National Aeronautics and Space Administration and the U.S. Air Force, Washington, 1976. *Z* = geometric altitude, *T* = temperature, *P* = pressure, *g* = acceleration of gravity, *M* = molecular weight, *a* = velocity of sound, μ = viscosity, *k* = thermal conductivity, λ = mean free path, ρ = density, and *H* = geopotential altitude. The notation 1.79.–5 signifies 1.79×10^{-5}.

TABLE 2-237 Saturated Benzene*

T, K	*P*, bar	v_f, m^3/kg	v_g, m^3/kg	h_f, kJ/kg	h_g, kJ/kg	s_f, kJ/(kg·K)	s_g, kJ/(kg·K)	c_{pf}, kJ/(kg·K)	μ_f, 10^{-4} Pa·s	k_f, W/(m·K)
290	0.0860	1.133.–10^{-3}	3.569.–10	371.1	810.3	2.172	3.686	1.719	6.75	0.147
300	0.1382	1.147.–10^{-3}	2.292.–10	388.3	820.4	2.229	3.670	1.746	5.80	0.144
310	0.2139	1.162.–10^{-3}	1.525.–10	405.9	830.8	2.286	3.657	1.774	5.14	0.141
320	0.3206	1.176.–10^{-3}	1.046.–10	423.8	841.5	2.344	3.650	1.804	4.52	0.138
330	0.4665	1.192.–10^{-3}	7.379.–10^{-1}	442.1	852.4	2.400	3.643	1.836	3.95	0.135
340	0.6615	1.207.–10^{-3}	5.332.–10^{-1}	460.8	863.6	2.455	3.641	1.868	3.55	0.132
350	0.9162	1.224.–10^{-3}	3.938.–10^{-1}	479.6	875.0	2.510	3.641	1.890	3.23	0.129
360	1.2419	1.241.–10^{-3}	2.965.–10^{-1}	498.7	886.7	2.564	3.642	1.920	2.99	0.126
370	1.6517	1.259.–10^{-3}	2.233.–10^{-1}	518.1	898.6	2.617	3.646	1.950	2.72	0.123
380	2.1588	1.277.–10^{-3}	1.767.–10^{-1}	537.7	910.6	2.669	3.651	1.989	2.46	0.120
390	2.7774	1.297.–10^{-3}	1.393.–10^{-1}	557.6	922.9	2.592	3.657	2.030	2.24	0.117
400	3.5228	1.318.–10^{-3}	1.112.–10^{-1}	577.9	935.2	2.644	3.665	2.070	2.05	0.114
410	4.4091	1.340.–10^{-3}	8.972.–10^{-2}	598.6	947.8	2.823	3.674	2.110	1.88	0.111
420	5.4540	1.363.–10^{-3}	7.309.–10^{-2}	619.7	960.4	2.873	3.684	2.160	1.73	0.107
430	6.6739	1.388.–10^{-3}	6.003.–10^{-2}	641.3	973.0	2.924	3.695	2.210	1.60	0.104
440	8.0861	1.415.–10^{-3}	4.965.–10^{-2}	663.5	985.6	2.974	3.706	2.260	1.48	0.101
450	9.7088	1.444.–10^{-3}	4.131.–10^{-2}	686.3	998.2	3.025	3.718	2.320	1.37	0.098
460	11.451	1.475.–10^{-3}	3.455.–10^{-2}	709.7	1010.7	3.075	3.730	2.380	1.28	0.095
470	13.660	1.510.–10^{-3}	2.901.–10^{-2}	733.8	1022.9	3.126	3.742	2.450	1.10	0.092
480	16.028	1.548.–10^{-3}	2.441.–10^{-2}	758.6	1034.9	3.179	3.753	2.519	1.12	0.089
490	18.685	1.591.–10^{-3}	2.059.–10^{-2}	784.3	1046.4	3.230	3.765	2.590	1.05	0.086
500	21.651	1.640.–10^{-3}	1.736.–10^{-2}	810.9	1057.3	3.284	3.777	2.670	0.98	0.083
510	24.952	1.697.–10^{-3}	1.462.–10^{-2}	838.5	1067.5	3.336	3.785	2.750	0.91	
520	28.613	1.765.–10^{-3}	1.226.–10^{-2}	867.2	1076.6	3.391	3.794	2.839	0.84	
530	32.669	1.849.–10^{-3}	1.020.–10^{-2}	897.2	1084.3	3.446	3.800	2.941	0.77	
540	37.161	2.126.–10^{-3}	8.349.–10^{-3}	928.8	1089.5	3.504	3.802		0.70	
550	42.144	2.258.–10^{-3}	6.616.–10^{-3}	963.2	1090.4	3.565	3.797		0.65	
560	47.696	2.512.–10^{-3}	4.696.–10^{-3}	1007.3	1077.6	3.642	3.769		0.60	
562.2	48.979	3.290.–10^{-3}	3.290.–10^{-3}	1043.0	1043.0	3.706	3.706			

*Converted from a tabulation by Counsell, Lawrenson, and Lees, Nat. Phys. Lab. Teddington (U.K.) Rep. Chem. 52, 1976. Another tabulation by Kesselman et al., in Vargaftik (ed.), *Tables on the Thermophysical Properties of Liquids and Gases,* Hemisphere, Washington and London, 1975, shows some differences. The notation 1.133.–6 signifies 1.133×10^{-6}. Other tables are given by Goodwin, R. D., *J. Phys. Chem. Ref. Data,* **17,** 4 (1988): 1541–1636.

TABLE 2-238 Saturated Bromine*

T, K	P, bar	v_f, m^3/kg	v_g, m^3/kg	h_f, kJ/kg	h_g, kJ/kg	s_f, kJ/(kg·K)	s_g, kJ/(kg·K)	c_{pf}, kJ/(kg·K)	μ_f, 10^{-4} Pa·s	k_f, W/(m·K)
260	0.042	3.106.–4	3.195	−147.2	51.8	0.903	1.669	0.486	13.4	0.131
280	0.124	3.168.–4	1.169	−138.9	56.2	0.933	1.629	0.479	11.5	0.127
300	0.310	3.232.–4	0.5002	−131.6	60.6	0.956	1.597	0.475	9.3	0.122
320	0.680	3.311.–4	0.2425	−124.2	64.8	0.978	1.570	0.473	7.8	0.118
340	1.330	3.385.–4	0.1309	−112.3	71.1	1.004	1.539	0.471	6.7	0.114
360	2.384	3.464.–4	0.0767	−108.6	73.1	1.026	1.531	0.470	5.7	0.109
380	4.010	3.550.–4	0.0477	−100.6	76.9	1.048	1.515	0.471	5.0	0.104
400	6.390	3.647.–4	0.0311	−93.4	80.6	1.063	1.501	0.475	4.5	0.099
420	9.730	3.752.–4	0.0211	−85.8	84.0	1.084	1.488	0.480	4.0	0.094
440	14.25	3.885.–4	0.0148	−77.7	87.1	1.103	1.477	0.489	3.7	0.089
460	20.17	4.023.–4	0.0107	−69.0	89.9	1.122	1.467	0.503	3.3	0.084
480	27.75	4.179.–4	0.00786	−59.7	92.2	1.142	1.457	0.527	3.1	0.079
500	37.21	4.378.–4	0.00589	−49.3	94.0	1.161	1.448	0.595	2.8	0.073
520	48.81	4.623.–4	0.00445	−37.7	95.0	1.183	1.438	0.710	2.6	0.066
540	62.80	4.938.–4	0.00337	−24.0	94.8	1.207	1.428	0.860	2.5	0.059
560	79.41	5.368.–4	0.00251	−7.1	92.5	1.237	1.414	1.063	2.3	0.050
580	98.90	6.250.–4	0.00167	18.8	82.5	1.280	1.390	2.31	2.2	0.035
584.2^c	103.4	8.475.–4	0.00085	64.8	64.8	1.356	1.356	∞	2.1	∞

*Reproduced or converted from a tabulation by Seshadri, Viswanath, and Kuloor, *Ind. J. Technol.*, 6 (1970): 191–198. *c* = critical point.

TABLE 2-239 Saturated Normal Butane (R600)*

T, K	P, bar	v_f, m^3/kg	v_g, m^3/kg	h_f, kJ/kg	h_g, kJ/kg	s_f, kJ/(kg·K)	s_g, kJ/(kg·K)	c_{pf}, kJ/(kg·K)	μ_f, 10^{-4} Pa·s	k_f, W/(m·K)
134.9^t	6.7.–6	1.360.–3	28630	0.00	494.21	2.3056	5.9702	1.946	15.8	0.181
140	1.7.–5	1.369.–3	11635	9.95	499.96	2.3778	5.8779	1.953	14.4	0.179
150	8.7.–5	1.387.–3	2470	29.44	511.39	2.5121	5.7251	1.970	12.0	0.175
160	3.5.–4	1.405.–3	654	49.10	523.13	2.6389	5.6016	1.985	9.94	0.171
170	1.17.–3	1.424.–3	207	68.94	535.16	2.7592	5.5017	2.001	8.26	0.167
180	3.37.–3	1.443.–3	76.4	88.97	547.48	2.8738	5.4211	2.018	6.87	0.163
190	8.53.–3	1.463.–3	31.8	109.22	560.07	2.9835	5.3564	2.035	5.71	0.160
200	1.94.–2	1.484.–3	14.7	129.71	572.93	3.0887	5.3048	2.055	4.83	0.156
210	4.05.–2	1.505.–3	7.39	150.45	586.06	3.1900	5.2643	2.077	4.15	0.152
220	7.81.–2	1.528.–3	4.00	171.49	599.42	3.2879	5.2331	2.101	3.61	0.148
230	0.1411	1.551.–3	2.31	192.83	613.02	3.3828	5.2097	2.128	3.18	0.144
240	0.2408	1.575.–3	1.40	214.50	626.83	3.4749	5.1929	2.158	2.83	0.140
250	0.3915	1.601.–3	0.893	236.52	640.82	3.5647	5.1818	2.192	2.55	0.136
260	0.6100	1.628.–3	0.592	258.92	654.97	3.6523	5.1755	2.231	2.31	0.132
270	0.9155	1.656.–3	0.406	281.72	669.24	3.7380	5.1732	2.274	2.10	0.128
280	1.3297	1.686.–3	0.286	309.94	683.60	3.8220	5.1744	2.323	1.93	0.124
290	1.8765	1.718.–3	0.207	328.62	697.99	3.9046	5.1783	2.377	1.77	0.120
300	2.5811	1.752.–3	0.1533	352.77	712.36	3.9860	5.1846	2.437	1.62	0.116
310	3.4706	1.790.–3	0.1156	377.46	726.67	4.0663	5.1928	2.503	1.47	0.113
320	4.5731	1.830.–3	0.0885	402.71	740.84	4.1458	5.2025	2.577	1.34	0.109
330	5.9179	1.874.–3	0.0687	428.61	754.80	4.2248	5.2132	2.657	1.21	0.105
340	7.5354	1.923.–3	0.0539	455.25	768.49	4.3035	5.2248	2.746	1.08	0.101
350	9.4573	1.978.–3	0.0427	482.74	781.79	4.3822	5.2367	2.842	0.97	0.097
360	11.72	2.041.–3	0.0340	511.22	794.60	4.4613	5.2485	2.947	0.87	0.093
370	14.35	2.114.–3	0.0272	540.88	806.72	4.5412	5.2597	3.062	0.78	0.089
380	17.40	2.200.–3	0.0218	571.94	817.86	4.6225	5.2696	3.20	0.69	0.085
390	20.90	2.307.–3	0.0174	604.76	827.56	4.7058	5.2771	3.34	0.62	0.081
400	24.92	2.447.–3	0.0138	639.85	834.95	4.7922	5.2800	3.50	0.55	0.077
410	29.54	2.652.–3	0.0106	678.30	838.10	4.8842	5.2740	3.69	0.49	0.074
420	34.86	3.048.–3	0.0075	723.89	830.34	4.9903	5.2437	3.84	0.44	0.072
425.2^c	37.96	4.405.–3	0.0044	783.50	783.50	5.1290	5.1290	∞		∞

*Values rounded and reproduced or converted from Goodwin, NBSIR 79-1621, 1979. *t* = triple point; *c* = critical point. The notation 6.7.–6 signifies 6.7×10^{-6}.

TABLE 2-240 Superheated Normal Butane*

		Temperature, K									
P, bar		150	200	250	300	350	400	450	500	600	700
	v	0.00139	0.00148	0.00160	0.4106	0.4847	0.5575	0.6297	0.7013	0.8440	0.9861
1.013	h	29.6	129.8	236.6	718.9	810.7	913.1	1026.0	1149.0	1423	1730
	s	2.512	3.088	3.564	5.334	5.616	5.889	6.155	6.414	6.913	7.386
	v	0.00139	0.00148	0.00160	0.00175	0.0909	0.1078	0.1238	0.1393	0.1693	0.1988
5	h	30.0	130.2	237.0	352.9	798.5	904.3	1019.3	1143.7	1420	1728
	s	2.511	3.088	3.563	3.985	5.363	5.645	5.916	6.178	6.680	7.155
	v	0.00139	0.00148	0.00160	0.00175	0.00198	0.0502	0.0593	0.0677	0.0835	0.0987
10	h	30.6	130.8	237.4	353.3	482.7	891.9	1010.3	1136.8	1415	1725
	s	2.510	3.087	3.562	3.983	4.382	5.524	5.803	6.069	6.575	7.052
	v	0.00138	0.00148	0.00160	0.00174	0.00196	0.0205	0.0268	0.0318	0.0406	0.0487
20	h	31.7	131.8	238.4	354.0	482.6	860.0	990.1	1122.0	1406	1718
	s	2.509	3.085	3.560	3.980	4.376	5.364	5.670	5.948	6.464	6.945
	v	0.00138	0.00148	0.00159	0.00174	0.00195	0.00240	0.0156	0.0198	0.0263	0.0320
30	h	32.8	132.9	239.3	354.7	482.6	637.3	965.5	1105.9	1396	1711
	s	2.507	3.082	3.557	3.976	4.370	4.783	5.570	5.866	6.394	6.880
	v	0.00138	0.00148	0.00159	0.00173	0.00194	0.00234	0.0097	0.0137	0.0192	0.0237
40	h	33.9	134.0	240.3	355.4	482.7	633.6	932.2	1088.1	1387	1705
	s	2.505	3.080	3.555	3.973	4.365	4.768	5.468	5.797	6.341	6.832
	v	0.00138	0.00148	0.00159	0.00173	0.00193	0.00229	0.00549	0.0101	0.0149	0.0188
50	h	35.0	135.0	241.3	356.2	428.8	631.0	877.0	1068.2	1377	1699
	s	2.503	3.078	3.552	3.970	4.360	4.755	5.329	5.734	6.297	6.792
	v	0.00138	0.00148	0.00159	0.00172	0.00192	0.00255	0.00352	0.00764	0.0121	0.0155
60	h	36.2	136.1	242.3	356.9	483.1	629.1	825.1	1046.4	1367	1692
	s	2.501	3.076	3.550	3.967	4.355	4.745	5.204	5.673	6.258	6.759
	v	0.00138	0.00147	0.00158	0.00172	0.00190	0.00219	0.00286	0.00482	0.00868	0.0114
80	h	38.4	138.3	244.2	358.5	483.7	626.5	798.1	1001.5	1347	1680
	s	2.498	3.072	3.545	3.960	4.346	4.727	5.130	5.559	6.191	6.704
	v	0.00138	0.00147	0.00158	0.00171	0.00188	0.00214	0.00264	0.00368	0.00669	0.00901
100	h	40.6	140.4	246.2	360.1	484.5	624.9	787.9	971.3	1329	1668
	s	2.495	3.069	3.540	3.954	4.337	4.712	5.095	5.310	6.134	6.658
	v	0.00137	0.00146	0.00156	0.00167	0.00178	0.00200	0.00225	0.00258	0.00349	0.00460
200	h	51.9	151.3	257.9	368.8	490.3	624.4	773.3	933.7	1270	1623
	s	2.478	3.049	3.518	3.927	4.301	4.660	5.010	5.348	5.960	6.849
	v	0.00136	0.00145	0.00154	0.00164	0.00176	0.00191	0.00209	0.00231	0.00284	0.00345
300	h	63.2	162.2	266.7	378.3	498.0	629.2	773.4	928.4	1255	1603
	s	2.462	3.032	3.498	3.903	4.273	4.623	4.962	5.288	5.884	6.419
	v	0.00136	0.00144	0.00152	0.00162	0.00173	0.00185	0.00200	0.00217	0.00255	0.00298
400	h	74.5	173.3	277.4	388.2	506.8	636.2	778.0	930.2	1253	1600
	s	2.447	3.015	3.479	3.882	4.248	4.593	4.927	5.247	5.836	6.366
	v	0.00136	0.00143	0.00151	0.00160	0.00170	0.00181	0.00193	0.00207	0.00240	0.00272
500	h	85.8	184.4	288.1	398.4	516.3	644.5	784.8	935.3	1256	1599
	s	2.432	2.999	3.461	3.863	4.226	4.569	4.898	5.215	5.799	6.328

*Converted and rounded from tables of Goodwin, NBSIR 79-1621, 1979.

Saturation and superheat tables and a diagram to 100 bar, 580 K are given by Reynolds, W. C., *Thermodynamic Properties in S.I.*, Stanford Univ. publ., 1979 (173 pp.). For material to 10,000 psia, 640°F, see Stewart, R. B., R. T. Jacobsen, et al., *Thermodynamic Properties of Refrigerants,* ASHRAE, Atlanta, GA, 1986 (521 pp.). For specific heat, thermal conductivity, and viscosity, see *Thermophysical Properties of Refrigerants,* ASHRAE, 1993.

TABLE 2-241 Saturated Carbon Dioxide*

T, K	P, bar	v_f, m^3/kg	v_g, m^3/kg	h_f, kJ/kg	h_g, kJ/kg	s_f, kJ/(kg·K)	s_g, kJ/(kg·K)	c_{pf}, kJ/(kg·K)	μ_f, 10^{-4} Pa·s	k_f, W/(m·K)
216.6	5.180	8.484.–4	0.0712	386.3	731.5	2.656	4.250	1.707		0.182
220	5.996	8.574.–4	0.0624	392.6	733.1	2.684	4.232	1.761		0.178
225	7.357	8.710.–4	0.0515	401.8	735.1	2.723	4.204			0.171
230	8.935	8.856.–4	0.0428	411.1	736.7	2.763	4.178	1.879	1.64	0.164
235	10.75	9.011.–4	0.0357	420.5	737.9	2.802	4.152			0.160
240	12.83	9.178.–4	0.0300	430.2	738.9	2.842	4.128	1.933	1.45	0.156
245	15.19	9.358.–4	0.0253	440.1	739.4	2.882	4.103			0.148
250	17.86	9.554.–4	0.0214	450.3	739.6	2.923	4.079	1.992	1.28	0.140
255	20.85	9.768.–4	0.0182	460.8	739.4	2.964	4.056			0.134
260	24.19	1.000.–3	0.0155	471.6	738.7	3.005	4.032	2.125	1.14	0.128
270	32.03	1.056.–3	0.0113	494.4	735.6	3.089	3.981	2.410	1.02	0.116
275	36.59	1.091.–3	0.0097	506.5	732.8	3.132	3.954			0.109
280	41.60	1.130.–3	0.0082	519.2	729.1	3.176	3.925	2.887	0.91	0.102
290	53.15	1.241.–3	0.0058	547.6	716.9	3.271	3.854	3.724	0.79	0.088
300	67.10	1.470.–3	0.0037	585.4	690.2	3.393	3.742		0.60	0.074
304.2^c	73.83	2.145.–3	0.0021	636.6	636.6	3.558	3.558	∞	0.31	∞

*c = critical point. The notation 8.484.–4 signifies 8.484×10^{-4}.

The 1993 ASHRAE *Handbook—Fundamentals* (SI ed.) gives material for integral degrees Celsius with temperatures on the LPTS 68 scale for saturation temperatures from –56.57 to 30.98 degrees Celsius. The thermodynamic diagram from 4 to 1000 bar extends to 420°C.

Saturation and superheat tables and a chart to 15,000 psia, 840°F appear in Stewart, R. B., R. T. Jacobsen, et al., *Thermodynamic Properties of Refrigerants,* ASHRAE, Atlanta, GA, 1986 (521 pp.). For specific heat, thermal conductivity, and viscosity, see ASHRAE *Thermophysical Properties of Refrigerants*, 1993.

Saturation and superheat tables and a diagram to 200 bar, 1000 K are given by Reynolds, W. C., *Thermodynamic Properties in S.I.*, Stanford Univ. publ., 1979 (173 pp.). Holste, J. C., D. M. Bailey, et al., *Energy Progr.*, **6,** 2 (1986): 125–130, give properties mainly in the range 0–100 bar, 200–450 K for the superheated vapor. Compare these with Angus, S., B. Armstrong, et al., *International Tables of the Fluid State—Carbon Dioxide,* Pergamon, Oxford, 1976 (377 pp.). In Miller, C. E. III and S. E. Wilder, NASA SP 3097, 1976 (489 pp.), many properties and decomposition products are tabulated for pressures from 10^{-7} to 10^{4} atm., 100–25,000 K. For the range to 50 kb, 400–2100 K, see Bottinga, Y. and P. Richet, *Amer. J. Sci.*, **281** (1981): 615–660.

TABLE 2-242 Superheated Carbon Dioxide*

	Temperature, K									
P, bar	300	350	400	450	500	600	700	800	900	1000
v	0.5639	0.6595	0.7543	0.8494	0.9439	1.1333	1.3324	1.5115	1.7005	1.8894
1 *h*	809.3	853.1	899.1	947.1	997.0	1102	1212	1327	1445	1567
s	4.860	4.996	5.118	5.231	5.337	5.527	5.697	5.850	5.990	6.120
v	0.1106	0.1304	0.1498	0.1691	0.1882	0.2264	0.2645	0.3024	0.3403	0.3782
5 *h*	805.5	850.3	897.0	945.5	995.8	1101	1211	1326	1445	1567
s	4.548	4.686	4.810	4.925	50.31	5.222	5.392	5.546	5.685	5.814
v	0.0539	0.0642	0.0742	0.0841	0.0938	0.1131	0.1322	0.1513	0.1703	0.1893
10 *h*	800.7	846.9	894.4	943.5	994.1	1100	1211	1326	1445	1567
s	4.405	4.548	4.674	4.790	4.897	5.089	5.260	5.414	5.555	5.683
v	0.0255	0.0311	0.0364	0.0416	0.0466	0.0564	0.0661	0.0757	0.0853	0.0948
20 *h*	790.2	839.8	889.3	939.4	990.8	1098	1209	1325	1444	1567
s	4.249	4.402	4.534	4.653	4.762	4.955	5.127	5.282	5.423	5.551
v	0.0159	0.0201	0.0238	0.0274	0.0309	0.0375	0.0441	0.0505	0.0570	0.0633
30 *h*	778.5	832.4	883.8	935.2	987.3	1096	1208	1324	1444	1566
s	4.144	4.341	4.447	4.569	4.679	4.876	5.049	5.204	5.346	5.474
v	0.0110	0.0146	0.0175	0.0203	0.0230	0.0281	0.0331	0.0379	0.0428	0.0476
40 *h*	764.9	824.6	878.3	931.1	984.3	1094	1205	1323	1443	1566
s	4.055	4.239	4.380	4.507	4.619	4.818	4.993	5.148	5.291	5.419
v	0.0080	0.0112	0.0138	0.0161	0.0183	0.0224	0.0265	0.0304	0.0343	0.0382
50 *h*	748.2	816.3	872.6	926.9	981.1	1091	1205	1322	1443	1566
s	3.968	4.179	4.330	4.457	4.572	4.773	4.948	5.104	5.247	5.377
v	0.0058	0.0090	0.0113	0.0133	0.0151	0.0187	0.0221	0.0254	0.0286	0.0318
60 *h*	726.9	807.7	866.9	922.7	977.8	1089	1204	1321	1442	1565
s	3.878	4.126	4.314	4.416	4.532	4.736	4.912	5.069	5.212	5.341
v		0.0062	0.0081	0.0097	0.0112	0.0140	0.0166	0.0191	0.0216	0.0240
80 *h*		788.4	855.1	914.2	971.3	1085	1201	1320	1441	1565
s		4.029	4.208	4.347	4.468	4.675	4.854	5.011	5.155	5.286
v		0.0045	0.0062	0.0076	0.0089	0.0111	0.0133	0.0153	0.0173	0.0193
100 *h*		766.2	843.0	905.7	964.9	1081	1198	1318	1440	1564
s		3.936	4.144	4.290	4.417	4.627	4.808	4.967	5.111	5.241
v		0.0023	0.0038	0.0049	0.0058	0.0074	0.0089	0.0103	0.0117	0.0130
150 *h*		704.5	811.9	884.8	949.4	1072	1192	1314	1437	1562
s		3.716	4.005	4.177	4.313	4.536	4.722	4.884	5.030	5.162
v		0.0017	0.0027	0.0035	0.0043	0.0056	0.0067	0.0078	0.0088	0.0099
200 *h*		670.0	783.2	865.2	934.9	1063	1186	1310	1435	1561
s		3.591	3.894	4.088	4.234	4.468	4.668	4.824	4.970	5.104
v			0.0017	0.0023	0.0029	0.0038	0.0046	0.0053	0.0060	0.0067
300 *h*			745.3	834.0	910.6	1047	1176	1303	1431	1559
s			3.747	3.956	4.118	4.367	4.573	4.743	4.886	5.021
v			0.0015	0.0018	0.0022	0.0029	0.0035	0.0041	0.0047	0.0052
400 *h*			728.1	814.6	893.3	1035	1168	1298	1428	1558
s			3.663	3.867	4.033	4.292	4.497	4.671	4.824	4.960
v				0.0016	0.0018	0.0024	0.0029	0.0034	0.0038	0.0043
500 *h*				803.5	881.9	1027	1162	1294	1426	1557
s				3.805	3.970	4.234	4.443	4.620	4.774	4.913

*Interpolated and rounded from Vukalovich and Altunin, *Thermophysical Properties of Carbon Dioxide,* Atomizdat, Moscow, 1965; and Collett, England, 1968.

TABLE 2-243 Saturated Carbon Monoxide*

T, K	*P*, bar	v_f, m^3/kg	v_g, m^3/kg	h_f, kJ/kg	h_g, kJ/kg	s_f, kJ/(kg·K)	s_g, kJ/(kg·K)
81.62	1.01	1.268.–3	0.0666	150.25	365.30	3.005	5.640
83.36	1.52	1.295.–3	0.0631	158.56	368.07	3.104	5.559
88.25	2.03	1.317.–3	0.0606	165.00	370.00	3.178	5.501
96.16	4.05	1.385.–3	0.0547	182.76	374.21	3.368	5.359
101.51	6.08	1.440.–3	0.0513	195.0	375.98	3.489	5.271
105.69	8.12	1.489.–3	0.0318	204.8	376.6	3.580	5.206
109.17	10.13	1.535.–3	0.0253	213.2	376.6	3.656	5.152
116.08	15.20	1.651.–3	0.0163	231.0	374.5	3.807	5.043
121.48	20.27	1.778.–3	0.0116	246.3	370.2	3.918	4.948
125.97	25.33	1.936.–3	0.0085	261.2	363.6	4.041	4.854
129.84	30.40	2.168.–3	0.0063	277.6	313.15	4.161	4.747
132.91^c	34.96	3.337.–3	0.0033				

*Pressure and volume values converted, and enthalpy and entropy values reproduced, from Hust and Stewart, NBS Tech. Note 202, 1963. This source gives values at and above 72.373 K at closer pressure intervals. *c* = critical point. The notation 1.268.–3 signifies 1.268×10^{-3}.

Goodwin, R. D., *J. Phys. Chem. Ref. Data,* **14,** 4 (1985): 849–932, gives properties to 1000 bar, 68–1000 K.

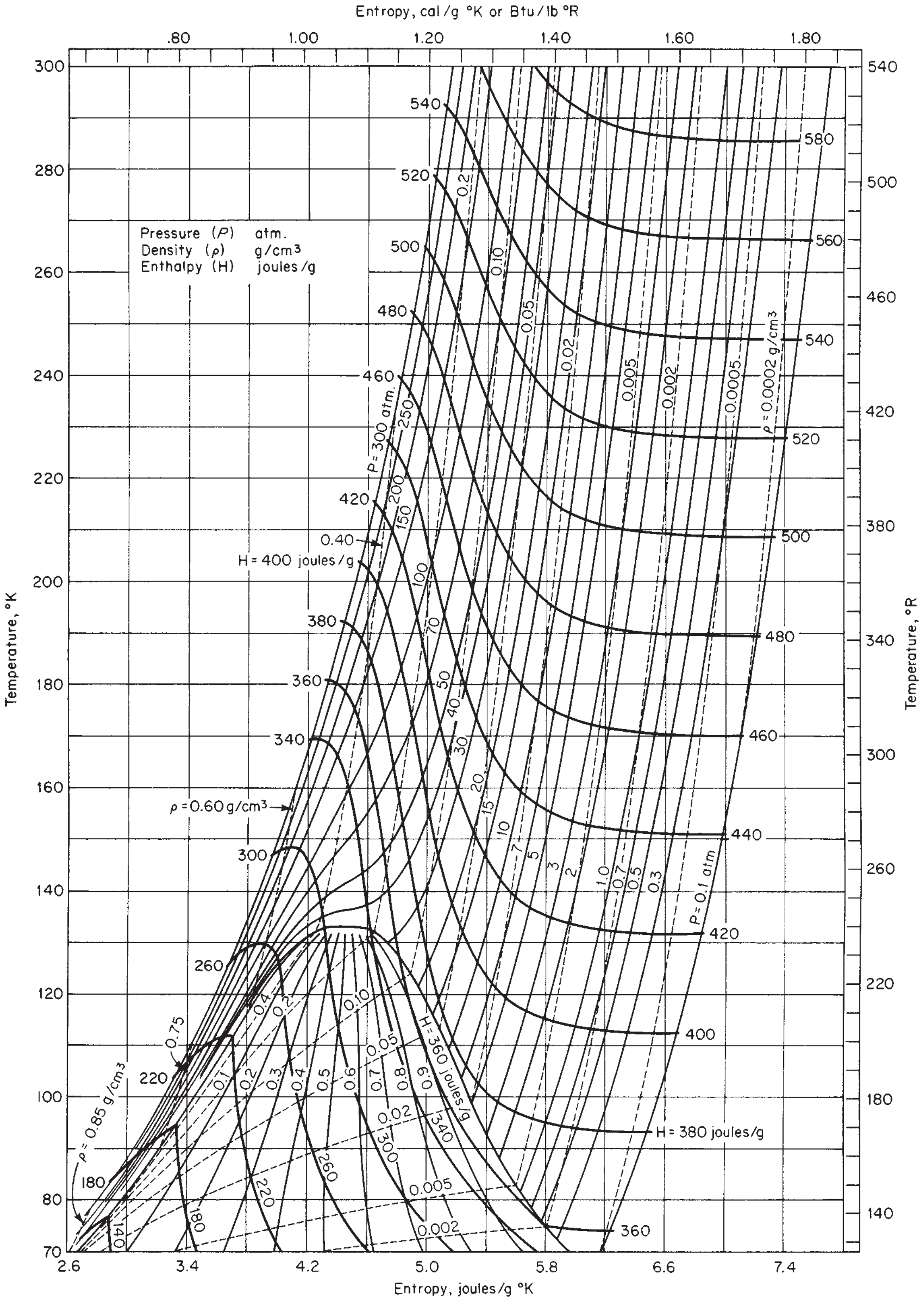

FIG. 2-8 Temperature-entropy diagram for carbon monoxide. Pressure *P*, in atmospheres; density ρ, in grams per cubic centimeter; enthalpy *H*, in joules per gram. (*From Hust and Stewart, NBS Tech. Note 202, 1963.*)

TABLE 2-244 Thermophysical Properties of Saturated Carbon Tetrachloride

T, K	P, bar	v_f, m^3/kg	v_g, m^3/kg	h_f, kJ/kg	h_g, kJ/kg	s_f, kJ/(kg·K)	s_g, kJ/(kg·K)	c_{pf}, kJ/(kg·K)	μ_f, 10^{-6} Pa·s	k_f, W/(m·K)	Pr
280	0.064	0.000 619	2.414	205.5	420.7	1.018	1.787	0.835	1042	0.1043	8.34
290	0.105	0.000 625	1.495	212.9	425.7	1.042	1.775	0.844	892	0.1020	7.38
300	0.165	0.000 633	0.971	220.9	430.9	1.068	1.768	0.853	774	0.0998	6.62
310	0.251	0.000 641	0.669	228.8	436.1	1.095	1.764	0.863	679	0.0975	6.01
320	0.370	0.000 649	0.463	236.9	441.3	1.121	1.760	0.874	603	0.0952	5.54
330	0.531	0.000 657	0.3306	246.0	446.4	1.149	1.756	0.885	539	0.0930	5.13
340	0.743	0.000 666	0.2407	254.5	451.5	1.174	1.754	0.897	486	0.0907	4.81
350	1.017	0.000 674	0.1802	263.1	456.6	1.199	1.752	0.910	441	0.0884	4.54
360	1.361	0.000 684	0.1370	271.8	461.7	1.224	1.751	0.924	402	0.0861	4.31
370	1.795	0.000 694	0.1053	280.8	466.6	1.248	1.751	0.939	368	0.0839	4.12
380	2.327	0.000 704	0.0820	289.7	471.5	1.272	1.750	0.954	338	0.0816	3.95
390	2.970	0.000 715	0.0651	298.1	475.8	1.295	1.751	0.970	311	0.0794	3.80
400	3.735	0.000 727	0.0525	307.9	481.2	1.319	1.752	0.987	287	0.0771	3.67
410	4.642	0.000 739	0.0426	317.1	485.8	1.341	1.753	1.010	265	0.0749	3.57
420	5.700	0.000 753	0.0350	326.0	490.4	1.363	1.754	1.034	246	0.0726	3.50
430	6.927	0.000 766	0.02899	335.2	494.9	1.384	1.756	1.060	227	0.0704	3.42
440	8.342	0.000 780	0.02413	344.3	499.2	1.405	1.757	1.094	211	0.0682	3.38
450	9.958	0.000 796	0.02020	353.6	503.4	1.426	1.759	1.141	195	0.0660	3.37
460	11.792	0.000 801	0.01692	363.1	507.3	1.446	1.760	1.207	180	0.0638	3.36
470	13.869	0.000 834	0.01425	372.8	511.1	1.467	1.761	1.240	167	0.0666	3.36
480	16.21	0.000 856	0.01205	382.6	514.6	1.487	1.762	1.278	156	0.0594	3.36
490	18.83	0.000 880	0.01011	392.0	517.5	1.507	1.763	1.320	145	0.0511	3.35
500	21.77	0.000 858	0.00858	402.5	520.2	1.526	1.762	1.375	133	0.0549	3.35
510	25.02	0.000 945	0.00722	412.9	522.6	1.546	1.761	1.44			
520	28.68	0.000 987	0.00607	424.3	524.2	1.568	1.760	1.52			
530	32.71	0.001 041	0.00500	436.4	524.5	1.590	1.756				
540	37.18	0.001 121	0.00400	448.3	522.7	1.614	1.749				
550	44.12	0.001 248	0.00309	463.4	518.2	1.638	1.738				
556.4^c	45.60	0.001 792	0.00179	494.4	494.4	1.692	1.692				

c = critical point. Base points: $h_f = 200$ at 273.15 K = 0°C = $h_A - 300$ kJ/kg; $s_f = 1.000$ at 273.15 K = 0°C = $s_A - 4.000$ kJ/(kg·K). Values mostly rounded and converted from Altunin, V. V., V. Z. Geller, et al., *Thermophysical Properties of Freons,* vol. 9, Hemisphere, Washington, DC, 1987 (243 pp.). Some irregularities exist in these data.

TABLE 2-245 Saturated Carbon Tetrafluoride (R14)*

T, K	P, bar	v_f, m^3/kg	v_g, m^3/kg	h_f, kJ/kg	h_g, kJ/kg	s_f, kJ/(kg·K)	s_g, kJ/(kg·K)	c_{pf}, kJ/(kg·K)	μ_f, 10^{-4} Pa·s	k_f, W/(m·K)
100	0.0089	5.370.–4	10.77	495.8	648.4	5.487	7.003	0.887		0.136
110	0.0286	5.515.–4	3.648	502.7	652.9	5.556	6.919	0.887		0.128
120	0.0924	5.668.–4	1.228	510.4	657.1	5.624	6.847	0.890		0.119
130	0.2986	5.834.–4	0.4051	518.8	661.1	5.691	6.786	0.896		0.111
140	0.6901	6.018.–4	0.1855	527.7	664.8	5.757	6.736	0.904	3.56	0.104
150	1.4074	6.225.–4	0.0951	537.2	668.3	5.822	6.696	0.922	3.28	0.097
160	2.598	6.460.–4	0.0532	549.4	671.4	5.885	6.662	0.975	3.03	0.089
170	4.426	6.733.–4	0.0318	557.6	674.0	5.947	6.629	1.031	2.80	0.081
180	7.067	7.055.–4	0.0200	568.2	676.1	6.007	6.607	1.104	2.59	0.072
190	10.702	7.449.–4	0.0131	579.3	677.4	6.066	6.583	1.203	2.39	0.064
200	15.531	7.957.–4	0.0087	591.0	677.8	6.124	6.558	1.334	2.19	0.057
210	21.794	8.674.–4	0.0058	603.5	676.4	6.182	6.536	1.506	2.01	0.049
220	29.269	9.931.–4	0.0036	618.5	671.4	6.233	6.490	1.73	1.85	0.042
227.5^c	37.45	1.598.–3	0.0016	646.9	646.9	6.371	6.371	∞		∞

*P, v, h, and s values interpolated, extrapolated, and converted from Oguchi, *Reito,* **52** (1977): 869–889. c = critical point. The notation 5.370.–4 signifies 5.370×10^{-4}.

Equations and constants approximated to ASHRAE tables are given by Mecaryk, K. and M. Masaryk, *Heat Recovery Systems and CHP,* **11,** 2–3 (1991). The 1993 ASHRAE *Handbook—Fundamentals* (S.I. ed.) contains a saturation table from −140 to −45.65°C and an enthalpy–log-pressure diagram from 0.1 to 300 bar, −140 to 300°C. For properties to 1000 bar from 90 to 420 K, see Rublo, R. G., J. A. Zollweg, et al., *J. Chem. Eng. Data,* **36** (1991): 171–184. Saturation and superheat tables and a diagram to 80 bar, 600 K are given by Reynolds, W. C., *Thermodynamic Properties in S.I.*, Stanford Univ. publ., 1979 (173 pp.). Chari, Ph.D. thesis, University of Michigan, 1960, presents saturation-temperature tables in fps units for 1°F increments from −270 to −51°F. Thermodynamic and transport properties, equations, and computer code and tables at constant entropy from 89 to 845 K are given by Hunt, J. L. and Boney, L. R., NASA TN D-7181, 1973 (105 pp.), largely based upon the Chari data.

TABLE 2-246 Saturated Cesium*

T, K	P, bar	v_f, m^3/kg	v_g, m^3/kg	h_f, kJ/kg	h_g, kJ/kg	s_f, kJ/(kg·K)	s_g, kJ/(kg·K)	c_{pf}, kJ/(kg·K)
301.6^m	2.66.–9	5.444.–4	7.01.+7	74.6	637.6	0.696	2.563	0.245
400	3.83.–6	5.615.–4	6.54.+4	98.5	651.9	0.765	2.148	0.240
500	3.11.–4	5.800.–4	1001	122.0	666.1	0.817	1.905	0.232
600	5.65.–3	5.999.–4	65.63	144.9	678.4	0.859	1.748	0.224
700	0.0440	6.215.–4	9.671	167.0	688.9	0.893	1.638	0.219
800	0.2029	6.443.–4	2.353	188.7	698.3	0.922	1.559	0.217
900	0.6620	6.689.–4	0.796	210.6	707.3	0.975	1.500	0.222
1000	1.693	6.954.–4	0.335	233.2	716.4	0.972	1.455	0.231
1200	6.790	7.628.–4	0.097	281.1	736.1	1.015	1.394	0.248
1500	27.6	8.84.–4	0.029	358.8	772.2	1.072	1.345	0.275

*Converted from tables in Vargaftik, *Tables of the Thermophysical Properties of Liquids and Gases,* Nauka, Moscow, 1972, and Hemisphere, Washington, 1975. m = melting point. The notation 2.66.–9 signifies 2.66×10^{9}.

Many of the Vargaftik values also appear in Ohse, R. W., *Handbook of Thermodynamic and Transport Properties of Alkali Metals,* Blackwell Sci. Pubs., Oxford, 1985 (1020 pp.). This source contains superheat data.

Saturation and superheat tables and a diagram to 30 bar, 1550 K are given by Reynolds, W. C., *Thermodynamic Properties in S.I.,* Stanford Univ. publ., 1979 (173 pp.).

For a Mollier diagram from 0.1 to 327 psia, 1300–2700°R, see Weatherford, W. D., J. C. Tyler, et al., WADD-TR-61-96, 1961.

An extensive review of properties of the solid and the saturated liquid was given by Alcock, C. B., M. W. Chase, et al., *J. Phys. Chem. Ref. Data,* **23,** 3 (1994): 385–497.

TABLE 2-247 Thermophysical Properties of Saturated Chlorine

T, °C	P, bar	v_f, m^3/kg	v_g, m^3/kg	h_f, kJ/kg	h_g, kJ/kg	s_f, kJ/(kg·K)	s_g, kJ/(kg·K)	c_{pf}, kJ/(kg·K)	c_{pg}, kJ/(kg·K)	μ_f, 10^{-6} Pa·s	μ_g, 10^{-6} Pa·s	k_f, W/(m·K)	k_g, W/(m·K)	Pr_f	Pr_g
−50	0.475	0.000 623	0.5448	221.5	518.2	1.7650	3.0946	0.9454	0.476	565	10.3	0.1684	0.0061	3.17	0.809
−40	0.773	0.000 634	0.3481	231.0	522.2	1.8074	3.0562	0.9474	0.484	520	10.8	0.1650	0.0065	2.99	0.815
−30	1.203	0.000 645	0.2314	240.6	526.1	1.8480	3.0223	0.9496	0.497	483	11.4	0.1613	0.0069	2.85	0.820
−20	1.802	0.000 656	0.1593	250.3	529.9	1.8869	2.9921	0.9520	0.513	452	11.9	0.1573	0.0074	2.74	0.826
−10	2.608	0.000 668	0.1134	260.0	533.9	1.9243	2.9649	0.9547	0.532	422	12.4	0.1527	0.0078	2.64	0.841
0	3.664	0.000 681	0.0829	269.7	537.4	1.9604	2.9402	0.9579	0.554	393	13.0	0.1478	0.0083	2.55	0.864
10	5.014	0.000 695	0.0619	279.4	540.5	1.9953	2.9177	0.9618	0.579	368	13.5	0.1427	0.0088	2.48	0.888
20	6.702	0.000 710	0.0471	289.2	543.3	2.0291	2.8924	0.9667	0.607	348	14.1	0.1378	0.0093	2.45	0.918
30	8.774	0.000 726	0.0364	299.0	545.7	2.0622	2.8777	0.9728	0.638	333	14.7	0.1327	0.0099	2.44	0.950
40	11.27	0.000 744	0.0286	308.8	548.0	2.0946	2.8593	0.9816	0.674	318	15.2	0.1282	0.0104	2.43	0.985
50	14.25	0.000 763	0.02276	318.6	549.8	2.1264	2.8417	0.9968	0.720	304	15.8	0.1230	0.0110	2.46	1.034
60	17.76	0.000 784	0.01827	329.1	551.2	2.1578	2.8245	1.022	0.786	290	16.4	0.1171	0.0117	2.53	1.107
70	21.85	0.000 808	0.01481	340.0	552.1	2.1892	2.8074	1.054	0.885	278	17.1	0.1122	0.0126	2.61	1.201
80	26.65	0.000 834	0.01202	351.4	552.5	2.2207	2.7900	1.124	1.017	267	17.9	0.1050	0.0137	2.85	1.331
90	32.17	0.000 865	0.00972	364.1	552.4	2.2528	2.7714	1.253	1.205	256	18.7	0.0986	0.0149	3.26	1.510
100	38.44	0.000 901	0.00789	377.8	551.0	2.2860	2.7502	1.418	1.434	247	19.5	0.0916	0.0163	3.82	1.700
110	45.54	0.000 956	0.00639	391.3	548.8	2.3207	2.7317	1.632	1.696	238	20.6	0.0850	0.0178	4.57	1.96
120	53.57	0.001 016	0.00508	407.1	543.7	2.3590	2.7064	1.891	1.960	230	22.2	0.0775	0.0195	5.61	2.23
130	62.68	0.001 121	0.00392	426.1	535.0	2.4032	2.6733								
140	72.84	0.001 335	0.00282	451.1	517.3	2.4595	2.6198								
144^c	77.10	0.001 77	0.00177	483.1	483.1	2.5365	2.5365								

c = critical point.

Values interpolated and converted from Martin, J. J., 1977 (private communication), and from *Heat Exchanger Design Handbook,* vol. 5, Hemisphere, Washington, DC, 1983. Values of Ziegler, *Chem.-Ing.-Tech.,* **22** (1950): 229, apparently were also used in Landolt-Bornstein, **IVa,** (1967): 238–239, and in Ullmans *Enzyklopädie der technische Chemie,* 9, Verlag Chemie, Weinheim, 1975 (317–372).

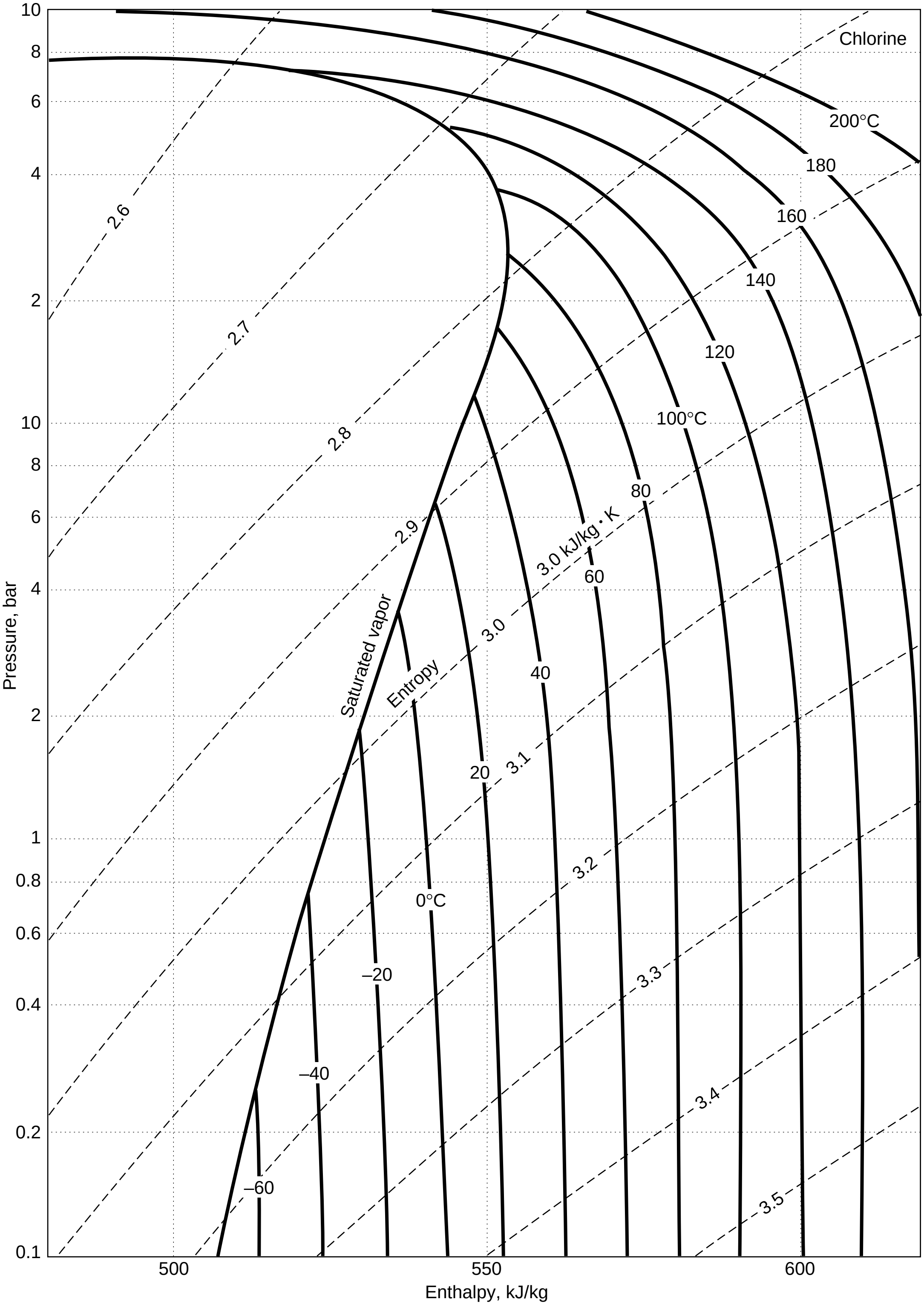

FIG. 2-9 Enthalpy–log-pressure diagram for chlorine.

TABLE 2-248 Saturated Chloroform (R20)

T, K	P, bar	v_f, m^3/kg	v_g, m^3/kg	h_f, kJ/kg	h_g, kJ/kg	s_f, kJ/(kg·K)	s_g, kJ/(kg·K)	c_{pf}, kJ/(kg·K)	μ_f, 10^{-6} Pa·s	k_f, W/(m·K)	Pr_f
280	0.115	0.000 660	1.689	–46.0	219.5	–0.165	0.798		748	0.120	
300	0.293	0.000 678	0.714	–32.6	230.6	–0.105	0.773		587	0.114	
320	0.620	0.000 695	0.358	–13.4	241.1	–0.041	0.754		468	0.109	
340	1.224	0.000 715	0.190	5.2	252.1	0.015	0.741		381	0.103	
360	2.255	0.000 739	0.107	23.3	263.0	0.065	0.731	1.03	319	0.095	3.35
380	3.830	0.000 765	0.0653	41.7	273.7	0.114	0.725	1.07	273	0.0921	3.17
400	6.039	0.000 795	0.0425	61.4	284.2	0.165	0.722	1.11	237	0.0863	3.04
420	9.058	0.000 822	0.0288	82.8	294.2	0.217	0.721	1.15	206	0.0808	2.93
440	13.39	0.000 871	0.0195	106.1	303.6	0.270	0.719	1.21	177	0.0750	2.86
460	18.80	0.000 921	0.0137	131.6	311.2	0.325	0.716	1.32	155	0.0694	2.95
480	26.00	0.000 980	0.00962	157.4	316.5	0.380	0.711	1.43	129.6	0.0641	2.89
500	34.66	0.001 059	0.00673	186.2	320.8	0.436	0.706	1.59	105.5	0.0584	2.87
520	44.68	0.001 193	0.00467	219.6	321.3	0.499	0.694		81.2	0.0518	
530	50.44	0.001 328	0.00359	242.7	315.7	0.540	0.678		67.7	0.0461	
536.6^c	54.72	0.002 00	0.00200	284.1	284.1	0.602	0.602				

c = critical point. $h_f = s_f = 0$ at n.b.p., 334.5 K.

P, v, h, and s interpolated from Altunin, V. V., V. Z. Geller, et al., *Thermophysical Properties of Freons,* U.S.S.R. N.S.R.D.S. series, vol. 9., Hemisphere.

TABLE 2-249 Saturated Decane*

T, K	P, bar	v_f, m^3/kg	v_g, m^3/kg	h_f, kJ/kg	h_g, kJ/kg	s_f, kJ/(kg·K)	s_g, kJ/(kg·K)	c_{pf}, kJ/(kg·K)	μ_f, 10^{-4} Pa·s	k_f, W/(m·K)
243.5^m	0.00001	1.319.–3	20750	418.1	812.5	2.561	4.092	2.119	25.0	0.149
260	0.00006	1.334.–3	3300.	452.7	836.3	2.699	4.120	2.109	16.6	0.144
280	0.00042	1.356.–3	443.	495.3	866.9	2.856	4.158	2.155	11.3	0.139
300	0.00197	1.381.–3	88.74	539.0	899.2	3.007	4.200	2.217	8.2	0.134
320	0.00720	1.410.–3	22.73	584.0	933.2	3.153	4.246	2.286	6.5	0.129
340	0.02155	1.442.–3	8.883	631.1	968.9	3.303	4.296		5.2	0.124
360	0.05522	1.478.–3	3.763	680.1	1006.2	3.443	4.350		4.16	0.119
380	0.1248	1.515.–3	1.750	730.7	1045.0	3.581	4.408		3.52	0.116
400	0.2549	1.552.–3	0.892	782.0	1085.0	3.712	4.469		2.98	0.110
420	0.4789	1.591.–3	0.490	835.6	1126.2	3.842	4.534		2.54	
440	0.8387	1.632.–3	0.290	889.6	1168.4	3.968	4.602		2.23	
447.3	1.0133	1.650.–3	0.243	909.4	1184.0	4.014	4.627		2.09	
460	1.3852	1.682.–3	0.178	944.5	1211.4	4.089	4.670			
480	2.1745	1.735.–3	0.115	1002.6	1255.2	4.213	4.739			
500	3.2690	1.797.–3	0.0759	1062.7	1299.4	4.335	4.808			
520	4.733	1.868.–3	0.0525	1124.5	1344.4	4.456	4.879			
540	6.633	1.952.–3	0.0369	1190.1	1389.5	4.573	4.949			
560	9.062	2.067.–3	0.0248	1256.1	1432.2	4.698	5.011			
580	12.16	2.255.–3	0.0154	1318.5	1468.1	4.802	5.060			
600	16.12	2.588.–3	0.0093	1384.5	1495.6	4.913	5.098			
617.5^c	20.97	4.238.–3	0.0042	1483.2	1483.2	5.073	5.073			

*Values converted from Das and Kuloor, *Ind. J. Technol.*, **5** (1967): 75. m = melting point; c = critical point. The notation 1.319.–3 signifies 1.319×10^{-3}.

TABLE 2-250 Saturated Normal Deuterium*

T, K	P, bar	v_f, m^3/kg	v_g, m^3/kg	h_f, kJ/kg	h_g, kJ/kg	s_f, kJ/(kg·K)	s_g, kJ/(kg·K)
18.71	0.1709	0.005752	2.232	−161.1	158.6	4.54	21.62
19	0.1944	0.005771	1.988	−160.0	159.1	4.68	21.48
20	0.2944	0.005840	1.365	−152.8	163.9	4.97	20.81
21	0.4297	0.005914	0.968	−145.9	167.6	5.30	20.23
22	0.6072	0.005993	0.705	−138.7	170.6	5.63	19.69
23	0.8344	0.00608	0.5256	−131.4	173.0	5.95	19.18
24	1.1192	0.00617	0.3995	−123.8	174.6	6.26	18.70
25	1.4694	0.00627	0.3088	−116.1	175.5	6.57	18.23
26	1.8932	0.00638	0.2421	−108.2	175.7	6.87	17.79
27	2.3989	0.00650	0.1921	−100.2	175.1	7.16	17.36
28	2.995	0.00663	0.1540	−92.0	173.8	7.44	16.94
29	3.690	0.00678	0.1246	−83.6	171.7	7.72	16.52
30	4.493	0.00694	0.1015	−74.9	168.7	8.00	16.12
31	5.412	0.00713	0.0831	−65.9	165.0	8.27	15.72
32	6.457	0.00735	0.0683	−56.5	160.3	8.54	15.32
33	7.455	0.00761	0.0563	−46.4	154.7	8.83	14.92
34	8.962	0.00793	0.0465	−35.5	148.0	9.12	14.52
35	10.44	0.00834	0.0382	−23.2	140.0	9.45	14.11
36	12.09	0.00890	0.0311	−8.6	130.1	9.82	13.67
37	13.91	0.00976	0.0249	10.0	117.1	10.28	13.17
38	15.92	0.01158	0.0185	39.7	95.0	11.01	12.47
38.34^c	16.65	0.01433	0.0143	69.2	69.2	11.76	11.76

*Condensed and converted from tables of Prydz, NBS Rep. 9276, 1967. c = critical point.

For equations and T-s and Z charts from 0.1 to 100 atm, 20–300 K, see also Prydz, R. and K. D. Timmerhaus, *Advan. Cryog. Eng.*, **13** (1968): 384–396.

TABLE 2-251 Saturated Deuterium Oxide*

T, K	P, bar	v_f, m^3/kg	v_g, m^3/kg	h_f, kJ/kg	h_g, kJ/kg	s_f, kJ/(kg·K)	s_g, kJ/(kg·K)
277.0^t	0.00668	9.047.–4	172.2	0.0	2320.9	0.000	8.380
278.2	0.00720	9.045.–4	160.4	5.0	2322.5	0.0188	8.351
283.2	0.01030	9.042.–4	114.1	25.9	2330.9	0.0920	8.233
288.2	0.01449	9.043.–4	82.48	46.9	2339.3	0.166	8.122
293.2	0.02011	9.047.–4	60.45	67.8	2347.6	0.239	8.016
298.2	0.02758	9.054.–4	44.88	88.7	2356.0	0.311	7.915
303.2	0.03730	9.063.–4	33.71	109.6	2364.0	0.382	7.818
308.2	0.04990	9.075.–4	25.59	130.5	2372.3	0.450	7.725
313.2	0.06598	9.091.–4	19.66	151.5	2380.7	0.518	7.637
318.2	0.08638	9.108.–4	15.24	172.4	2388.6	0.585	7.550
323.2	0.1120	9.127.–4	11.93	193.3	2396.6	0.650	7.468
333.2	0.1831	9.170.–4	7.52	234.7	2413.3	0.776	7.315
353.2	0.4439	9.274.–4	3.27	318.4	2445.1	1.020	7.042
373.2	0.9646	9.403.–4	1.58	402.0	2474.8	1.253	6.807
398.2	2.2427	9.599.–4	0.72	507.5	2509.6	1.527	6.555
423.2	4.653	9.835.–4	0.362	612.5	2541.8	1.781	6.341
448.2	8.806	1.012.–3	0.198	718.8	2569.4	2.020	6.149
473.2	15.46	1.044.–3	0.115	826.8	2585.7	2.256	5.973
498.2	25.52	1.082.–3	0.0704	938.5	2597.0	2.483	5.812
523.2	39.99	1.133.–3	0.0447	1055.2	2598.7	2.707	5.658
548.2	60.04	1.200.–3	0.0290	1177.4	2587.0	2.930	5.501
573.2	86.97	1.276.–3	0.0191	1306.7	2555.6	3.153	5.332
598.2	122.4	1.392.–3	0.0124	1445.6	2492.4	3.356	5.132
623.2	168.3	1.596.–3	0.0075	1607.1	2366.5	3.631	4.850
644.7^c	218.4	2.950.–3	0.0030				

*Extracted or converted from values in Kazavchinskii, Kesselman, et al., *Thermophysical Properties of Heavy Water,* Moscow and Leningrad, 1963; NBS-NSF transl. 70-50094, 1971. t = triple point; c = critical point. The notation 9.047.–4 signifies 9.047×10^{-4}.

Hill, P. G., MacMillan, R. D. and others give extensive tables for 0–1000 bar, 4–800°C in Atomic Energy of Canada, Chalk River rept. AECL-7531, 1981 (196 pp.). See also *J. Phys. Chem. Ref. Data,* **11,** 1 (1982): 1–14; **19,** 5 (1990): 1233–1274.

TABLE 2-252 Deuterium Oxide Gas at 1-kg/cm³ Pressure

T, K	400	450	500	550	600	650	700	750
v, m^3/kg	1.676	1.895	2.112	2.322	2.535	2.747	2.960	3.172
h, kJ/kg	2525	2619	2712	2807	2904	3002	3102	3205
s, kJ/(kg·K)	6.931	7.151	7.349	7.529	7.697	7.855	8.003	8.153

TABLE 2-253 Saturated Diphenyl*

T, K	P, bar	v_f, m^3/kg	v_g, m^3/kg	h_f, kJ/kg	h_g, kJ/kg	s_f, kJ/(kg·K)	s_g, kJ/(kg·K)	c_{pf}, kJ/(kg·K)	μ_f, 10^{-4} Pa·s	k_f, W/(m·K)
343	0.0010	1.010.–3	252.5	0.0	444.2	0.000	1.298	1.760	15.0	0.139
350	0.0016	1.014.–3	156.1	13.0	444.2	0.036	1.266	1.782	13.5	0.138
360	0.0029	1.021.–3	85.0	30.0	446.7	0.084	1.236	1.813	11.7	0.136
370	0.0049	1.030.–3	49.9	47.2	449.7	0.130	1.213	1.844	10.3	0.135
380	0.0064	1.037.–3	29.9	65.0	454.5	0.178	1.200	1.875	9.1	0.133
390	0.0129	1.046.–3	18.3	82.7	462.7	0.224	1.194	1.906	8.1	0.132
400	0.0200	1.054.–3	11.7	99.3	461.2	0.273	1.202	1.936	7.3	0.130
420	0.0432	1.072.–3	5.84	139.9	499.0	0.358	1.228	1.998	6.0	0.127
440	0.0879	1.092.–3	3.021	180.3	532.4	0.451	1.267	2.060	5.0	0.125
460	0.1694	1.112.–3	1.652	222.7	569.7	0.545	1.378	2.122	4.3	0.122
480	0.3112	1.132.–3	0.9594	267.6	611.6	0.652	1.367	2.184	3.7	0.119
500	0.5218	1.154.–3	0.4452	314.9	651.8	0.746	1.424	2.246	3.3	0.116
520	0.8375	1.177.–3	0.3652	361.5	687.8	0.824	1.477	2.308	2.7	0.113
540	1.290	1.204.–3	0.2261	404.5	723.8	0.915	1.529	2.370	2.4	0.110
560	1.941	1.230.–3	0.1447	457.2	762.7	1.032	1.582	2.432	2.2	0.107
580	2.818	1.258.–3	0.0977	522.3	801.7	1.125	1.635	2.494	1.90	0.105
600	3.926	1.291.–3	0.0685	563.7	842.4	1.223	1.688	2.556	1.71	0.102
620	5.408	1.326.–3	0.0504	630.4	886.4	1.316	1.740	2.618	1.54	0.099
640	7.328	1.366.–3	0.0381	689.1	930.9	1.375	1.748	2.680	1.39	0.096
660	9.572	1.412.–3	0.0301	745.9	977.1	1.457	1.791	2.741	1.24	0.093
680	12.05	1.465.–3	0.0236	802.8	1024.9	1.585	1.856	2.803	1.10	0.090
700	15.21	1.529.–3	0.0186	860.1	1073.1	1.663	1.951	2.865	0.97	0.087
720	19.14	1.56.–3	0.0147	917.5	1116.7	1.746	2.003	2.93		
740	23.93	1.70.–3	0.0113	975.2	1152.8	1.822	2.058	3.00		
760	28.71	1.95.–3	0.0085	1033.1	1182.5	1.901	2.099			
780	34.83	2.16.–3	0.0058	1091.2	1163.0	1.977	2.107			
800	42.46	3.18.–3	0.0032	1148.4	1148.4	2.047	2.047			

*Interpolated by P. E. Liley from the Landolt-Börnstein band IVa, p. 557, 1967 tables based on *Technical Data on Fuel,* British National Committee, World Energy Conference, London.

TABLE 2-254 Saturated Ethane (R170)*

T, K	P, bar	v_f, m^3/kg	v_g, m^3/kg	h_f, kJ/kg	h_g, kJ/kg	s_f, kJ/(kg·K)	s_g, kJ/(kg·K)	c_{pf}, kJ/(kg·K)	μ_f, 10^{-4} Pa·s	k_f, W/(m·K)
90.4^t	1.131.–5	1.534.–3	21945	176.8	769.4	2.560	9.113	2.260	14.19	0.215
100	1.110.–4	1.546	2484.5	198.7	782.4	2.790	8.627	2.274	9.37	0.208
110	7.467.–3	1.573	407.0	221.5	795.0	3.008	8.222	2.284	6.57	0.201
120	3.545.–3	1.615	93.61	244.4	807.2	3.207	7.897	2.292	4.89	0.194
130	1.291.–2	1.644	27.83	267.4	819.3	3.391	7.637	2.302	3.81	0.187
140	3.831.–2	1.675	10.08	290.5	831.4	3.562	7.426	2.316	3.07	0.180
150	9.672.–2	1.708	4.263	313.7	843.5	3.722	7.254	2.333	2.55	0.174
160	0.2146	1.743	2.039	337.2	855.6	3.873	7.113	2.355	2.17	0.167
170	0.4290	1.780	1.075	360.9	867.6	4.017	6.998	2.383	1.88	0.160
180	0.7874	1.819	0.6139	384.9	879.4	4.154	6.901	2.417	1.65	0.153
190	1.347	1.862	0.3738	409.3	890.8	4.285	6.819	2.458	1.47	0.147
200	2.174	1.908	0.2395	434.2	901.7	4.412	6.750	2.508	1.33	0.140
210	3.340	1.958	0.1602	459.7	911.9	4.535	6.689	2.568	1.21	0.133
220	4.922	2.014	0.1109	485.9	921.4	4.655	6.635	2.640	1.11	0.126
230	7.004	2.076	0.0789	512.8	929.6	4.773	6.585	2.730	1.03	0.119
240	9.670	2.148	0.0573	540.8	936.6	4.890	6.539	2.843	0.96	0.112
250	13.01	2.231	0.0423	569.9	941.9	5.006	6.493	2.991	0.82	0.106
260	17.12	2.330	0.0316	600.7	945.4	5.123	6.449	3.214	0.73	0.099
270	22.10	2.452	0.0237	633.6	946.4	5.233	6.392	3.511	0.64	0.092
280	28.06	2.613	0.0177	669.3	943.6	5.370	6.350	4.011	0.55	0.085
290	35.14	2.847	0.0129	709.8	934.7	5.502	6.278	5.089	0.44	0.078
300	43.54	3.295	0.0087	761.6	910.8	5.669	6.166	9.919	0.31	0.067
305.3^c	48.71	4.891	0.0048	841.2	841.2	5.919	5.919	∞		

*Values reproduced or converted from Goodwin, Roder, and Straty, NBS Tech. Note 684, 1976. t = triple point; c = critical point. The notation 1.131.–5 signifies 1.131×10^{-5}.

TABLE 2-255 Superheated Ethane*

		Temperature, K										
P, bar		100	150	200	250	300	350	400	450	500	600	700
	v	0.00156	0.00171	0.5310	0.6725	0.8118	0.9500	1.0877	1.2250	1.3622	1.6360	1.9096
1.013	h	198.9	313.8	909.3	984.7	1068.3	1161.5	1265.3	1379.8	1504.6	1783	2097
	s	2.790	3.722	6.993	7.330	7.634	7.921	8.198	8.467	8.730	9.237	9.720
	v	0.00156	0.00171	0.00191	0.1288	0.1595	0.1890	0.2178	0.2464	0.2747	0.3308	0.3867
5	h	199.4	314.3	434.5	973.3	1060.3	1155.6	1260.7	1376.1	1501.5	1781	2096
	s	2.789	3.720	4.411	6.858	7.175	7.468	7.748	8.020	8.284	8.793	9.227
	v	0.00156	0.00171	0.00190	0.0590	0.0765	0.0923	0.1073	0.1220	0.1365	0.1650	0.1933
10	h	200.0	314.9	435.0	956.5	1050.0	1148.2	1255.0	1371.5	1497.9	1777	2094
	s	2.788	3.719	4.408	6.618	6.959	7.262	7.547	7.821	8.087	8.598	9.083
	v	0.00156	0.00170	0.00190	0.00222	0.0346	0.0438	0.0521	0.0599	0.0674	0.0822	0.0966
20	h	201.3	316.1	435.9	569.8	1026.1	1132.3	1243.3	1362.4	1490.5	1774	2090
	s	2.785	3.715	4.404	4.999	6.710	7.038	7.334	7.614	7.884	8.399	8.886
	v	0.00155	0.00170	0.00189	0.00219	0.0118	0.0193	0.0244	0.0288	0.0329	0.0407	0.0482
40	h	203.9	318.5	437.9	569.9	947.9	1096.2	1218.6	1343.8	1475.9	1764	2083
	s	2.780	3.709	4.394	4.982	6.309	6.770	7.097	7.391	7.670	8.194	8.686
	v	0.00155	0.00170	0.00188	0.00217	0.00290	0.0109	0.0132	0.0185	0.0215	0.0270	0.0321
60	h	206.5	321.0	439.8	570.3	738.1	1050.9	1192.0	1324.8	1461.2	1754	2077
	s	2.775	3.702	4.385	4.966	5.574	6.557	6.934	7.247	7.535	8.068	8.564
	v	0.00155	0.00169	0.00188	0.00215	0.00273	0.00667	0.0106	0.0134	0.0158	0.0201	0.0459
80	h	209.1	323.4	441.9	570.9	728.1	993.8	1163.6	1305.5	1446.7	1745	2070
	s	2.769	3.696	4.377	4.951	5.522	6.345	6.800	7.135	7.432	7.975	8.476
	v	0.00155	0.00169	0.00187	0.00213	0.00263	0.00465	0.00791	0.0104	0.0124	0.0160	0.0193
100	h	211.7	325.8	443.9	571.8	722.7	924.4	1134.7	1286.3	1432.4	1736	2064
	s	2.764	3.690	4.368	4.938	5.486	6.166	6.682	7.040	7.348	7.900	8.406
	v	0.00155	0.00168	0.00185	0.00209	0.00247	0.00328	0.00488	0.00655	0.00805	0.0107	0.0130
150	h	218.1	332.0	449.2	574.6	716.4	887.4	1075.2	1242.3	1399.3	1715	2050
	s	2.752	3.674	4.348	4.907	5.423	5.955	6.457	6.851	7.182	7.758	8.274
	v	0.00154	0.00167	0.00184	0.00205	0.00237	0.00291	0.00383	0.00495	0.00605	0.00806	0.00986
200	h	224.6	338.2	454.7	578.2	714.8	870.5	1041.7	1210.2	1327.3	1697	2038
	s	2.738	3.660	4.329	4.880	5.377	5.863	6.320	6.717	7.059	7.651	8.176
	v	0.00153	0.00166	0.00181	0.00200	0.00225	0.00259	0.00307	0.00367	0.00433	0.00563	0.00686
300	h	237.6	350.6	465.9	586.8	715.9	860.9	1014.9	1175.5	1338.7	1671	2019
	s	2.715	3.632	4.294	4.833	5.309	5.757	6.168	6.547	6.891	7.496	8.032
	v	0.00153	0.00165	0.00179	0.00195	0.00216	0.00244	0.00276	0.00316	0.00361	0.00454	0.00545
400	h	250.6	363.2	477.6	596.6	723.7	861.6	1008.3	62.5	1322.7	1657	2008
	s	2.692	3.605	4.262	4.793	5.257	5.688	6.080	6.443	6.780	7.388	7.930
	v	0.00152	0.00163	0.00176	0.00192	0.00210	0.00232	0.00258	0.00288	0.00322	0.00392	0.00465
500	h	263.5	375.8	489.3	607.1	732.0	866.5	1009.3	1159.3	1316.9	1650	2003
	s	2.670	3.580	4.234	4.758	5.213	5.634	6.015	6.369	6.00	7.306	7.851

*Converted and rounded off from the tables of Goodwin, Roder, and Straty, NBS Tech. Note 684, 1976. v = specific volume, m^3/kg; h = specific enthalpy, kJ/kg; s = specific entropy, kJ/(kg·K).

Saturation and superheat tables and a diagram to 300 bar, 580 K are given by Reynolds, W. C., *Thermodynamic Properties in S.I.,* Stanford Univ. publ., 1979 (173 pp.). Saturation and superheat tables and a chart to 10,000 psia, 640°F appear in Stewart, R. B., R. T. Jacobsen, et al., *Thermodynamic Properties of Refrigerants,* ASHRAE, Atlanta, GA, 1986 (521 pp.). For specific heat, thermal conductivity, and viscosity, see *Thermophysical Properties of Refrigerants,* ASHRAE, 1993. The 1993 ASHRAE *Handbook—Fundamentals* (SI ed.) contains a thermodynamic diagram from 0.1 to 700 bar for temperatures to 600 K.

TABLE 2-256 Saturated Ethanol

T, K	P, bar	v_f, m³/kg	v_g, m³/kg	h_f, kJ/kg	h_g, kJ/kg	s_f, kJ/(kg·K)	s_g, kJ/(kg·K)	c_{pf}, kJ/(kg·K)	μ_f, 10^{-6} Pa·s	k_f, W/(m·K)	Pr_f
250	0.0027	0.001 184						2.113	295	0.177	35.2
260	0.0059	0.001 196						2.167	229	0.175	28.4
270	0.0128	0.001 208						2.227	193	0.173	24.8
280	0.025	0.001 220						2.294	156	0.171	20.9
290	0.048	0.001 233						2.369	127	0.170	17.7
300	0.088	0.001 246						2.45	104	0.168	15.2
310	0.151	0.001 260						2.54	86	0.165	13.2
320	0.253	0.001 274						2.64	72	0.162	11.7
330	0.406	0.001 288						2.75	61	0.159	10.6
340	0.632	0.001 304						2.86	52	0.157	9.5
350	0.956	0.001 318	0.7656	199.9	1161.9			2.99	45.0	0.155	8.7
360	1.409	0.001 337	0.5052	230.1	1178.4			3.12	39.0	0.153	8.0
370	2.023	0.001 357	0.3555	262.2	1193.9			3.27	34.2	0.151	7.4
380	2.837	0.001 379	0.2556	295.1	1208.4			3.42	30.0	0.149	6.9
390	3.897	0.001 403	0.1873	329.1	1221.5			3.58	26.1	0.147	6.3
400	5.251	0.001 430	0.1398	364.2	1233.6			3.74	22.7	0.145	5.9
410	6.954	0.001 461	0.1058	400.8	1244.2			3.99	20.0	0.144	5.5
420	9.063	0.001 495	0.0812	435.7	1254.2			4.26	17.6	0.142	5.3
430	11.64	0.001 532	0.0631	472.2	1262.3			4.55	15.3	0.140	5.0
440	14.72	0.001 574	0.0493	512.7	1269.2			4.88	13.9	0.139	4.9
450	18.33	0.001 623	0.0389	557.2	1274.2			5.23	12.5	0.137	4.8
460	22.61	0.001 682	0.0308	605.0	1275.5						
470	27.66	0.001 752	0.0243	653.7	1271.1						
480	33.55	0.001 832	0.0193	704.5	1262.3						
490	40.39	0.001 950	0.0148	757.7	1250.2						
500	48.28	0.002 091	0.0110	818.9	1232.7						
510	57.32										
516.3[c]	63.90										

c = critical point.
Values interpolated and converted from *Heat Exchanger Design Handbook,* vol. 5, Hemisphere, Washington, DC, 1983, and from various literature sources.

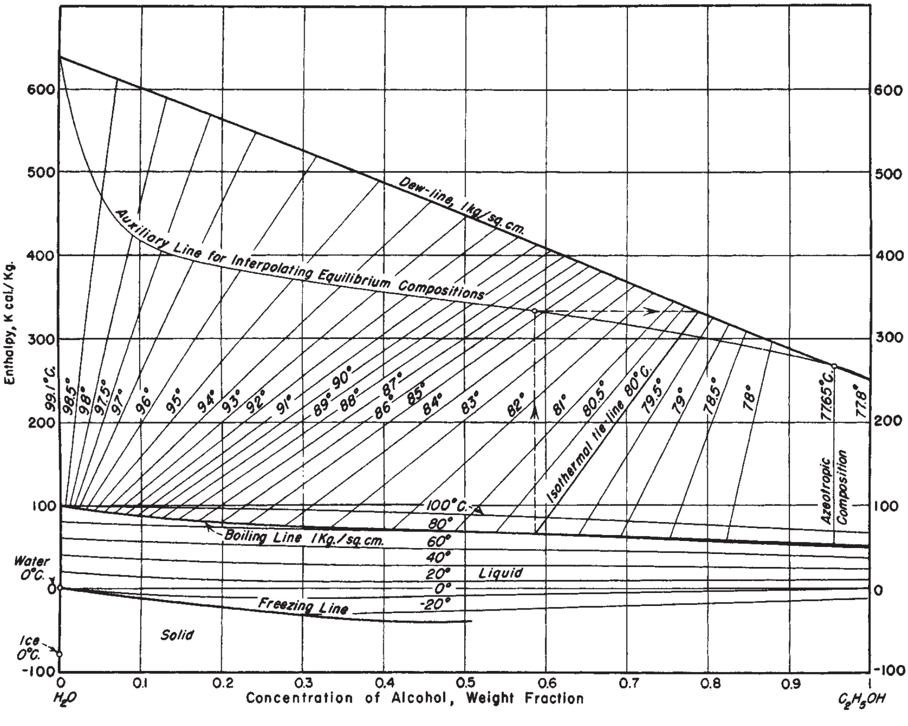

FIG. 2-10 Enthalpy-concentration diagram for aqueous ethyl alcohol. Reference states: Enthalpies of liquid water and ethyl alcohol at 0°C are zero. NOTE: In order to interpolate equilibrium compositions, a vertical may be erected from any liquid composition on the boiling line and its intersection with the auxiliary line determined. A horizontal from this intersection will establish the equilibrium vapor composition on the dew line. (*Bosnjakovic,* Technische Thermodynamik, *T. Steinkopff, Leipzig, 1935.*)

TABLE 2-257 Saturated Ethylene (Ethene—R1150)

Temperature, K	Pressure, bar	v_f, m^3/kg	v_g, m^3/kg	h_f, kJ/kg	h_g, kJ/kg	s_f, kJ/(kg·K)	s_g, kJ/(kg·K)	c_{pf}, kJ/(kg·K)
104.0[t]	0.00123	0.001 527	251.36	−323.81	244.36	−1.9901	3.4730	2.497
110	0.00334	0.001 545	97.57	−309.54	251.47	−1.8571	3.2431	2.500
120	0.01380	0.001 576	25.75	−284.17	263.23	−1.6362	2.9255	2.539
130	0.04456	0.001 609	8.62	−259.13	274.87	−1.4358	2.6717	2.465
140	0.1191	0.001 644	3.46	−234.80	286.28	−1.2554	2.4663	2.405
150	0.2747	0.001 681	1.5977	−210.90	297.37	−1.0908	2.2977	2.377
160	0.5636	0.001 721	0.8232	−187.12	308.00	−0.9378	2.1566	2.377
170	1.0526	0.001 763	0.4625	−163.23	318.04	−0.7935	2.0375	2.395
180	1.8207	0.001 810	0.2784	−139.05	327.35	−0.6559	1.9352	2.427
190	2.9574	0.001 861	0.1770	−114.46	335.79	−0.5244	1.7812	2.472
200	4.560	0.001 918	0.1177	−89.33	343.21	−0.3967	1.7659	2.531
210	6.730	0.001 981	0.0810	−63.52	349.41	−0.2730	1.6932	2.608
220	9.575	0.002 054	0.0573	−36.84	354.18	−0.1515	1.6258	2.711
230	13.206	0.002 139	0.0413	−9.04	357.17	−0.0314	1.5609	2.852
240	17.742	0.002 241	0.0302	20.23	357.90	0.0088	1.4957	3.055
250	23.307	0.002 369	0.02222	51.55	355.37	0.2114	1.4276	3.372
260	30.046	0.002 541	0.01624	85.91	348.68	0.3397	1.3503	3.945
270	38.132	0.002 804	0.01152	125.79	333.71	0.4819	1.3054	5.40
280	47.834	0.003 442	0.00720	183.40	292.83	0.6803	1.0711	20.0
282.3[c]	50.403	0.004 669	0.00467	234.55	234.55	0.8585	0.8585	

t = triple point; c = critical point. $h_f = s_f = 0$ at 233.15 K = −40°C.

Converted from Jacobsen, R. T., M. Jahangiri, et al., *Ethylene—Intl. Thermodyn. Tables of the Fluid State—10,* Blackwell Sci. Publ., Oxford, U.K., 1988 (299 pp.). Saturation and superheat tables and a diagram to 100 bar, 460 K are given by Reynolds, W. C., *Thermodynamic properties in S.I.,* Stanford Univ. publ., 1979 (173 pp.). Saturation and superheat tables and a chart to 6000 psia, 360°F appear in *Thermodynamic Properties of Refrigerants,* ASHRAE, Atlanta, GA, 1986 (521 pp.). For specific heat, thermal conductivity, and viscosity, see *Thermophysical Properties of Refrigerants,* ASHRAE, 1993.

The 1993 ASHRAE *Handbook—Fundamentals* (SI ed.) has a thermodynamic chart for pressures from 0.1 to 400 bar and temperatures up to 460 K.

TABLE 2-258 Compressed Ethylene

		Temperature, K							
Pressure, bar		110	125	150	175	200	225	250	275
1	v (m^3/kg)	0.001 545	0.001 592	0.001 681	0.5036	0.5814	0.6580	0.7337	0.8091
	h (kJ/kg)	−309.4	−271.4	−210.8	324.8	357.0	389.9	424.0	459.7
	s (kJ/kg·K)	−1.858	−1.534	−1.091	2.091	2.264	2.419	2.562	2.698
5	v (m^3/kg)	0.001 544	0.001 591	0.001 680	0.001 785	0.001 917	0.1240	0.1407	0.1569
	h (kJ/kg)	−308.9	−271.0	−210.4	−150.8	−89.3	378.4	415.0	452.3
	s (kJ/kg·K)	−1.859	−1.535	−1.093	−0.726	−0.397	1.907	2.061	2.203
10	v (m^3/kg)	0.001 543	0.001 591	0.001 679	0.001 783	0.001 914	0.05643	0.06672	0.07525
	h (kJ/kg)	−308.3	−270.4	−209.8	−150.3	−89.0	361.2	402.4	442.3
	s (kJ/kg·K)	−1.860	−1.537	−1.095	−0.728	−0.400	1.646	1.820	1.973
20	v (m^3/kg)	0.001 542	0.001 589	0.001 676	0.001 780	0.001 908	0.002 084	0.02810	0.03405
	h (kJ/kg)	−307.1	−269.2	−208.7	−149.4	−88.2	−23.0	370.3	419.7
	s (kJ/kg·K)	−1.863	−1.540	−1.098	−0.733	−0.406	−0.099	1.520	1.708
30	v (m^3/kg)	0.001 541	0.001 588	0.001 674	0.001 776	0.001 903	0.002 072	0.002 347	0.01978
	h (kJ/kg)	−305.9	−268.0	−207.6	−148.4	−87.5	−22.8	50.5	390.7
	s (kJ/kg·K)	−1.866	−1.543	−1.102	−0.737	−0.412	−0.107	0.201	1.508
40	v (m^3/kg)	0.001 540	0.001 587	0.001 672	0.001 773	0.001 897	0.002 062	0.002 318	0.01163
	h (kJ/kg)	−304.7	−266.8	−206.5	−147.4	−86.7	−22.5	49.1	344.7
	s (kJ/kg·K)	−1.869	−1.546	−1.106	−0.741	−0.418	−0.115	0.186	1.284
50	v (m^3/kg)	0.001 539	0.001 585	0.001 670	0.001 770	0.001 892	0.002 052	0.002 293	0.002 846
	h (kJ/kg)	−303.5	−265.7	−205.4	−146.4	−85.9	−22.2	48.1	139.8
	s (kJ/kg·K)	−1.872	−1.550	−1.110	−0.746	−0.423	−0.123	0.173	0.521
60	v (m^3/kg)	0.001 538	0.001 584	0.001 668	0.001 767	0.001 887	0.002 043	0.002 270	0.002 723
	h (kJ/kg)	−302.3	−264.5	−204.2	−145.4	−85.1	−21.8	47.4	132.3
	s (kJ/kg·K)	−1.875	−1.553	−1.113	−0.750	−0.428	−0.130	0.161	0.484
80	v (m^3/kg)	0.001 535	0.001 581	0.001 664	0.001 761	0.001 877	0.002 025	0.002 232	0.002 585
	h (kJ/kg)	−299.8	−262.1	−202.0	−143.4	−83.5	−20.9	46.5	124.1
	s (kJ/kg·K)	−1.881	−1.559	−1.120	−0.759	−0.439	−0.145	0.139	0.434
100	v (m^3/kg)	0.001 533	0.001 579	0.001 660	0.001 754	0.001 867	0.002 009	0.002 199	0.002 495
	h (kJ/kg)	−297.4	−259.7	−199.7	−141.2	−81.8	−19.9	46.1	119.6
	s (kJ/kg·K)	−1.887	−1.565	−1.127	−0.767	−0.449	−0.158	0.120	0.400
150	v (m^3/kg)	0.001 528	0.001 571	0.001 650	0.001 740	0.001 846	0.001 973	0.002 136	0.002 356
	h (kJ/kg)	−291.3	−253.7	−194.0	−136.0	−77.3	−16.7	46.6	114.4
	s (kJ/kg·K)	−1.901	−1.580	−1.145	−0.787	−0.473	−0.188	0.079	0.337
200	v (m^3/kg)	0.001 522	0.001 565	0.001 641	0.001 727	0.001 826	0.001 943	0.002 086	0.002 268
	h (kJ/kg)	−285.3	−247.7	−188.3	−130.7	−72.5	−13.0	48.6	113.2
	s (kJ/kg·K)	−1.914	−1.595	−1.161	−0.806	−0.495	−0.215	0.045	0.291
250	v (m^3/kg)	0.001 517	0.001 559	0.001 633	0.001 715	0.001 809	0.001 918	0.002 046	0.002 203
	h (kJ/kg)	−279.2	−241.7	−182.5	−125.2	−67.6	−8.9	51.4	113.9
	s (kJ/kg·K)	−1.928	−1.610	−1.177	−0.824	−0.516	−0.240	0.015	0.253
300	v (m^3/kg)	0.001 512	0.001 552	0.001 625	0.001 704	0.001 793	0.001 895	0.002 012	0.002 151
	h (kJ/kg)	−273.0	−235.7	−174.5	−119.6	−62.5	−4.4	54.9	115.9
	s (kJ/kg·K)	−1.942	−1.623	−1.192	−0.841	−0.536	−0.262	−0.012	0.220
400	v (m^3/kg)	0.001 503	0.001 542	0.001 609	0.001 683	0.001 765	0.001 855	0.001 957	0.002 072
	h (kJ/kg)	−260.8	−223.6	−164.8	−108.3	−51.9	5.1	63.0	122.1
	s (kJ/kg·K)	−1.968	−1.650	−1.221	−0.873	−0.572	−0.303	−0.059	0.166
500	v (m^3/kg)	0.001 499	0.001 531	0.001 596	0.001 665	0.001 740	0.001 823	0.001 913	0.002 01
	h (kJ/kg)	−246.9	−211.4	−152.9	−96.8	−40.9	15.3	72.3	130.1
	s (kJ/kg·K)	−1.978	−1.676	−1.249	−0.906	−0.605	−0.339	−0.099	0.121

Converted from Jacobsen, R. T., M. Jahangiri, et al., *Ethylene—Intl. Thermodyn. Tables of the Fluid State—10,* Blackwell Sci. Publ., Oxford, 1988 (299 pp.). $s_f = h_f = 0$ at 233.15 K = −40°C.

TABLE 2-258 Compressed Ethylene (*Concluded*)

Pressure, bar		Temperature, K						
		300	325	350	375	400	425	450
1	v (m^3/kg)	0.8842	0.9591	1.0339	1.1084	1.1830	1.2575	1.3319
	h (kJ/kg)	497.3	536.9	578.8	622.8	668.9	717.2	767.9
	s (kJ/kg·K)	2.829	2.956	3.079	3.201	3.320	3.437	3.553
5	v (m^3/kg)	0.1728	0.1884	0.2039	0.2193	0.2346	0.2499	0.2650
	h (kJ/kg)	491.0	531.5	574.1	618.6	665.2	713.9	764.9
	s (kJ/kg·K)	2.338	2.467	2.593	2.716	2.836	2.954	3.071
10	v (m^3/kg)	0.08380	0.09207	0.1002	0.1081	0.1160	0.1238	0.1316
	h (kJ/kg)	482.8	542.5	568.0	613.3	660.5	709.7	761.1
	s (kJ/kg·K)	2.113	2.247	2.375	2.500	2.622	2.742	2.859
20	v (m^3/kg)	0.03914	0.04379	0.04823	0.05257	0.05675	0.06088	0.06491
	h (kJ/kg)	465.0	509.8	555.5	602.4	650.9	701.2	753.5
	s (kJ/kg·K)	1.866	2.009	2.144	2.274	2.399	2.521	2.640
30	v (m^3/kg)	0.02404	0.02763	0.03090	0.03400	0.03700	0.03990	0.04270
	h (kJ/kg)	444.7	493.8	542.3	591.2	641.2	692.6	745.9
	s (kJ/kg·K)	1.696	1.853	1.996	2.131	2.261	2.387	2.508
40	v (m^3/kg)	0.01630	0.01947	0.02220	0.02473	0.02710	0.02938	0.03160
	h (kJ/kg)	420.6	476.3	528.3	579.5	631.2	688.9	738.2
	s (kJ/kg·K)	1.550	1.728	1.882	2.023	2.157	2.286	2.409
50	v (m^3/kg)	0.01140	0.01451	0.01697	0.01916	0.02119	0.02311	0.02495
	h (kJ/kg)	390.4	456.9	513.4	567.5	621.1	675.1	730.5
	s (kJ/kg·K)	1.404	1.617	1.784	1.933	2.072	2.207	2.330
60	v (m^3/kg)	0.007 757	0.01116	0.01347	0.01546	0.01725	0.01892	0.02052
	h (kJ/kg)	347.8	435.1	497.7	555.2	610.9	666.3	722.9
	s (kJ/kg·K)	1.230	1.510	1.696	1.854	1.999	2.135	2.263
80	v (m^3/kg)	0.003 672	0.006 864	0.009 136	0.01085	0.01237	0.01374	0.01502
	h (kJ/kg)	238.7	382.8	463.5	529.4	590.1	648.5	707.6
	s (kJ/kg·K)	0.832	1.295	1.534	1.717	1.874	2.016	2.151
100	v (m^3/kg)	0.003 094	0.004 698	0.006 596	0.008 163	0.009 492	0.01068	0.01177
	h (kJ/kg)	210.2	330.2	427.5	503.1	569.3	630.9	692.7
	s (kJ/kg·K)	0.715	1.098	1.387	1.596	1.768	1.918	2.059
150	v (m^3/kg)	0.002 684	0.003 223	0.004 040	0.004 983	0.005 914	0.006 765	0.007 578
	h (kJ/kg)	188.8	272.7	361.4	445.5	521.6	592.1	658.1
	s (kJ/kg·K)	0.596	0.864	1.126	1.359	1.556	1.722	1.878
200	v (m^3/kg)	0.002 508	0.002 840	0.003 292	0.003 838	0.004 445	0.005 058	0.005 664
	h (kJ/kg)	181.7	255.0	332.4	410.6	487.0	560.1	629.5
	s (kJ/kg·K)	0.529	0.763	0.992	1.208	1.406	1.580	1.742
250	v (m^3/kg)	0.002 397	0.002 644	0.003 024	0.003 327	0.003 743	0.004 190	0.004 648
	h (kJ/kg)	179.2	247.7	319.1	392.1	465.5	538.2	608.5
	s (kJ/kg·K)	0.480	0.698	0.910	1.111	1.301	1.476	1.639
300	v (m^3/kg)	0.002 317	0.002 517	0.002 578	0.003 037	0.003 351	0.003 690	0.004 042
	h (kJ/kg)	179.1	244.6	312.6	382.2	452.9	524.1	593.9
	s (kJ/kg·K)	0.440	0.670	0.850	1.043	1.226	1.398	1.558
400	v (m^3/kg)	0.002 203	0.002 352	0.002 522	0.002 711	0.002 919	0.003 413	0.003 382
	h (kJ/kg)	182.7	244.9	308.8	374.3	441.3	509.8	578.3
	s (kJ/kg·K)	0.377	0.576	0.764	0.946	1.119	1.285	1.442
500	v (m^3/kg)	0.002 122	0.002 245	0.002 379	0.002 524	0.002 678	0.002 847	0.003 022
	h (kJ/kg)	189.1	250.7	312.8	376.1	440.4	505.8	572.0
	s (kJ/kg·K)	0.326	0.523	0.707	0.882	1.048	1.206	1.358

TABLE 2-259 Saturated Fluorine*

T, K	P, bar	v_f, m^3/kg	v_g, m^3/kg	h_f, kJ/kg	h_g, kJ/kg	s_f, kJ/(kg·K)	s_g, kJ/(kg·K)	c_{pf}, kJ/(kg·K)	μ_f, 10^{-4} Pa·s	k_f, W/(m·K)
53.5^t	0.0025	5.866.–4	46.2	–158.6	40.9	1.602	5.314	1.446	8.8	0.186
55	0.0041	5.898.–4	17.1	–153.5	42.0	1.642	5.235	1.442	8.0	0.184
60	0.0155	6.005.–4	8.46	–149.1	45.8	1.768	5.004	1.437	6.0	0.177
65	0.0477	6.119.–4	2.93	–141.8	49.6	1.885	4.816	1.442	4.7	0.170
70	0.1230	6.240.–4	1.24	–134.4	53.2	1.995	4.666	1.450	3.8	0.162
75	0.276	6.369.–4	0.583	–127.0	56.8	2.097	4.540	1.460	3.19	0.154
80	0.555	6.508.–4	0.309	–119.5	60.1	2.194	4.433	1.474	2.71	0.146
85	1.019	6.657.–4	0.176	–111.9	63.3	2.285	4.342	1.498	2.33	0.137
90	1.740	6.819.–4	0.108	–104.3	66.1	2.372	4.262	1.535	2.00	0.129
95	2.802	6.997.–4	0.069	–96.5	68.6	2.455	4.191	1.555	1.76	0.120
100	4.280	7.193.–4	0.0466	–88.6	70.7	2.535	4.127	1.585	1.53	0.112
105	6.280	7.412.–4	0.0323	–80.5	72.4	2.612	4.068	1.630	1.36	0.103
110	8.885	7.659.–4	0.0231	–72.2	73.6	2.688	4.012	1.692	1.21	0.095
115	12.20	7.948.–4	0.0168	–63.6	74.1	2.763	3.959	1.782	1.08	0.087
120	16.33	8.283.–4	0.0125	–54.5	73.9	2.837	3.906	1.888	0.96	0.080
125	21.37	8.696.–4	0.0093	–44.9	72.7	2.912	3.864	2.05	0.86	0.073
130	27.48	9.223.–4	0.0069	–34.5	70.2	2.989	3.795	2.33	0.74	0.066
135	34.72	9.963.–4	0.0051	–22.7	65.6	3.073	3.727	2.90	0.63	0.070
140	43.47	1.119.–3	0.0036	–8.4	56.9	3.170	3.636	3.64	0.49	0.105
144.3^c	52.15	1.743.–3	0.0017	23.9	23.9	3.388	3.388	∞		∞

*Values reproduced or converted from Prydz and Straty, NBS Tech. Note 392, rev., September 1973. t = triple point; c = critical point. The notation 5.866.–4 signifies 5.866×10^{-4}.

TABLE 2-260 Fluorine Gas at Atmospheric Pressure*

T, K	84.95	90	100	120	140	160	180	200	220	240	260	280	300
v, m^3/kg	0.1776	0.1892	0.2118	0.2562	0.3002	0.3439	0.3874	0.4309	0.4744	0.5176	0.5610	0.6043	0.6476
h, kJ/kg	63.22	67.30	75.27	90.96	106.53	122.06	137.62	153.2	169.0	184.9	201.0	217.2	233.7
s, kJ/(kg·K)	4.342	4.390	4.474	4.616	4.737	4.840	4.932	5.014	5.090	5.158	5.221	5.282	5.340

*Extracted from Prydz and Straty, NBS Tech. Note 392, 1970. This source is recommended for other pressures and temperatures. Other information is contained in *J. Chem. Phys.*, **53** (1970): 2359; and *J. Res. NBS*, **74A** (1970): 499, 661, 747.

TABLE 2-261 Flutec

Proprietary name for a series of fluorocarbons produced by the Imperial Smelting Corp., Avonmouth, Bristol, UK. Bulletins of thermodynamic properties include PP1 (C_6F_{14}), PP2 (C_7F_{14}), PP3 (C_8F_{16}), PP5 ($C_{10}F_{18}$), PP9 ($C_{11}F_{20}$), and PP50, usually for 0.1–100 kg/m^2, 0–500°C. See also Green, S. W., *Chem. & Ind.* (1969): 63–67.

TABLE 2-262 Halon

A series of fire-extinguishing fluids. Halon 1211 is produced by ICI, and Halon 1301, by duPont, the latter issuing a bulletin with thermodynamic properties and a diagram for the range 0.6–600 psia, –160–460°F.

TABLE 2-263 Saturated Helium^3*

T, K	P, bar	v_f, m^3/kg	v_g, m^3/kg	h_f, kJ/kg	h_g, kJ/kg	s_f, kJ/(kg·K)	s_g, kJ/(kg·K)
1.0	0.0122	0.01222	1.72	–5.69	6.75	2.28	14.72
1.1	0.0182	0.01224	1.33	–5.49	7.40	2.65	14.34
1.2	0.0274	0.01227	1.02	–5.26	8.03	2.95	14.02
1.3	0.0370	0.01231	0.805	–5.01	8.65	3.20	13.70
1.4	0.0517	0.01236	0.649	–4.75	9.27	3.40	13.41
1.5	0.0659	0.01241	0.526	–4.47	9.88	3.60	13.13
1.6	0.0871	0.01247	0.437	–4.17	10.46	3.80	12.88
1.7	0.107	0.01254	0.363	–3.84	11.04	3.91	12.53
1.8	0.137	0.01262	0.308	–3.47	11.60	4.01	12.38
1.9	0.163	0.01271	0.260	–3.07	12.15	4.13	12.14
2.0	0.202	0.01282	0.222	–2.64	12.68	4.26	11.91
2.1	0.237	0.01294	0.189	–2.17	13.19	4.40	11.69
2.2	0.284	0.01308	0.164	–1.55	13.67	4.55	11.47
2.3	0.326	0.01324	0.142	–0.99	14.13	4.71	11.25
2.4	0.385	0.01343	0.124	–0.34	14.57	4.87	11.04
2.5	0.438	0.01365	0.109	0.36	14.98	5.03	10.84
2.6	0.508	0.01390	0.096	1.16	15.37	5.20	10.64
2.7	0.576	0.01419	0.085	2.01	15.89	5.38	10.41
2.8	0.653	0.01456	0.074	2.96	16.40	5.57	10.17
2.9	0.732	0.01497	0.064	4.01	16.37	5.77	9.92
3.0	0.803	0.01549	0.055	5.28	16.32	6.00	9.66
3.1	0.907	0.01614	0.047	6.70	16.20	6.24	9.34
3.2	1.023	0.01720	0.039	8.44	15.98	6.54	8.90
3.3	1.128	0.01902	0.028	10.66	14.50	6.96	8.35
3.32^c	1.165	0.02394	0.024	13.25	13.25	7.50	7.50

*Converted and smoothed from a tabulation of Gibbons and Nathan, USAF Rep. AFML-TR-67-175, 1967. c = critical point. Kelly, D. P. and W. K. Haubach, in AEC R&D rept. MLM 1161, 1963 (56 pp.), give a comprehensive graphical comparison of the properties of He^3 and He^4.

TABLE 2-264 Saturated Helium^4

Temperature, K	Pressure, bar	v_f, m^3/kg	v_g, m^3/kg	h_f, kJ/kg	h_g, kJ/kg	s_f, kJ/(kg·K)	s_g, kJ/(kg·K)	c_{pf}, kJ/(kg·K)	c_{pg}, kJ/(kg·K)
0.8	1.475.–5	0.00689	1125.9	0.0019	19.42	0.0047	23.94	0.022	5.210
0.9	5.379.–5	0.00689	347.1	0.0054	19.94	0.0087	21.86	0.050	5.230
1.0	1.557.–4	0.00689	133.0	0.0127	20.44	0.0163	20.44	0.100	5.262
1.1	3.800.–4	0.00689	59.8	0.0268	20.95	0.0296	18.82	0.185	5.305
1.2	8.148.–4	0.00689	30.4	0.0518	21.44	0.0510	17.67	0.318	5.360
1.3	0.00158	0.00689	16.93	0.0932	21.92	0.0836	16.70	0.511	5.424
1.4	0.00282	0.00689	10.17	0.1579	22.40	0.1308	15.86	0.780	5.496
1.5	0.00472	0.00689	6.49	0.2543	22.87	0.1962	15.13	1.138	5.574
1.6	0.00746	0.00688	4.35	0.3923	23.32	0.2839	14.49	1.602	5.654
1.7	0.01128	0.00688	3.04	0.5836	23.77	0.3981	13.93	2.193	5.736
1.8	0.01638	0.00688	2.1993	0.8422	24.20	0.5437	13.43	2.938	5.818
1.9	0.02299	0.00687	1.6420	1.186	24.63	0.7270	12.98	3.893	5.898
2.0	0.03129	0.00686	1.2601	1.642	25.04	0.9578	12.58	5.187	5.975
2.1	0.04141	0.00685	0.9921	2.261	25.45	1.256	12.23	7.244	6.046
2.2	0.05335	0.00684	0.7994	3.090	25.85	1.638	11.92	4.222	6.111
2.3	0.06730	0.00685	0.6566	3.418	26.24	1.780	11.65	2.685	6.170
2.4	0.08354	0.00687	0.5470	3.678	26.63	1.886	11.40	2.375	6.228
2.5	0.01023	0.00690	0.4608	3.922	27.00	1.980	11.17	2.284	6.285
2.6	0.1237	0.00693	0.3923	4.161	27.37	2.068	10.96	2.320	6.344
2.7	0.1481	0.00695	0.3367	4.408	27.72	2.155	10.76	2.351	6.406
2.8	0.1755	0.00699	0.2913	4.662	28.06	2.240	10.57	2.403	6.470
2.9	0.2063	0.00703	0.2537	4.923	28.38	2.324	10.39	2.486	6.540
3.0	0.2405	0.00707	0.2223	5.195	28.69	2.408	10.22	2.597	6.616
3.1	0.2784	0.00713	0.1958	5.483	28.98	2.494	10.05	2.740	6.700
3.2	0.3201	0.00717	0.1728	5.787	29.26	2.581	9.90	2.896	6.792
3.3	0.3659	0.00723	0.1542	6.108	29.52	2.670	9.747	3.061	6.897
3.4	0.4159	0.00728	0.1376	6.448	29.76	2.780	9.600	3.273	7.015
3.5	0.4704	0.00735	0.1232	6.806	29.97	2.852	9.458	3.413	7.150
3.6	0.5296	0.00742	0.1107	7.184	30.17	2.946	9.318	3.601	7.305
3.7	0.5935	0.00749	0.0997	7.581	30.34	3.042	9.181	3.801	7.484
3.8	0.6625	0.00758	0.0900	7.998	30.48	3.140	9.046	4.017	7.694
3.9	0.7366	0.00766	0.0814	8.437	30.60	3.239	8.911	4.254	7.942
4.0	0.8162	0.00776	0.0738	8.899	30.68	3.341	8.776	4.519	8.238
4.1	0.9014	0.00786	0.0669	9.387	30.73	3.444	8.641	4.820	8.641
4.2	0.9923	0.00797	0.0606	9.901	30.74	3.551	8.504	5.170	9.033
4.3	1.089	0.00810	0.0550	10.45	30.71	3.661	8.363	5.587	9.58
4.4	1.193	0.00824	0.0499	11.02	30.62	3.775	8.218	6.097	10.29
4.5	1.303	0.00841	0.0452	11.64	30.47	3.893	8.067	6.742	11.22
4.6	1.419	0.00860	0.0408	12.31	30.24	4.018	7.906	7.590	12.50
4.7	1.543	0.00881	0.0367	13.04	29.91	4.151	7.732	8.763	14.37
4.8	1.674	0.00907	0.0329	13.85	29.45	4.296	7.539	10.51	17.32
4.9	1.813	0.00941	0.0291	14.76	28.80	4.458	7.327	13.38	22.64
5.0	1.960	0.00986	0.0252	15.85	27.83	4.649	7.041	19.02	34.93
5.1	2.116	0.01056	0.0207	17.26	26.08	4.898	6.624	34.60	95.84
5.195^c	2.275	0.01436	0.0145						

c = critical pt.

From Arp, V. D. and R. D. McCarty, N.I.S.T. TN 1334, 1989 (142 pp.).

TABLE 2-265 Superheated Helium[*]

P, bars		Temp., °C								
		0	100	200	300	400	500	600	800	1000
1	*v*	5.677	7.754	9.831	11.908	13.985	16.063	18.140	22.294	26.448
	h	0.327	519.6	1039	1558	2078	2597	3116	4155	5193
	s	0.0116	1.620	2.853	3.849	4.684	5.403	6.035	7.106	7.993
5	*v*	1.138	1.553	1.968	2.384	2.799	3.215	3.630	4.461	5.291
	h	1.636	520.9	1040	1560	2079	2598	3117	4156	5194
	s	−3.343	−1.723	−0.490	0.506	1.341	2.060	2.692	3.763	4.650
10	*v*	0.5704	0.780	0.986	1.193	1.401	1.609	1.816	2.232	2.647
	h	3.272	522.5	1042	1561	2080	2600	3119	4157	5196
	s	−4.782	−3.162	−1.929	−0.934	−0.098	0.621	1.252	2.323	3.211
20	*v*	0.2867	0.3904	0.4942	0.5979	0.7017	0.9093	1.1169	1.3245	1.8435
	h	6.544	525.8	1045	1564	2083	2603	3122	4160	5199
	s	−6.221	−4.601	−3.368	−2.373	−1.537	−0.818	−0.187	0.884	1.771
50	*v*	0.1164	0.1579	0.1993	0.2408	0.2822	0.3257	0.3652	0.4481	0.5311
	h	16.360	535.5	1055	1574	2093	2612	3131	4169	5207
	s	−8.121	−6.501	−5.268	−4.273	−3.438	−2.719	−2.088	−1.017	−0.130
100	*v*	0.0597	0.0803	0.1010	0.1217	0.1424	0.1631	0.1838	0.2252	0.2666
	h	37.720	551.7	1071	1590	2108	2627	3146	4184	5222
	s	−9.555	−7.936	−6.703	−5.709	−4.874	−4.155	−3.524	−2.454	−1.567
150	*v*	0.0407	0.0545	0.0682	0.0820	0.0958	0.1095	0.1233	0.1509	0.1785
	h	49.080	567.9	1087	1605	2124	2643	3161	4199	5236
	s	−10.391	−8.773	−7.541	−6.546	−5.712	−4.994	−4.363	−3.293	−2.407
200	*v*	0.0312	0.0416	0.0518	0.0622	0.0725	0.0828	0.0931	0.1137	0.1344
	h	65.440	584.1	1103	1621	2140	2658	3176	4213	5250
	s	−10.983	−9.635	−8.134	−7.139	−6.306	−5.588	−4.957	−3.888	−3.002

[*] Extracted from Tsederberg, Popov, et al., *Thermodynamic and Thermophysical Properties of Helium,* Atomizdat, Moscow, 1969, and NBS-NSF TT 50096, 1971. Copyright material. Reproduced by permission. This source contains entries for many more temperatures and pressures than can be reproduced here. *v* = volume, m^3/kg; *h* = enthalpy, kJ/kg; *s* = entropy, kJ/(kg·K).

The 1993 ASHRAE *Handbook—Fundamentals* (SI ed.) has a thermodynamic chart for pressures from 0.1 to 50 bar and temperatures from 2.5 to 15 K. Saturation and superheat tables to 9000 psia, 800°R; and a chart to 700 psia, 40°R appear in Stewart, R. B., R. T. Jacobsen, et al., *Thermodynamic Properties of Refrigerants,* ASHRAE, Atlanta, GA, 1986 (521 pp.). For specific heat, thermal conductivity, and viscosity, see *Thermophysical Properties of Refrigerants,* ASHRAE, 1993. A useful compilation of properties is given by Betts, D. S., *Cryogenics,* **16,** 1 (1976): 3–16. A 32-term equation of state for the range up to 20,000 bar, 2–1500 K is given by McCarty, R. D. and V. D. Arp, *Advan. Cryog. Engng.,* **35** (1990): 1465–1475.

TABLE 2-266 Helium^4 Gas at Atmospheric Pressure[*]

T, K	4.224	5	10	20	30	40	50	75	100	200	300	400	500	600	800	1000
v, m^3/kg	0.0591	0.0834	0.1612	0.4094	0.6161	0.8218	1.0273	1.5403	2.053	4.102	6.154	8.191	10.24	12.31	16.40	20.50
h, kJ/kg	30.30	36.18	64.91	117.95	170.24	222.4	274.4	404.4	534.2	1054	1573	2092	2612	3131	4170	5208
s, kJ/(kg·K)	8.327	9.614	13.369	17.321	19.442	20.94	22.10	24.21	25.71	29.30	31.41	32.90	34.06	35.01	36.50	37.66

[*] From McCarty, NBS Rep. 9762, 1970. Reproduced by permission. The source contains values for further temperatures and for other functions, usually to additional significant figures.

TABLE 2-267 Saturated *n*-Heptane[*]

T, K	P, bar	v_f, m^3/kg	v_g, m^3/kg	h_f, kJ/kg	h_g, kJ/kg	s_f, kJ/(kg·K)	s_g, kJ/(kg·K)	c_{pf}, kJ/(kg·K)	μ_f, 10^{-4} Pa·s	k_f, W/(m·K)
182.6^t		1.292.–3		284.1		2.260		2.025	39.4	0.150
200	0.00002	1.316.–3		319.4	722.6	2.441	4.457	2.011	21.0	0.148
220	0.00019	1.344.–3		359.7	757.1	2.636	4.442	2.026	12.6	0.145
240	0.00133	1.374.–3		400.5	791.4	2.814	4.443	2.063	8.52	0.142
250	0.00303	1.389.–3		421.3	808.3	2.899	4.447	2.088	7.23	0.140
260	0.00635	1.405.–3		442.3	824.9	2.981	4.453	2.117	6.52	0.137
270	0.01316	1.422.–3		463.6	841.2	3.061	4.460	2.147	5.46	0.135
280	0.02347	1.440.–3		485.2	857.8	3.140	4.471	2.180	4.83	0.132
290	0.03997	1.457.–3		507.2	874.8	3.217	4.485	2.216	4.29	0.129
300	0.06674	1.475.–3	3.744	529.6	891.9	3.293	4.501	2.252	3.85	0.126
310	0.1070	1.494.–3	2.412	552.3	908.9	3.367	4.517	2.291	3.48	0.123
320	0.1656	1.514.–3	1.596	575.4	926.0	3.441	4.537	2.329	3.17	0.121
330	0.2461	1.534.–3	1.101	598.8	943.3	3.513	4.557	2.370	2.89	0.119
340	0.3614	1.555.–3	0.7650	622.8	961.2	3.584	4.579	2.412	2.66	0.116
350	0.5130	1.578.–3	0.5510	647.0	979.1	3.655	4.604	2.454	2.45	0.114
360	0.712	1.601.–3	0.4058	671.9	997.5	3.725	4.629	2.500	2.24	0.111
370	0.967	1.625.–3	0.3036	697.1	1016.1	3.794	4.656	2.548	2.04	0.109
371.6	1.013	1.629.–3	0.2904	701.9	1019.8	3.805	4.660	2.556	2.01	0.108
380	1.289	1.651.–3	0.2308	723.9	1035.4	3.864	4.684	2.60	1.86	0.107
390	1.689	1.678.–3	0.1781	750.4	1054.2	3.932	4.711	2.65	1.71	0.105
400	2.180	1.708.–3	0.1388	777.2	1073.2	4.000	4.740	2.70	1.58	0.103
420	3.471	1.775.–3	0.0734					2.81	1.35	0.099
440	5.268	1.853.–3	0.0576					2.93	1.15	0.095
460	7.691	1.954.–3	0.0389					3.05	0.97	0.091
480	10.92	2.065.–3	0.0265					3.19	0.82	0.087
500	15.10	2.235.–3	0.0178					3.38	0.67	0.080
520	20.43	2.52.–3						3.7		
540.1^c	27.35	4.3.–3	0.0043							

[*] Values of P and v interpolated and converted from tables in Vargaftik, *Handbook of Thermophysical Properties of Gases and Liquids,* Hemisphere, Washington, and McGraw-Hill, New York, 1975. Values of h and s calculated from API tables published by the Thermodynamics Research Center, Texas A&M University, College Station. t = triple point; c = critical point.

Saturation and superheat tables and a diagram to 200 bar, 680 K are given by Reynolds, W. C., *Thermodynamic Properties in S.I.,* Stanford Univ. publ., 1979 (173 pp.).

TABLE 2-268 Hexane

Saturation and superheat tables and a diagram to 100 bar, 680 K, are given by Reynolds, W. C., *Thermodynamic Properties in S.I.*, Stanford Univ. publ., 1979 (173 pp.).

TABLE 2-269 Saturated Hydrazine

Temperature, K	Pressure, bar	v_f, m^3/kg	v_g, m^3/kg	h_f, kJ/kg	h_g, kJ/kg	s_f, kJ/(kg·K)	s_g, kJ/(kg·K)
386.6	1.013	0.001 053	0.9833	−105.9	65.4	0.5994	1.0426
390	1.135	0.001 060	0.8850	−104.8	66.0	0.6029	1.0409
400	1.560	0.001 081	0.6579	−101.4	68.2	0.6120	1.0360
410	2.102	0.001 104	0.4994	−97.6	70.6	0.6211	1.0314
420	2.786	0.001 127	0.3850	−93.9	73.0	0.6300	1.0275
440	4.732	0.001 178	0.2355	−86.1	77.6	0.6492	1.0212
460	7.610	0.001 235	0.1500	−76.9	82.1	0.6707	1.0163
480	11.76	0.001 299	0.1005	−67.1	86.6	0.6916	1.0118
500	17.42	0.001 374	0.0690	−57.3	90.8	0.7124	1.0086
520	29.59	0.001 460	0.0407	−47.8	94.6	0.7320	1.0058
540	34.75	0.001 563	0.0353	−36.0	97.7	0.7566	1.0042
560	47.09	0.001 681	0.0263	−25.2	101.2	0.7762	1.0020
580	62.44	0.001 835	0.0196	−12.4	103.6	0.8002	1.0002
600	81.17	0.002 045	0.0142	5.2	104.2	0.8335	0.9988
620	102.7	0.002 320	0.0106	23.2	103.6	0.8671	0.9967
640	128.1	0.002 86	0.0074	45.9	98.1	0.9035	0.9906
653[c]	146.9	0.004 33	0.0043	83.7	83.7	0.9715	0.9715

Converted from E. F. Fricke, Republic Aviation Co. rept. F-5028-101. *c* = critical point.

TABLE 2-270 Saturated *n*-Hydrogen*

T, K	*P*, bar	v_f, m^3/kg	v_g, m^3/kg	h_f, kJ/kg	h_g, kJ/kg	s_f, kJ/(kg·K)	s_g, kJ/(kg·K)	c_{pf}, kJ/(kg·K)	μ_f, 10^{-4} Pa·s	k_f, W/(m·K)
13.95[t]	0.072	0.01298	7.974	218.3	667.4	14.079	46.635	6.36	0.255	0.073
14	0.074	0.01301	7.205	219.6	669.3	14.173	46.301	6.47	0.248	0.075
15	0.127	0.01316	4.488	226.4	678.2	14.640	44.763	6.91	0.218	0.083
16	0.204	0.01332	2.954	233.8	686.7	15.104	43.418	7.36	0.194	0.089
17	0.314	0.01348	2.032	241.6	694.7	15.568	42.227	7.88	0.175	0.093
18	0.461	0.01366	1.449	249.9	702.1	16.032	41.158	8.42	0.159	0.095
19	0.654	0.01387	1.064	258.8	708.8	16.498	40.188	8.93	0.146	0.097
20	0.901	0.01407	0.8017	268.3	714.8	16.966	39.299	9.45	0.135	0.098
21	1.208	0.01430	0.6177	278.4	720.2	17.440	38.485	10.13	0.125	0.100
22	1.585	0.01455	0.4828	289.2	724.4	17.919	37.710	10.82	0.116	0.101
23	2.039	0.01483	0.3829	300.8	727.6	18.405	36.973	11.69	0.108	0.101
24	2.579	0.01515	0.3072	313.3	729.8	18.901	36.266	12.52	0.101	0.101
25	3.213	0.01551	0.2489	326.7	730.7	19.408	35.579	13.44	0.094	0.100
26	3.950	0.01592	0.2032	341.2	730.2	19.929	34.900	14.80	0.088	0.098
27	4.800	0.01639	0.1667	357.0	728.0	20.473	34.221	16.17	0.082	0.096
28	5.770	0.01696	0.1370	374.3	723.7	21.041	33.524	18.48	0.076	0.094
29	6.872	0.01765	0.1125	393.6	716.6	21.650	32.795	22.05	0.070	0.091
30	8.116	0.01854	0.0919	415.4	705.9	22.315	32.002	26.59	0.065	0.087
31	9.510	0.01977	0.0738	441.3	689.7	23.075	31.091	36.55	0.058	0.086
32	11.07	0.02174	0.0571	474.7	663.2	24.032	29.926	65.37	0.051	0.092
33.18[c]	13.13	0.03182	0.0318	565.4	565.4	26.680	26.680	∞		∞

*Values extracted and occasionally rounded off from McCarty, Hord, and Roder, NBS Monogr. 168, 1981. *t* = triple point; *c* = critical point.

TABLE 2-271 Compressed *n*-Hydrogen*

Pressure, bar		Temperature, K									
		15	20	30	40	50	60	80	100	150	200
0.1	v	6.076	8.176	12.333	16.473	20.606	24.736	32.991	41.244	61.870	82.495
	h	679.2	731.6	835.5	938.9	1042.3	1146	1356	1575	2172	2826
	s	46.02	49.04	53.25	56.23	58.53	60.43	63.45	65.89	70.68	74.46
1	v	0.0131	0.0141	1.196	1.625	2.046	2.463	3.295	4.123	6.190	8.254
	h	227.3	268.3	826.0	932.7	1037.9	1143	1354	1574	2172	2826
	s	14.62	16.96	43.56	46.63	48.98	50.89	53.93	56.38	61.17	64.96
5	v	0.0131	0.0140	0.2006	0.3039	0.3958	0.4839	0.6553	0.8238	1.241	1.655
	h	231.7	272.1	775.0	903.4	1017.6	1128	1345	1568	2170	2826
	s	14.57	16.88	35.80	39.52	42.07	44.07	47.20	49.68	54.66	58.31
10	v	0.0130	0.0138	0.0181	0.1376	0.1895	0.2366	0.3255	0.4116	0.6221	0.8303
	h	237.2	277.0	412.1	861.8	991.1	1109	1334	1560	2167	2826
	s	14.50	16.77	22.09	35.95	38.85	40.99	44.23	46.75	51.63	55.44
20	v	0.0129	0.0136	0.0167	0.0521	0.0866	0.1135	0.1611	0.2057	0.3129	0.4179
	h	248.2	286.9	406.5	752.0	934.7	1070	1312	1546	2163	2826
	s	14.37	16.58	21.33	31.07	35.19	37.67	41.15	43.76	48.71	52.55
40	v		0.0133	0.0155	0.0216	0.0376	0.0533	0.0796	0.1033	0.1586	0.2119
	h		307.3	413.5	589.3	823.5	997	1271	1521	2155	2826
	s		16.26	20.50	25.49	30.73	33.91	37.87	40.65	45.75	49.64
60	v		0.0130	0.0147	0.0182	0.0254	0.0351	0.0532	0.0697	0.1073	0.1433
	h		328.0	427.2	570.1	757.0	940	1237	1499	2149	2828
	s		15.98	19.95	24.03	28.19	31.54	35.82	38.76	43.99	47.92
80	v		0.0127	0.0142	0.0167	0.0211	0.0273	0.0406	0.0531	0.0818	0.1090
	h		348.9	443.5	572.3	732.8	905	1210	1482	2146	2831
	s		15.74	19.53	23.21	26.78	29.93	34.34	37.37	42.72	46.69
100	v		0.0125	0.0138	0.0158	0.0190	0.0233	0.0335	0.0434	0.0666	0.0885
	h		369.8	461.1	581.5	727.4	888	1192	1469	2144	2835
	s		15.53	19.19	22.63	25.88	28.80	33.19	36.28	41.73	45.73
200	v		0.0117	0.0125	0.0136	0.0150	0.0167	0.0207	0.0253	0.0368	0.0480
	h		474.4	556.1	658.7	776.9	908	1182	1458	2156	2869
	s		14.71	17.99	20.93	23.56	25.94	29.88	32.97	38.59	42.72
400	v			0.0113	0.0119	0.0126	0.0134	0.0151	0.0171	0.0225	0.0279
	h			751.0	841.9	945.4	1059	1303	1560	2249	2973
	s			16.59	19.20	21.50	23.58	27.07	29.94	35.48	39.67
600	v			0.0106	0.0110	0.0115	0.0120	0.0131	0.0144	0.0178	0.0214
	h			941.5	1027	1124	1231	1463	1709	2385	3107
	s			15.68	18.14	20.29	22.24	25.57	28.31	33.74	37.92
800	v				0.0104	0.0107	0.0111	0.0120	0.0130	0.0155	0.0181
	h				1209	1302	1405	1628	1870	2535	3255
	s				17.35	19.43	21.30	24.50	27.20	32.54	36.70
1000	v				0.0099	0.0102	0.0106	0.0112	0.0120	0.0140	0.0160
	h				1387	1478	1578	1796	2032	2692	3403
	s				16.72	18.75	20.58	23.70	26.33	31.63	35.75

*Values extracted and sometimes rounded off from the tables of McCarty, Hord, and Roder, NBS Monogr. 168, 1981. This source contains an exhaustive tabulation of property values for both the normal and the para forms of hydrogen. v = specific volume, m^3/kg; h = specific enthalpy, kJ/kg; s = specific entropy, kJ/(kg·K).

The 1993 ASHRAE *Handbook—Fundamentals* (SI ed.) has a thermodynamic diagram for 0.1 to 500 bar for temperatures up to 100 K. Tables and a Mollier chart from 10^{-4} to 1000 atm, 300–20,000 K are given by Kubin, R. F. and L. L. Presley, NASA SP 3002, 1964. Liebenberg, D. H., R. L. Mills, and others, in LA-6645-MS, 1977 (26 pp.), give properties from 75 to 307 K for pressures from 2 to 20 kbar. See also Baker, J. R. and H. F. Swift, *J. Appl. Phys.*, **43,** 3 (1972): 950–953. An extensive collection of data for H_2, D_2, T_2, and so on below 30 K is given by Souers, P. C., UCRL 52628, 1979 (91 pp.); and for temperatures below 40 K by Roder, H. M., G. E. Childs, et al., NBS TN 641, 1973 (114 pp.).

Saturation and superheat tables to 10,000 psia, 900°R and a chart to 180°R appear in Stewart, R. B., R. T. Jacobsen, et al., *Thermodynamic Properties of Refrigerants,* ASHRAE, Atlanta, GA, 1986 (521 pp.). For viscosity, thermal conductivity, and specific heat, see *Thermophysical Properties of Refrigerants,* ASHRAE, 1993.

Temperature, K										
250	300	350	400	450	500	600	700	800	900	1000
103.12	123.23	144.35	164.97	185.60	206.22	247.46	288.70	329.94	371.18	412.43
3517	4227	4945	5668	6393	7118	8571	10028	11493	12969	14458
77.53	80.13	82.34	84.27	85.98	87.51	90.15	92.40	94.36	96.10	97.66
10.32	12.38	14.44	16.50	18.57	20.63	24.75	28.88	33.00	37.13	41.25
3517	4227	4946	5669	6393	7118	8571	10029	11494	12969	14459
68.03	70.63	72.85	74.78	76.48	78.01	80.66	82.91	84.86	86.60	88.17
2.069	2.482	2.895	3.307	3.720	4.132	4.957	5.782	6.607	7.432	8.257
3518	4229	4948	5671	6396	7121	8574	10032	11497	12973	14462
61.39	63.99	66.21	68.14	69.84	71.37	74.02	76.27	78.23	79.96	81.53
1.038	1.245	1.451	1.658	1.864	2.070	2.483	2.896	3.308	3.720	4.133
3519	4231	4951	5674	6399	7125	8578	10036	11501	12977	14467
58.52	61.12	63.34	65.28	66.98	68.51	71.16	73.41	75.37	77.10	78.67
0.522	0.6259	0.7294	0.8328	0.9361	1.040	1.246	1.452	1.658	1.865	2.071
3522	4235	4956	5680	6406	7132	8586	10044	11509	12985	14475
55.65	58.26	60.48	62.41	64.12	65.65	68.30	70.55	72.51	74.24	75.81
0.2644	0.3166	0.3685	0.4204	0.4721	0.5238	0.6271	0.7303	0.8335	0.9366	1.040
3527	4244	4967	5692	6419	7146	8601	10059	11525	13002	14492
52.76	55.38	57.61	59.55	61.26	62.79	65.44	67.69	69.65	71.39	72.95
0.1786	0.2136	0.2483	0.2829	0.3174	0.3519	0.4209	0.4897	0.5585	0.6273	0.6961
3533	4253	4978	5705	6432	7160	8616	10075	11542	13018	14508
51.05	53.69	55.92	57.86	59.58	61.11	63.76	66.02	67.97	70.51	71.28
0.1357	0.1621	0.1882	0.2142	0.2401	0.2660	0.3177	0.3694	0.4120	0.4726	0.5242
3540	4263	4989	5718	6446	7174	8631	10091	11558	13035	14525
49.84	52.49	54.73	56.67	58.39	59.92	62.57	64.83	66.79	68.52	70.09
0.1099	0.1312	0.1521	0.1730	0.1937	0.2145	0.2559	0.2972	0.3385	0.3798	0.4211
3547	4273	5001	5731	6460	7189	8647	10107	11574	13051	14542
48.89	51.55	53.79	55.74	57.46	59.00	61.65	63.90	65.87	67.60	69.17
0.0588	0.0695	0.0801	0.0905	0.1001	0.1114	0.1321	0.1528	0.1734	0.1941	0.2147
3594	4329	5064	5798	6531	7263	8724	10187	11656	13134	14625
45.94	48.62	50.89	52.85	54.58	56.12	58.78	61.04	63.00	64.74	66.31
0.0334	0.0388	0.0441	0.0493	0.0545	0.0597	0.0701	0.0804	0.0908	0.1011	0.1114
3716	4458	5202	5943	6681	7416	8883	10349	11820	13300	14792
42.98	45.68	47.97	49.95	51.69	53.24	55.91	58.17	60.14	61.88	63.45
0.0249	0.0285	0.0321	0.0355	0.0390	0.0425	0.0494	0.0562	0.0631	0.0700	0.0768
3854	4600	5349	6095	6836	7574	9045	10513	11985	13466	14958
41.24	43.95	46.26	48.26	50.00	51.56	54.24	56.50	58.47	60.21	61.78
0.0207	0.0234	0.0260	0.0286	0.0312	0.0338	0.0390	0.0441	0.0492	0.0543	0.0594
4003	4748	5501	6249	6993	7734	9207	10677	12150	13631	15124
40.03	42.73	45.05	47.05	48.81	50.37	53.05	55.32	57.29	59.03	60.60
0.0181	0.0202	0.0223	0.0244	0.0265	0.0286	0.0327	0.0367	0.0408	0.0449	0.0490
4156	4898	5654	6405	7151	7893	9370	10842	12316	13797	15289
39.10	41.79	44.12	46.12	47.88	49.45	52.14	54.41	56.38	58.12	59.69

TABLE 2-272 Saturated *para*-Hydrogen*

T, K	P, bar	v_f, m^3/kg	v_g, m^3/kg	h_f, kJ/kg	h_g, kJ/kg	s_f, kJ/(kg·K)	s_g, kJ/(kg·K)	c_{pf}, kJ/(kg·K)	μ_f, 10^{-4} Pa·s	k_f, W/(m·K)
13.8^t	0.070	0.0130	7.97	−308.9	140.3	4.97	37.52	6.37	0.255	0.073
14	0.079	0.0130	7.20	−307.6	142.1	5.06	37.19	6.47	0.248	0.075
15	0.134	0.0132	4.49	−300.9	151.1	5.53	36.65	6.91	0.218	0.082
16	0.216	0.0133	2.96	−293.4	159.6	5.99	34.31	7.36	0.194	0.089
17	0.329	0.0135	2.03	−285.6	167.6	6.45	33.11	7.88	0.175	0.092
18	0.482	0.0137	1.45	−277.3	175.0	6.92	32.05	8.42	0.159	0.095
19	0.682	0.0139	1.07	−268.4	181.7	7.38	31.08	8.93	0.146	0.097
20	0.935	0.0141	0.802	−258.9	187.7	7.85	30.19	9.45	0.135	0.098
21	1.250	0.0143	0.618	−248.8	193.0	8.32	29.37	10.13	0.125	0.100
22	1.634	0.0146	0.483	−237.9	197.3	8.80	28.60	10.82	0.116	0.101
23	2.096	0.0148	0.383	−226.3	200.5	9.29	27.86	11.69	0.108	0.101
24	2.645	0.0152	0.307	−213.9	202.7	9.78	27.15	12.52	0.101	0.100
25	3.288	0.0155	0.249	−200.4	203.6	10.29	26.46	13.44	0.094	0.099
26	4.035	0.0159	0.203	−185.9	203.1	10.81	25.79	14.81	0.088	0.098
27	4.892	0.0164	0.167	−170.2	200.9	11.36	25.11	16.18	0.082	0.096
28	5.88	0.0170	0.137	−152.9	196.5	11.93	24.41	18.5	0.076	0.094
29	6.98	0.0177	0.113	−133.6	189.5	12.54	23.68	22.1	0.070	0.091
30	8.23	0.0185	0.092	−111.7	178.8	13.20	22.89	26.6	0.065	0.087
31	9.63	0.0198	0.074	−85.8	162.6	13.96	21.98	36.6	0.058	0.088
32	11.20	0.0217	0.057	−52.4	136.1	14.92	20.81	65.4	0.051	0.092
33^c	12.93	0.0318	0.032	38.3	38.3	17.56	17.56	∞		∞

*Values extracted and occasionally rounded off from McCarty, Hord, and Roder, NBS *Monogr.* 168, 1981. t = triple point; c = critical point.

Saturation and superheat tables to 12,000 psia, 900°R and a chart to 180°R appear in Stewart, R. B., R. T. Jacobsen, et al., *Thermodynamic Properties of Refrigerants*, ASHRAE, Atlanta, GA, 1986 (521 pp.). For specific heat, thermal conductivity, and viscosity, see *Thermophysical Properties of Refrigerants*, ASHRAE, 1993. The 1993 ASHRAE *Handbook—Fundamentals* (SI ed.) has a thermodynamic chart for pressures from 0.1 to 1000 bar for temperatures up to 100 K.

TABLE 2-273 Saturated Hydrogen Peroxide*

T, K	P, bar	v_f, m^3/kg	v_g, m^3/kg	h_f, kJ/kg	h_g, kJ/kg	s_f, kJ/(kg·K)	s_g, kJ/(kg·K)	c_{pf}, kJ/(kg·K)	μ_f, 10^{-4} Pa·s	k_f, W/(m·K)
273	0.0004	0.00068	1672	−5577	−4027	2.990	8.662	1.45	18.0	0.483
300	0.0031	0.00069	235	−5510	−3995	3.224	8.269	1.48	11.3	0.481
350	0.0564	0.00072	15.1	−5376	−3933	3.631	7.758	1.54	4.3	0.474
400	0.4521	0.00076	2.12	−5238	−3878	4.032	7.440	1.61	2.2	0.464
450	2.143	0.00081	0.487	−5091	−3820	4.346	7.172	1.68	1.3	0.453
500	7.126	0.00088	0.155	−4945	−3777	4.656	6.992	1.75	0.89	0.443
550	18.56	0.00095	0.0605	−4794	−3745	4.941	6.846	1.82	0.65	0.431
600	40.75	0.00107	0.0268	−4635	−3731	5.209	6.720	1.90	0.50	0.416
650	79.27	0.00125	0.0125	−4463	−3746	5.485	6.582			
700	141.7	0.00171	0.0048	−4195	−3860	5.682	6.339			
708.5^c	155.3	0.00284	0.0028	−4012	−4012	5.732	5.732			

*Values reproduced or converted from a tabulation by Tsykalo and Tabachnikov in V. A. Rabinovich (ed.), *Thermophysical Properties of Gases and Liquids*, Standartov, Moscow, 1968; NBS-NSF transl. TT 69-55091, 1970. The reader may be reminded that very pure hydrogen peroxide is very difficult to obtain owing to its decomposition or instability. c = critical point. The FMC Corp., Philadelphia, PA tech. bull. 67, 1969 (100 pp.) contains an enthalpy-pressure diagram to 3000 psia, 1100 K.

TABLE 2-274 Hydrogen Sulfide

West, J. R., *Chem. Eng. Progr.*, **44,** 4 (1948): 207–292 gives tables and a chart for the range 1–90 atm., −76 to 1300°F while properties from 10 to 330 bar, 300 to 500 K were tabulated by Lui, C-H., D. M. Bailey, et al., *Hydroc. Proc.*, **65,** 7 (July 1986): 41–43.

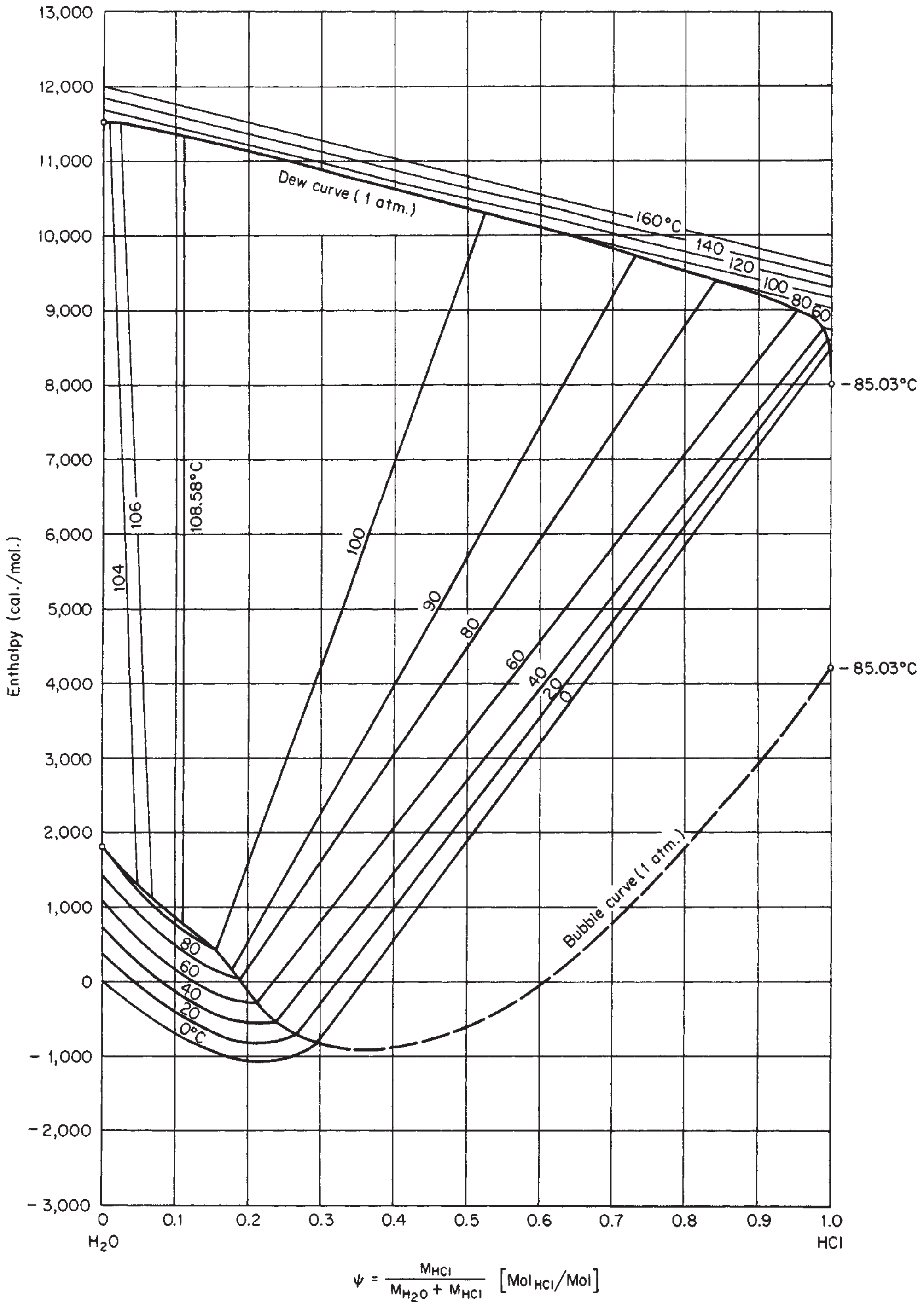

FIG. 2-11 Enthalpy-concentration diagram for aqueous hydrogen chloride at 1 atm. Reference states: enthalpy of liquid water at 0°C is zero; enthalpy of pure saturated HCl vapor at 1 atm (−85.03°C) is 8000 kcal/mol. NOTE: It should be observed that the weight basis includes the vapor, which is particularly important in the two-phase region. Saturation values may be read at the ends of the tie lines. [*Van Nuys,* Trans. Am. Inst. Chem. Eng., **39,** *663 (1943).*]

TABLE 2-275 Saturated Isobutane (R600a)*

T, K	P, bar	v_f, m^3/kg	v_g, m^3/kg	h_f, kJ/kg	h_g, kJ/kg	s_f, kJ/(kg·K)	s_g, kJ/(kg·K)	c_{pf}, kJ/(kg·K)	μ_f, 10^{-4} Pa·s	k_f, W/(m·K)
113.6[t]	1.9.–7	1.349.–3	8.60.+6	0.0	485.3	1.863	6.136			
120	9.3.–7	1.360.–3	1.84.+6	11.0	491.1	1.957	5.957	1.78		
140	4.8.–5	1.396.–3	4210	46.0	510.1	2.226	5.541	1.87		0.163
160	8.2.–4	1.435.–3	278.2	82.1	530.8	2.467	5.272	1.93		0.158
180	0.0070	1.476.–3	36.66	119.5	533.0	2.688	5.097	1.99	9.46	0.149
200	0.0369	1.520.–3	7.723	158.5	576.7	2.893	4.984	2.05	6.06	0.142
220	0.1374	1.568.–3	2.265	199.0	601.5	3.086	4.916	2.12	4.21	0.134
240	0.3989	1.621.–3	0.8432	241.4	627.4	3.270	4.878	2.19	3.11	0.127
260	0.9600	1.680.–3	0.3738	285.8	654.2	3.446	4.863	2.28	2.40	0.120
270	1.4081	1.712.–3	0.2617	308.8	667.7	3.532	4.861	2.33	2.14	0.117
280	2.0020	1.746.–3	0.1882	332.3	681.3	3.617	4.863	2.39	1.93	0.113
290	2.7686	1.784.–3	0.1385	356.4	694.9	3.700	4.867	2.46	1.75	0.110
300	3.7365	1.824.–3	0.1040	381.1	708.4	3.783	4.874	2.53	1.59	0.106
310	4.934	1.868.–3	0.0794	406.4	721.7	3.865	4.882	2.61	1.46	0.102
320	6.392	1.916.–3	0.0614	432.4	734.8	3.946	4.891	2.70	1.35	0.099
330	8.140	1.971.–3	0.0481	459.2	747.7	4.028	4.902	2.81	1.25	0.095
340	10.21	2.032.–3	0.0380	486.9	760.0	4.109	4.912	2.92	1.15	0.092
350	12.64	2.103.–3	0.0301	515.7	771.8	4.191	4.923	3.04	1.05	0.088
360	15.46	2.187.–3	0.0240	545.6	782.7	4.273	4.932	3.17	0.95	0.083
370	18.72	2.289.–3	0.0190	577.1	792.3	4.357	4.939	3.31	0.85	0.080
380	22.48	2.420.–3	0.0150	610.6	799.8	4.444	4.942	3.45	0.75	0.076
390	26.82	2.604.–3	0.0115	647.1	803.7	4.536	4.937	3.62	0.63	0.071
400	31.86	2.920.–3	0.0083	689.6	799.6	4.639	4.915	3.85	0.51	0.065
408.0[c]	36.55	4.464.–3	0.0045	752.5	752.5	4.791	4.791	∞		∞

*Values reproduced or converted from Goodwin, NBSIR 79-1612, 1979. t = triple point; c = critical point. The notation 1.9.–7 signifies 1.9×10^{-7}.

Slightly different values for the range 0.5 to 34.5 bar, 250–404 K appear in Waxman, M. and J. S. Gallagher, *J. Chem. Eng. Data,* **28,** (1983): 224–241. This source also contains superheat tables for 1–400 bar, 250–600 K.

Saturation and superheat tables and a diagram to 200 bar, 600 K are given by Reynolds, W. C., *Thermodynamic properties in S.I.,* Stanford Univ. publ., 1979 (173 pp.). Saturation and superheat tables and a chart to 10,000 psia, 640°F appear in Stewart, R. B., R. T. Jacobsen, et al., *Thermodynamic Properties of Refrigerants,* ASHRAE, Atlanta, GA, 1986 (521 pp.). For specific heat, thermal conductivity, and viscosity, see *Thermophysical Properties of Refrigerants,* ASHRAE, 1993. Equations and data for thermal conductivity and viscosity are given by Nieuwoldt, J. C., B. LeNeindre, et al., *J. Chem. Eng. Data,* **32,** (1987): 1–8.

TABLE 2-276 Saturated Krypton*

T, K	P, bar	v_f, m^3/kg	v_g, m^3/kg	h_f, kJ/kg	h_g, kJ/kg	s_f, kJ/(kg·K)	s_g, kJ/(kg·K)	c_{pf}, kJ/(kg·K)	μ_f, 10^{-4} Pa·s	k_f, W/(m·K)
10		3.235.–4		0.22		0.0256		0.070		
20		3.246.–4		1.59		0.1141		0.188		
30		3.265.–4		3.84		0.2034		0.247		
40		3.288.–4		6.49		0.2791		0.276		
50		3.313.–4		9.37		0.3431		0.295		
60		3.341.–4		12.40		0.3982		0.311		
70		3.372.–4		15.57		0.4471		0.327		
80		3.407.–4		18.97		0.4925		0.345		
90		3.446.–4		22.58		0.5353		0.366		
100		3.492.–4		26.42		0.5765		0.389		
110		3.544.–4		30.52		0.6165		0.414		
115.76		3.579.–4		33.18		0.6390		0.427		
115.76	0.732	4.090.–4	0.1529	52.78	161.8	0.8095	1.751	0.547		
119.76	1.013	4.143.–4	0.1136	54.99	162.6	0.8279	1.726	0.545		
120	1.032	4.146.–4	0.1116	55.09	162.6	0.8291	1.724	0.544	3.72	0.0900
130	2.112	4.284.–4	0.0578	60.55	164.1	0.8724	1.669	0.542	3.16	0.0828
140	3.878	4.440.–4	0.0330	66.02	165.3	0.9124	1.622	0.546	2.64	0.0756
150	6.552	4.619.–4	0.0201	71.58	166.1	0.9499	1.580	0.559	2.20	0.0688
160	10.37	4.831.–4	0.0130	77.34	166.4	0.9859	1.543	0.587	1.87	0.0625
170	15.57	5.091.–4	0.0086	83.48	166.0	1.022	1.507	0.641	1.54	0.0558
180	22.41	5.423.–4	0.0059	90.26	164.6	1.058	1.472	0.734	1.28	0.0494
190	31.20	5.882.–4	0.0040	98.19	161.8	1.098	1.433	0.905	1.05	0.0433
200	42.23	6.641.–4	0.0026	108.40	156.0	1.147	1.386	1.515	0.80	0.0348
209.39	54.96	1.098.–3	0.0011	133.90	133.9	1.262	1.262	∞		∞

*Values extracted and in some cases rounded off from those cited in Rabinovich (ed.), *Thermophysical Properties of Neon, Argon, Krypton and Xenon,* Standards Press, Moscow, 1976. This source contains values for the compressed state for pressures up to 1000 bar, etc. The notation 3.235.–4 signifies 3.235×10^{-4}. This book was published in English translation by Hemisphere, New York, 1988 (604 pp.).

TABLE 2-277 Compressed Krypton*

Temperature, K		Pressure, bar											
		1	10	20	40	60	80	100	200	400	600	800	1000
100	v	3.49.–4	3.49.–4	3.49.–4	3.48.–4	3.48.–4	3.47.–4	3.47.–4	3.45.–4	3.42.–4	3.39.–4	3.36.–4	3.33.–4
	h	26.42	26.69	26.99	27.59	28.18	28.78	29.38	32.38	38.42	44.47	50.52	56.57
	s	0.5765	0.5760	0.5755	0.5745	0.5735	0.5724	0.5714	0.5667	0.5580	0.5503	0.5432	0.5366
200	v	0.1971	0.0184	8.39.–3	3.00.–3	6.19.–4	5.94.–4	5.76.–4	5.27.–4	4.83.–4	4.58.–4	4.41.–4	4.28.–4
	h	183.1	179.3	174.5	159.4	105.6	104.4	103.6	102.7	105.3	109.7	114.9	120.3
	s	1.859	1.618	1.533	1.405	1.129	1.116	1.106	1.073	1.037	1.013	0.993	0.977
300	v	0.2971	0.0292	0.0143	6.84.–3	4.37.–3	3.14.–3	2.41.–3	1.09.–3	6.92.–4	5.94.–4	5.44.–4	5.13.–4
	h	208.1	206.3	204.2	200.0	195.7	191.2	186.6	166.8	155.1	155.2	158.2	162.3
	s	1.961	1.728	1.654	1.575	1.525	1.485	1.451	1.333	1.239	1.196	1.169	1.149
400	v	0.3966	0.0394	0.0196	9.67.–3	6.37.–3	4.73.–3	3.75.–3	1.85.–3	1.01.–3	7.79.–4	6.76.–4	6.14.–4
	h	233.0	231.9	230.7	228.3	225.9	223.6	221.3	211.4	199.7	196.8	197.9	200.8
	s	2.032	1.802	1.730	1.657	1.612	1.579	1.552	1.463	1.368	1.317	1.284	1.259
500	v	0.4960	0.0495	0.0247	0.0123	8.20.–3	6.15.–3	4.91.–3	2.49.–3	1.33.–3	9.81.–4	8.22.–4	7.29.–4
	h	257.8	257.1	256.3	254.9	253.3	251.9	250.5	244.5	236.9	234.2	234.7	237.4
	s	2.088	1.858	1.788	1.716	1.673	1.642	1.617	1.537	1.451	1.400	1.365	1.340
600	v	0.5953	0.0596	0.0298	0.0149	9.96.–3	7.49.–3	6.01.–3	3.07.–3	1.64.–3	1.18.–3	9.67.–4	8.44.–4
	h	282.7	282.2	281.7	280.7	279.7	278.8	277.9	274.2	269.6	268.1	269.1	271.7
	s	2.133	1.904	1.834	1.763	1.721	1.691	1.667	1.591	1.511	1.462	1.428	1.403
700	v	0.6946	0.0696	0.0348	0.0175	0.0117	8.80.–3	7.07.–3	3.62.–3	1.93.–3	1.38.–3	1.11.–3	9.56.–4
	h	307.5	307.2	306.9	306.2	305.6	305.1	304.5	302.2	299.8	299.6	301.1	304.0
	s	2.171	1.942	1.873	1.803	1.761	1.732	1.708	1.634	1.557	1.511	1.478	1.453
800	v	0.7939	0.0795	0.0399	0.0200	0.0134	0.0101	8.11.–3	4.16.–3	2.21.–3	1.57.–3	1.25.–3	1.07.–3
	h	332.3	332.2	331.9	331.6	331.2	330.9	330.5	329.3	328.6	329.4	331.5	334.6
	s	2.204	1.975	1.906	1.837	1.795	1.766	1.743	1.671	1.596	1.551	1.518	1.494
900	v	0.8931	0.0895	0.0448	0.0225	0.0151	0.0114	9.13.–3	4.68.–3	2.48.–3	1.75.–3	1.39.–3	1.18.–3
	h	357.1	357.0	356.9	356.8	356.6	356.4	356.3	355.8	356.3	358.0	360.7	364.2
	s	2.233	2.005	1.936	1.866	1.825	1.796	1.773	1.702	1.628	1.584	1.553	1.528
1000	v	0.9924	0.0994	0.0498	0.0250	0.0168	0.0126	0.0102	5.20.–3	2.74.–3	1.93.–3	1.53.–3	1.29.–3
	h	381.9	381.9	381.9	381.8	381.8	381.8	381.8	381.9	383.4	385.9	389.0	392.8
	s	2.260	2.031	1.962	1.893	1.852	1.823	1.800	1.729	1.657	1.614	1.583	1.559

*Values extracted and in some cases rounded off from those cited in Rabinovich (ed.), *Thermophysical Properties of Neon, Argon, Krypton and Xenon,* Standards Press, Moscow, 1976. This source contains an exhaustive tabulation of values. v = specific volume, m^3/kg; h = specific enthalpy, kJ/kg; s = specific entropy, kJ/(kg·K). The notation 3.49.–4 signifies 3.49×10^{-4}. This book was published in English translation by Hemisphere, New York, 1988 (604 pp.).

TABLE 2-278 Saturated Lithium*

T, K	P, bar	v_f, m^3/kg	v_g, m^3/kg	h_f, kJ/kg	h_g, kJ/kg	s_f, kJ/(kg·K)	s_g, kJ/(kg·K)	c_{pf}, kJ/(kg·K)
453.7[m]	1.78.–13	1.912.–3		1703	24259	6.776	56.492	4.30
500	8.21.–12	1.946.–3		1905	24390	7.199	52.169	4.34
600	4.18.–9	1.988.–3		2334	24674	7.983	45.216	4.23
700	3.51.–7	2.028.–3	2.40.+7	2697	24869	8.633	40.307	4.19
800	9.57.–6	2.070.–3	9.94.+5	3174	25162	9.192	36.678	4.17
900	1.24.–4	2.114.–3	8.55.+4	3590	25341	9.682	33.850	4.16
1000	9.60.–4	2.160.–3	1.22.+4	4006	25477	10.120	31.591	4.16
1200	0.0204	2.262.–3	669.3	4835	25654	10.876	28.225	4.14
1400	0.1794	2.370.–3	86.06	5668	25778	11.518	25.882	4.19
1500	0.4269	2.433.–3	38.17	6088	25845	11.808	24.979	4.20

*Converted from tables in Vargaftik, *Tables of the Thermophysical Properties of Liquids and Gases,* Nauka, Moscow, 1972, and Hemisphere, Washington, 1975. m = melting point. The notation 1.78.–13 signifies 1.78×10^{-13}.

Many of the Vargaftik values also appear in Ohse, R. W., *Handbook of Thermodynamic and Transport Properties of Alkali Metals,* Blackwell Sci. Pubs., Oxford, 1985 (1020 pp.). This source contains superheat data.

Saturation and superheat tables and a diagram to 14 bar, 2200 K are given by Reynolds, W. C., *Thermodynamic properties in S.I.,* Stanford Univ. publ., 1979 (173 pp.). For a Mollier diagram from 0.1 to 140 psia, 2100–3600°R, see Weatherford, P. M., J. C. Tyler, et al., WADD-TR-61-96, 1961.

An extensive review of properties of the solid and the saturated liquid was given by Alcock, C. B., M. W. Chase, et al., *J. Phys. Chem. Ref. Data,* **23,** 3 (1994): 385–497.

TABLE 2-279 Lithium Bromide—Water Solutions

Ruiter, J. P., *Rev. Int. Froid = Int. J. Refrig.,* **13** (1990): 223–236 gives subroutines for computer calculations. See also ASHRAE *Handbook—Fundamentals.*

TABLE 2-280 Saturated Mercury*

T, K	P, bar	$v_f \times 10^5$, m^3/kg	v_g, m^3/kg	h_f, kJ/kg	h_g, kJ/kg	h_{fg}, kJ/kg	s_f, kJ/(kg·K)	s_g, kJ/(kg·K)
203.15	$2.298 \cdot 10^{-11}$	7.26239	$3.665 \cdot 10^{9}$	33.131	342.637	309.506	0.32434	1.84787
213.15	$1.288 \cdot 10^{-10}$	7.27570	$6.862 \cdot 10^{8}$	34.567	343.674	309.107	0.33124	1.78142
223.15	$6.169 \cdot 10^{-10}$	7.28900	$1.499 \cdot 10^{8}$	35.997	344.710	308.713	0.33780	1.72123
233.15	$2.580 \cdot 10^{-9}$	7.30231	$3.746 \cdot 10^{7}$	37.422	345.746	308.324	0.34404	1.66647
243.15	$9.573 \cdot 10^{-9}$	7.31563	$1.053 \cdot 10^{7}$	38.842	346.782	307.940	0.35001	1.61647
253.15	$3.198 \cdot 10^{-8}$	7.32896	$3.281 \cdot 10^{6}$	40.258	347.819	307.561	0.35571	1.57065
263.15	$9.736 \cdot 10^{-8}$	7.34229	$1.120 \cdot 10^{6}$	41.668	348.855	307.187	0.36118	1.52852
273.15	$2.728 \cdot 10^{-7}$	7.35563	$4.150 \cdot 10^{5}$	43.074	349.891	306.817	0.36642	1.48967
283.15	$7.101 \cdot 10^{-7}$	7.36898	$1.653 \cdot 10^{5}$	44.476	350.927	306.451	0.37146	1.45375
293.15	$1.729 \cdot 10^{-6}$	7.38234	$7.026 \cdot 10^{4}$	45.874	351.964	306.090	0.37631	1.42045
303.15	$3.968 \cdot 10^{-6}$	7.39572	$3.167 \cdot 10^{4}$	47.268	353.000	305.732	0.38099	1.38951
313.15	$8.626 \cdot 10^{-6}$	7.40911	$1.505 \cdot 10^{4}$	48.659	354.036	305.377	0.38550	1.36068
323.15	$1.786 \cdot 10^{-5}$	7.42252	$7.501 \cdot 10^{3}$	50.046	355.072	305.026	0.38986	1.33378
333.15	$3.356 \cdot 10^{-5}$	7.43594	$3.905 \cdot 10^{3}$	51.430	356.108	304.678	0.39408	1.30862
343.15	$6.724 \cdot 10^{-5}$	7.44938	$2.115 \cdot 10^{3}$	52.810	357.145	304.335	0.39816	1.28505
353.15	$1.232 \cdot 10^{-4}$	7.46285	$1.188 \cdot 10^{3}$	54.188	358.181	303.993	0.40212	1.26292
363.15	$2.182 \cdot 10^{-4}$	7.47633	$6.899 \cdot 10^{2}$	55.563	359.217	303.654	0.40596	1.24213
373.15	$3.745 \cdot 10^{-4}$	7.48984	413.0	56.936	360.253	303.317	0.40969	1.22255
383.15	$6.247 \cdot 10^{-4}$	7.50337	254.2	58.306	361.289	302.983	0.41331	1.20408
393.15	$1.015 \cdot 10^{-3}$	7.51693	153.6	59.674	362.326	302.652	0.41684	1.18665
403.15	$1.608 \cdot 10^{-3}$	7.53052	103.9	61.039	363.362	302.323	0.42027	1.17017
413.15	$2.491 \cdot 10^{-3}$	7.55415	68.75	62.403	364.397	301.994	0.42361	1.15456
423.15	$3.778 \cdot 10^{-3}$	7.55780	46.43	63.765	365.433	301.668	0.42687	1.13978
433.15	$5.618 \cdot 10^{-3}$	7.57148	31.96	65.125	366.469	301.344	0.43004	1.12575
443.15	$8.204 \cdot 10^{-3}$	7.58520	22.39	66.484	367.504	301.020	0.43314	1.11242
453.15	$1.178 \cdot 10^{-2}$	7.59897	15.95	67.842	368.539	300.697	0.43617	1.09975
463.15	$1.664 \cdot 10^{-2}$	7.61277	11.54	69.198	369.574	300.376	0.43913	1.08768
473.15	$2.315 \cdot 10^{-2}$	7.62662	8.469	70.553	370.609	300.056	0.44203	1.07619
483.15	$3.177 \cdot 10^{-2}$	7.64051	6.301	71.908	371.642	299.734	0.44486	1.06524
493.15	$4.304 \cdot 10^{-2}$	7.65444	4.748	73.261	372.676	299.415	0.44763	1.05478
503.15	$5.758 \cdot 10^{-2}$	7.66843	3.621	74.614	373.708	299.094	0.45035	1.04479
513.15	$7.614 \cdot 10^{-2}$	7.68247	2.793	75.967	374.740	298.773	0.45301	1.03525
523.15	$9.959 \cdot 10^{-2}$	7.69656	2.176	77.319	375.771	298.452	0.45562	1.02611
533.15	0.12892	7.71071	1.7132	78.671	376.800	298.129	0.45818	1.01737
543.15	0.16527	7.72491	1.3613	80.023	377.829	297.806	0.46069	1.00899
553.15	0.20993	7.73918	1.0912	81.375	378.855	297.480	0.46316	1.00095
563.15	0.26435	7.75351	0.88213	82.728	379.880	297.152	0.46558	0.99324
573.15	0.33015	7.7679	0.71874	84.080	380.904	296.824	0.46796	0.98584
583.15	0.40910	7.7823	0.59002	85.434	381.925	296.491	0.47030	0.97893
593.15	0.50320	7.7969	0.48779	86.788	382.944	296.156	0.47260	0.97190
603.15	0.61460	7.8115	0.40600	88.143	383.960	295.817	0.47487	0.96532
613.15	0.74567	7.8262	0.34008	89.499	384.973	295.474	0.47709	0.95899
623.15	0.89896	7.8409	0.28660	90.856	385.984	295.128	0.47929	0.95289
633.15	1.0772	7.8558	0.24291	92.215	386.991	294.776	0.48145	0.94702
643.15	1.2834	7.8707	0.20702	93.575	387.994	294.419	0.48358	0.94135
653.15	1.5207	7.8858	0.17735	94.937	388.994	294.057	0.48568	0.93589
663.15	1.9725	7.9008	0.15269	96.300	389.989	293.689	0.48774	0.93061
673.15	2.1024	7.9160	0.13207	97.666	390.980	293.314	0.48978	0.92552
683.15	2.454	7.9313	0.11476	99.033	391.966	292.933	0.49180	0.92059
693.15	2.852	7.9467	0.10014	100.403	392.947	292.544	0.49378	0.91583
703.15	3.299	7.9622	0.08775	101.775	393.923	292.148	0.49574	0.91123
713.15	3.801	7.9778	0.07719	103.150	394.893	291.743	0.49768	0.90677
723.15	4.362	7.9935	0.06815	104.528	395.858	291.330	0.49959	0.90245
733.15	4.986	8.0094	0.06039	105.908	396.816	290.908	0.50148	0.89827
743.15	5.679	8.0252	0.05369	107.292	397.767	290.475	0.50335	0.89422
753.15	6.446	8.0413	0.04789	108.679	398.711	290.032	0.50519	0.89029
763.15	7.292	8.0574	0.04285	110.069	399.649	289.580	0.50702	0.88647
773.15	8.222	8.074	0.03846	111.463	400.579	289.116	0.50882	0.88277
783.15	9.242	8.090	0.03462	112.861	401.501	288.640	0.51061	0.87917
793.15	10.358	8.106	0.03124	114.262	402.415	288.153	0.51238	0.87568
803.15	11.576	8.123	0.02827	115.668	403.321	287.653	0.51412	0.87228
813.15	12.901	8.140	0.02565	117.078	404.218	287.140	0.51586	0.86898
823.15	14.340	8.157	0.02333	118.492	405.106	286.614	0.51757	0.86576
833.15	15.899	8.174	0.02126	119.911	405.985	286.074	0.51927	0.86263

*From Vukalovich, Ivanov, Fokin, and Yakovlev, *Thermophysical Properties of Mercury*, Standartov, Moscow, 1971. For the saturated liquid the specific volume at 203.15 K is 7.26239×10^{-5} m^3/kg, etc. All the tabular values for 203.15 K, 213.15 K, 223.15 K, and 233.15 K represent a metastable equilibrium between the subcooled liquid and the saturated vapor.

Saturation and superheat tables and a diagram to 100 bar, 1600 K are given by Reynolds, W. C., *Thermodynamic properties in S.I.*, Stanford Univ. publ., 1979 (173 pp.). For a Mollier diagram from 1 to 8200 psia and 2700°R, see Weatherford, W. D., J. C. Tyler, et al., WADD-TR-61-96, 1961.

TABLE 2-280 Saturated Mercury* *(Concluded)*

T, K	P, bar	$v_f \times 10^5$, m^3/kg	v_g, m^3/kg	h_f, kJ/kg	h_g, kJ/kg	h_{fg}, kJ/kg	s_f, kJ/(kg·K)	s_g, kJ/(kg·K)
843.15	17.584	8.191	0.019426	121.335	406.855	285.520	0.52095	0.85959
853.15	19.403	8.209	0.017785	122.763	407.715	284.952	0.52262	0.85662
863.15	21.36	8.226	0.016317	124.197	408.565	284.368	0.52427	0.85372
873.15	23.46	8.244	0.015000	125.636	409.405	283.769	0.52591	0.85090
883.15	25.72	8.262	0.013815	127.080	410.235	283.155	0.52753	0.84815
893.15	28.14	8.280	0.012748	128.530	411.054	282.524	0.52914	0.84546
903.15	30.72	8.298	0.011784	129.986	411.861	281.875	0.53074	0.84284
913.15	33.47	8.316	0.010911	131.448	412.658	281.210	0.53232	0.84028
923.15	36.41	8.335	0.010120	132.915	413.444	280.529	0.53389	0.83777
933.15	39.53	8.353	0.009401	134.389	414.218	279.829	0.53545	0.83533
943.15	42.85	8.372	0.008746	135.869	414.980	279.111	0.53700	0.83294
953.15	46.36	8.391	0.008150	137.356	415.731	278.375	0.53854	0.83060
963.15	50.09	8.410	0.007604	138.850	416.469	277.619	0.54006	0.82831
973.15	54.03	8.430	0.007105	140.350	417.195	276.845	0.54158	0.82606
983.15	58.20	8.450	0.006648	141.858	417.909	276.051	0.54308	0.82387
993.15	62.59	8.468	0.006228	143.372	418.610	275.238	0.54458	0.82172
1003.15	67.22	8.488	0.005842	144.894	419.298	274.404	0.54607	0.81961
1013.15	72.10	8.508	0.005487	146.424	419.974	273.550	0.54754	0.81754
1023.15	77.22	8.529	0.005159	147.961	420.636	272.675	0.54901	0.81552
1033.15	82.60	8.550	0.004856	149.506	421.286	271.780	0.55047	0.81353
1043.15	88.25	8.570	0.004576	151.059	421.923	270.864	0.55192	0.81158
1053.15	94.17	8.590	0.004317	152.619	422.546	269.927	0.55336	0.80966
1063.15	100.37	8.612	0.004077	154.188	423.156	268.968	0.55479	0.80778
1073.15	106.85	8.632	0.003854	155.766	423.752	267.986	0.55621	0.80593

TABLE 2-281 Saturated Methane*

T, K	P, bar	v_f, m^3/kg	v_g, m^3/kg	h_f, kJ/kg	h_g, kJ/kg	s_f, kJ/(kg·K)	s_g, kJ/(kg·K)	c_{pf}, kJ/(kg·K)	μ_f, 10^{-4} Pa·s	k_f, W/(m·K)
90.7[t]	0.117	2.215.−3	3.976	216.4	759.9	4.231	10.225	3.288	2.02	0.225
95	0.198	2.244.−3	2.463	232.5	769.0	4.406	10.034	3.318	1.71	0.215
100	0.345	2.278.−3	1.479	246.3	776.9	4.556	9.862	3.369	1.56	0.206
105	0.565	2.316.−3	0.940	263.2	785.7	4.719	9.710	3.425	1.33	0.197
110	0.884	2.353.−3	0.625	280.1	794.5	4.882	9.558	3.478	1.22	0.189
115	1.325	2.396.−3	0.430	297.7	802.5	5.035	9.436	3.525	1.09	0.181
120	1.919	2.438.−3	0.306	315.3	810.4	5.188	9.314	3.570	0.98	0.173
125	2.693	2.487.−3	0.223	333.5	817.3	5.332	9.062	3.620	0.89	0.165
130	3.681	2.536.−3	0.167	351.7	824.1	5.476	8.810	3.679	0.81	0.158
135	4.912	2.594.−3	0.127	370.6	829.5	5.614	8.871	3.755	0.73	0.150
140	6.422	2.652.−3	0.098	389.5	834.8	5.751	8.932	3.849	0.66	0.143
145	8.246	2.722.−3	0.077	409.5	844.4	5.885	8.891	3.965	0.61	0.136
150	10.41	2.792.−3	0.061	429.4	853.9	6.019	8.849	4.101	0.56	0.129
155	12.97	2.882.−3	0.049	450.8	848.5	6.151	8.725	4.27	0.51	0.122
160	15.94	2.971.−3	0.039	472.1	843.0	6.283	8.601	4.47	0.46	0.115
165	19.39	3.095.−3	0.032	495.4	840.0	6.417	8.513	4.75	0.42	0.108
170	23.81	3.218.−3	0.026	518.6	837.0	6.551	8.424	5.16	0.38	0.101
175	27.81	3.419.−3	0.020	545.8	827.6	6.697	8.315	5.89	0.34	0.094
180	32.86	3.619.−3	0.016	572.9	818.1	6.843	8.205	7.27	0.30	0.088
185	38.59	3.979.−3	0.012	605.4	797.7	7.017	8.049	11.1	0.25	0.085
190	45.20	4.900.−3	0.008	661.6	750.7	7.293	7.762	70.	0.19	0.090
190.6[c]	45.99	6.233.−3	0.006	704.4	704.4	7.516	7.516	∞	0.17	∞

*Values reproduced or converted from Goodwin, NBS Tech. Note 653, 1974. t = triple point; c = critical point. The notation 2.215.−3 signifies 2.215×10^{-3}.

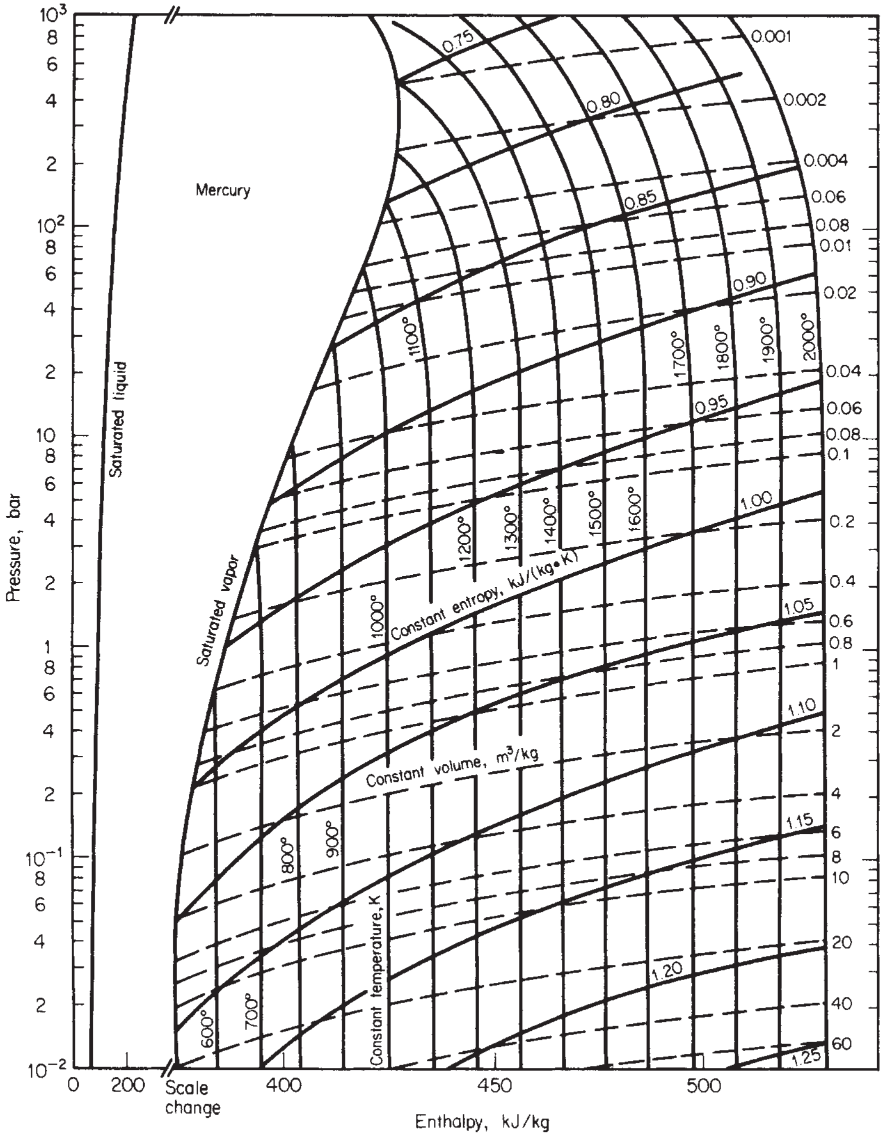

FIG. 2-12 Enthalpy-log-pressure diagram for mercury. (*Drawn from tabular data in footnote reference to Table 2-280.*)

TABLE 2-282 Superheated Methane*

P, bar		Temperature, K								
		100	150	200	250	300	350	400	450	500
1	v	0.00228	0.7661	1.0299	1.2915	1.5521	1.8122	2.0719	2.3669	2.5911
	h	246.4	879.0	984.3	1090.4	1199.8	1314.8	1437.4	1568.8	1708.9
	s	4.555	10.152	10.757	11.230	11.629	11.983	12.310	12.618	12.914
5	v	0.00228	0.1434	0.2006	0.2549	0.3083	0.3611	0.4136	0.4657	0.5181
	h	247.0	865.0	976.1	1084.7	1195.5	1311.5	1434.7	1566.6	1706.9
	s	4.553	9.256	9.896	10.381	10.785	11.142	11.471	11.781	12.066
10	v	0.00227	0.0643	0.0968	0.1254	0.1528	0.1798	0.2063	0.2327	0.2590
	h	247.8	843.6	965.5	1077.9	1190.6	1307.9	1432.0	1564.1	1705.3
	s	4.549	8.797	9.501	10.002	10.414	10.775	11.106	11.417	11.715
20	v	0.00227	0.00277	0.0446	0.0606	0.0751	0.0891	0.1027	0.1162	0.1295
	h	249.4	429.8	941.9	1063.6	1180.7	1300.6	1426.5	1560.3	1702.1
	s	4.542	6.003	9.059	9.603	10.030	10.400	10.736	11.050	11.349
40	v	0.00226	0.00274	0.0176	0.0281	0.0363	0.0438	0.0510	0.0579	0.0648
	h	252.5	430.8	879.3	1032.9	1160.5	1286.0	1415.7	1552.1	1696.0
	s	4.528	5.973	8.465	9.155	9.621	10.008	10.354	10.674	10.978
60	v	0.00226	0.00271	0.00615	0.0173	0.0234	0.0287	0.0338	0.0386	0.0432
	h	255.7	432.2	734.0	999.8	1140.0	1271.7	1405.1	1544.2	1690.0
	s	4.515	5.946	7.623	8.847	9.359	9.765	10.121	10.440	10.756
80	v	0.00225	0.00268	0.00411	0.0119	0.0171	0.0213	0.0252	0.0289	0.0324
	h	258.9	433.8	660.5	964.4	1119.7	1257.7	1394.9	1536.6	1684.4
	s	4.502	5.920	7.209	8.590	9.158	9.584	9.951	10.283	10.595
100	v	0.00224	0.00266	0.00375	0.00888	0.0133	0.0169	0.0201	0.0231	0.0260
	h	262.1	435.5	644.5	928.5	1099.6	1244.2	1385.2	1529.4	1679.0
	s	4.489	5.897	7.090	8.364	8.991	9.437	9.814	10.153	10.469
150	v	0.00223	0.00261	0.00337	0.00555	0.00852	0.0111	0.0134	0.0155	0.0175
	h	270.2	440.7	630.2	860.0	1054.1	1213.1	1362.8	1513.0	1667.0
	s	4.458	5.843	6.930	7.953	8.664	9.155	9.555	9.907	10.233
200	v	0.00221	0.00256	0.00318	0.00447	0.00644	0.00837	0.0101	0.0118	0.0133
	h	278.3	446.5	626.5	825.0	1019.8	1187.2	1343.8	1498.9	1656.9
	s	4.429	5.796	6.829	7.719	8.426	8.944	9.362	9.727	10.060
300	v	0.00218	0.00249	0.00296	0.00369	0.00474	0.00593	0.00708	0.00818	0.00924
	h	294.7	459.6	629.2	804.4	982.9	1153.6	1316.8	1478.5	1642.2
	s	4.373	5.714	6.690	7.471	8.122	8.649	9.085	9.465	9.811
400	v		0.00244	0.00282	0.00336	0.00406	0.00486	0.00569	0.00560	0.00729
	h		473.8	637.7	802.4	970.1	1137.8	1303.0	1467.7	1634.7
	s		5.645	6.588	7.323	7.935	8.451	8.893	9.280	9.633
500	v		0.00239	0.00272	0.00315	0.00368	0.00428	0.00492	0.00555	0.00616
	h		488.8	648.9	807.7	969.0	1132.8	1297.8	1464.2	1633.2
	s		5.584	6.507	7.215	7.802	8.307	8.748	9.139	9.496

*Converted and rounded off from the tables of Goodwin, NBS Tech. Note 654, 1974. v = specific volume, m^3/kg; h = specific enthalpy, kJ/kg; s = specific entropy, kJ/(kg·K).

For a thermodynamic diagram from 0.1 to 400 bar and 620°C, see the 1993 ASHRAE *Handbook—Fundamentals* (SI ed.).

Saturation and superheat tables and a chart to 6000 psia, 680°F appear in Stewart, R. B., R. T. Jacobsen, et al., *Thermodynamic Properties of Refrigerants,* ASHRAE, Atlanta, GA, 1986 (521 pp.). For specific heat, thermal conductivity, and viscosity, see *Thermophysical Properties of Refrigerants,* ASHRAE, 1993. See also Friend, D. G., J. F. Ely, et al., *J. Phys. Chem. Ref. Data.* **18,** 2 (1989): 583–638.

TABLE 2-283 Thermophysical Properties of Saturated Methanol

Pressure, bar	Temp., K	v_f, m^3/kg	v_g, m^3/kg	h_f, kJ/kg	h_g, kJ/kg	s_f, kJ/(kg·K)	s_g, kJ/(kg·K)	c_{pf}, kJ/(kg·K)	μ_f, 10^{-6} Pa·s	k_f, W/(m·K)	Pr_f
4×10^{-6}[t]	175.6	0.001 057	1700000	0.0	1303.1	2.8114	10.2328				
0.1	288.4	0.001 257	7.309	261.0	1440.3	3.9383	8.0281	2.531	625	0.204	7.75
0.2	301.7	0.001 276	3.801	293.9	1455.4	4.0493	7.9032	2.554	525	0.196	6.84
0.5	320.7	0.001 307	1.599	345.0	1476.2	4.2117	7.7386	2.669	401	0.193	5.55
1.013	337.7	0.001 336	0.819	391.7	1492.1	4.3516	7.6104	2.777	329	0.189	4.83
1.5	348.0	0.001 356	0.5632	421.0	1500.3	4.4361	7.5379	2.845	288	0.186	4.41
2.0	356.0	0.001 371	0.4276	444.2	1505.8	4.5014	7.4836	2.894	268	0.184	4.22
2.5	362.5	0.001 385	0.3443	463.6	1509.8	4.5536	7.4398	2.946	242	0.182	3.92
3.0	368.0	0.001 396	0.2893	479.8	1512.4	4.5992	7.4051	2.984	227	0.181	3.74
4.0	377.1	0.001 417	0.2188	507.8	1515.9	4.6728	7.3474	3.050	204	0.179	3.48
5	384.5	0.001 434	0.17569	529.7	1517.4	4.7307	7.2992	3.117	187	0.178	3.27
6	390.8	0.001 450	0.14683	549.6	1518.4	4.7836	7.2624	3.176	174	0.177	3.12
8	401.3	0.001 479	0.11015	582.7	1518.0	4.8678	7.1988	3.265	156	0.175	2.91
10	409.8	0.001 504	0.08783	610.3	1516.1	4.9366	7.1471	3.349	141	0.173	2.73
15	426.3	0.001 560	0.05761	665.8	1507.9	5.0708	7.0461	3.540	117	0.171	2.42
20	438.9	0.001 611	0.04224	710.5	1553.8	5.1744	6.9677	3.72	102	0.169	2.25
25	449.3	0.001 666	0.03290	749.0	1486.4	5.2605	6.9017	3.91	92	0.167	2.15
30	458.2	0.001 710	0.02661	783.8	1474.7	5.3355	6.8435	4.12	84	0.165	2.10
40	472.9	0.001 814	0.01863	846.7	1450.1	5.4650	6.7409	4.67	72	0.160	2.10
50	484.9	0.001 934	0.01373	905.2	1423.2	5.5793	6.6475	5.55	63	0.154	2.27
60	495.1	0.002 086	0.01032	963.3	1391.8	5.6889	6.5543				
80	508.1	0.002 507	0.00642	1065.3	1318.7	5.8803	6.3791				
80.95[c]	512.6	0.003 715	0.00372	1186.8	1186.8	6.0979	6.0979				

t = triple point; c = critical point. v, h, s, and c_p interpolated and converted from Goodwin, R. D., *J. Phys. Chem. Ref. Data*, **16,** 4 (1987): 799–891.

TABLE 2-284 Thermodynamic Properties of Compressed Methanol

		Temperature, K								
Pressure, bar		200	250	300	350	400	450	500	550	600
0.1	v (m^3/kg)	0.001137	0.001203	7.630	8.942	10.23	11.56	12.84		15.45
	h (kJ/kg)	57.5	169.8	1456.7	1529.5	1607.5	1691.5	1781.7	1878.1	1980.2
	s (kJ/kg·K)	3.096	3.597	8.081	8.305	8.514	8.711	8.901	9.085	9.263
0.5	v (m^3/kg)	0.001137	0.001202	0.001274	1.764	2.033	2.296	2.558	2.818	3.078
	h (kJ/kg)	57.5	169.9	290.5	1522.7	1603.0	1687.9	1778.9	1875.3	1977.4
	s (kJ/kg·K)	3.096	3.597	4.038	7.877	8.091	8.291	8.482	8.666	8.844
1.013	v (m^3/kg)	0.001137	0.001202	0.001274	0.8560	0.9958	1.1283	1.2843	1.3870	1.5157
	h (kJ/kg)	57.6	169.9	290.5	1514.0	1598.7	1685.1	1795.4	1873.5	1975.8
	s (kJ/kg·K)	3.096	3.597	4.038	7.675	7.902	8.105	8.117	8.482	8.660
10	v (m^3/kg)	0.001136	0.001201	0.001272	0.001357	0.001474	0.1068	0.1236	0.1381	0.1519
	h (kJ/kg)	58.4	170.7	291.2	427.4	578.8	1638.1	1751.5	1858.0	1965.2
	s (kJ/kg·K)	3.095	3.596	4.036	4.451	4.857	7.427	7.667	7.870	8.056
15	v (m^3/kg)	0.001136	0.001201	0.001272	0.001356	0.001472	0.0673	0.0806	0.0911	0.1007
	h (kJ/kg)	58.8	171.1	291.6	427.7	578.9	1601.9	1735.6	1849.4	1960.2
	s (kJ/kg·K)	3.094	3.595	4.035	4.450	4.856	7.253	7.536	7.752	7.946
20	v (m^3/kg)	0.001135	0.001200	0.001271	0.001355	0.001469	0.0466	0.0589	0.0675	0.0751
	h (kJ/kg)	59.2	171.6	292.0	428.1	579.0	1565.3	1717.7	1840.0	1954.8
	s (kJ/kg·K)	3.094	3.595	4.035	4.449	4.854	7.087	7.431	7.664	7.864
30	v (m^3/kg)	0.001134	0.001199	0.001269	0.001355	0.001465	0.001659	0.0367	0.0436	0.0492
	h (kJ/kg)	60.1	172.4	292.9	428.8	579.4	751.3	1675.4	1818.7	1942.7
	s (kJ/kg·K)	3.092	3.593	4.036	4.447	4.851	5.264	7.253	7.526	7.743
40	v (m^3/kg)	0.001133	0.001198	0.001268	0.001350	0.001461	0.001649	0.0251	0.0314	0.0361
	h (kJ/kg)	61.0	173.3	293.7	429.5	579.8	750.4	1623.0	1794.2	1928.8
	s (kJ/kg·K)	3.091	3.592	4.032	4.445	4.849	5.258	7.088	7.414	7.650
50	v (m^3/kg)	0.001133	0.001197	0.001266	0.001348	0.001457	0.001637	0.0176	0.0239	0.0282
	h (kJ/kg)	61.9	174.2	294.5	430.2	580.2	749.7	1556.4	1766.7	1913.4
	s (kJ/kg·K)	3.090	3.591	4.030	4.443	4.846	5.579	6.912	7.314	7.570
60	v (m^3/kg)	0.001131	0.001196	0.001265	0.001346	0.001453	0.001628	0.0120	0.0188	0.0228
	h (kJ/kg)	62.8	175.0	295.3	430.9	580.6	749.1	1461.8	1736.1	1896.6
	s (kJ/kg·K)	3.089	3.589	4.029	4.442	4.843	5.248	6.692	7.220	7.500
75	v (m^3/kg)	0.001130	0.001194	0.001263	0.001343	0.001448	0.001614	0.002084	0.01359	0.0174
	h (kJ/kg)	64.1	176.3	296.6	431.9	581.2	748.3	982.1	1683.9	1869.1
	s (kJ/kg·K)	3.087	3.587	4.027	4.439	4.839	5.241	5.718	7.081	7.405
100	v (m^3/kg)	0.001128	0.001191	0.001259	0.001337	0.001439	0.001595	0.001952	0.	0.01188
	h (kJ/kg)	66.3	178.5	298.6	433.8	582.4	747.5	964.8	1572.9	1818.8
	s (kJ/kg·K)	3.084	3.584	4.023	4.435	4.833	5.230	5.673	6.829	7.261
150	v (m^3/kg)	0.001125	0.001186	0.001252	0.001328	0.001423	0.001562	0.001825		0.006513
	h (kJ/kg)	70.7	182.8	302.8	437.4	584.9	746.8	948.4	1248.8	1704.3
	s (kJ/kg·K)	3.078	3.578	4.016	4.426	4.822	5.211	5.622	6.302	6.997
200	v (m^3/kg)	0.001121	0.001182	0.001246	0.001317	0.001408	0.001535	0.001751	0.002314	0.004091
	h (kJ/kg)	75.1	187.2	307.0	441.2	587.8	747.0	939.9	1223.5	1583.5
	s (kJ/kg·K)	3.071	3.571	4.009	4.418	4.811	5.194	5.587	6.125	6.752
300	v (m^3/kg)	0.001113	0.001172	0.001234	0.001302	0.001384	0.001492	0.001656	0.001957	0.002600
	h (kJ/kg)	83.9	195.9	315.4	448.9	593.8	749.4	932.0	1173.4	1443.5
	s (kJ/kg·K)	3.060	3.559	3.996	4.403	4.791	5.166	5.537	5.996	6.466
400	v (m^3/kg)	0.001107	0.001164	0.001223	0.001288	0.001363	0.001459	0.001593	0.001808	0.002182
	h (kJ/kg)	92.7	204.7	324.0	456.9	600.5	753.4	929.6	1154.4	1388.1
	s (kJ/kg·K)	3.048	3.548	3.983	4.388	4.774	5.142	5.500	5.926	6.335
500	v (m^3/kg)	0.001101	0.001156	0.001213	0.001274	0.001345	0.001431	0.001546	0.001716	0.001980
	h (kJ/kg)	101.5	213.4	332.6	465.1	607.7	758.4	930.4	1145.6	1360.6
	s (kJ/kg·K)	3.037	3.536	3.971	4.375	4.757	5.121	5.470	5.880	6.254

Converted and interpolated from Goodwin, R. D., *J. Phys. Chem. Ref. Data,* **16,** 4 (1987): 799–891. These extensive tables extend to 700 bar for temperatures from 175.6 to 800 K. Another extensive compilation is by deReuck, K. M. and R. J. B. Craven, *Methanol,* C.R.C. Press, 1993 (320 pp.).

Equations and diagrams to 30 bar, 200°C are given by Eicholz, H. D., S. Schulz, et al., *Kalte u Klim.,* no. 9, (1981) 322–331. For pressures to 1040 bar, 298–489 K, see Machado, J. R. S. and W. B. Street, *J.Chem.Eng.Data,* **28** (1983): 218–223; to 2800 bar from 273 to 333 K, see Sun, T., S. N. Biswas, et al., *J. Chem. Eng. Data,* **33** (1988): 395–398. Dissociation was considered by Yerlett, T. K. and C. J. Wormald, *J. Chem. Thermo.,* **18** (1986): 719–726, and by Kazarnovskii, Ya. S. and E. V. Pavlova, *Russ. J. Phys. Chem.,* **56,** 6 (1982): 847–851.

TABLE 2-285 Saturated Methyl Chloride*

T, K	P, bar	v_f, m^3/kg	v_g, m^3/kg	h_f, kJ/kg	h_g, kJ/kg	s_f, kJ/(kg·K)	s_g, kJ/(kg·K)	c_{pf}, kJ/(kg·K)	μ_f, 10^{-4} Pa·s	k_f, W/(m·K)
175	0.0117	8.84.–4	27.90	274.5	764.3	3.529	6.328	1.469		
180	0.0165	8.91.–4	19.85	280.9	767.7	3.570	6.274	1.472		
185	0.0233	8.97.–4	14.12	287.5	771.0	3.603	6.222	1.475		
190	0.0327	9.04.–4	10.12	294.5	774.3	3.647	6.172	1.477		
195	0.0462	9.10.–4	7.208	301.7	777.5	3.684	6.124	1.480		
200	0.0653	9.17.–4	5.137	309.0	780.7	3.722	6.080	1.483	4.44	0.241
205	0.0919	9.25.–4	3.835	316.3	783.9	3.756	6.038	1.486	4.27	0.236
210	0.1315	9.33.–4	2.656	323.7	787.0	3.791	5.998	1.489	4.11	0.232
215	0.181	9.40.–4	1.975	331.0	790.1	3.825	5.961	1.492	3.96	0.228
220	0.243	9.48.–4	1.505	338.4	793.2	3.859	5.928	1.496	3.82	0.224
225	0.319	9.56.–4	1.168	345.7	796.3	3.892	5.896	1.500	3.69	0.219
230	0.417	9.65.–4	0.911	353.1	799.3	3.925	5.866	1.504	3.57	0.215
235	0.539	9.73.–4	0.718	360.5	802.3	3.957	5.845	1.508	3.46	0.211
240	0.688	9.81.–4	0.572	368.0	805.3	3.988	5.822	1.513	3.35	0.207
245	0.866	9.89.–4	0.462	375.6	808.2	4.019	5.786	1.518	3.25	0.202
250	1.076	9.98.–4	0.377	383.2	811.1	4.050	5.762	1.523	3.16	0.198
255	1.328	10.08.–4	0.311	390.7	814.0	4.080	5.740	1.528	3.08	0.194
260	1.627	10.18.–4	0.257	398.3	816.8	4.110	5.720	1.533	3.00	0.190
265	1.970	10.27.–4	0.215	406.0	819.4	4.139	5.699	1.539	2.92	0.186
270	2.364	10.36.–4	0.1807	413.7	822.0	4.168	5.680	1.546	2.85	0.182
275	2.830	10.46.–4	0.1524	421.5	824.4	4.197	5.662	1.554	2.78	0.177
280	3.347	10.57.–4	0.1301	429.4	826.8	4.225	5.644	1.565	2.72	0.173
285	3.936	10.68.–4	0.1115	437.3	829.0	4.253	5.628	1.574	2.66	0.169
290	4.612	10.79.–4	0.0960	445.2	831.2	4.280	5.612	1.583	2.61	0.165
295	5.361	10.91.–4	0.0830	453.2	833.2	4.308	5.597	1.594	2.56	0.160
300	6.189	11.03.–4	0.0723	461.2	835.2	4.334	5.581	1.605	2.51	0.156
305	7.110	11.15.–4	0.0632	469.3	837.0	4.361	5.567	1.617	2.46	0.152
310	8.111	11.27.–4	0.0556	477.4	838.8	4.388	5.553	1.631	2.42	0.148
315	9.243	11.40.–4	0.0489	485.6	840.5	4.414	5.540	1.644	2.37	0.143
320	10.47	11.55.–4	0.0433	493.8	841.9	4.440	5.527	1.658	2.33	0.139
325	11.78	11.70.–4	0.0386	502.1	843.3	4.465	5.516		2.30	0.135
330	13.27	11.86.–4	0.0343	510.4	844.5	4.491	5.504		2.27	0.131
340	16.52	12.17.–4	0.0282	518.8	846.4	4.542	5.481		2.12	0.124
350	20.53	12.54.–4	0.0228	538.3	847.5	4.592	5.457		1.99	0.117
360	25.29	12.97.–4	0.0186	562.9	847.6	4.643	5.434		1.87	0.110
370	30.74	13.47.–4	0.0151	581.6	845.9	4.694	5.398		1.77	0.103
380	36.99	14.11.–4	0.0117	602.8	842.6	4.747	5.382		1.67	0.095
390	44.05	14.67.–4	0.0096	622.9	837.4	4.805	5.358		1.59	0.086
400	52.29	15.66.–4	0.0075	643.6	826.4	4.870	5.323		1.51	0.075
405	56.6	16.48.–4	0.0063	663.2	819.1	4.904	5.289			
410	61.5	17.97.–4	0.0052	677.3	807.1	4.954	5.256			
415	67.4	21.10.–4	0.0038	714.1	778.6	5.025	5.200			
416^c	69.0	27.40.–4	0.0027	749.3	749.3	5.116	5.116			

*Interpolated by P. E. Liley from the Landolt-Börnstein band IVa, p. 677, 1967 tables by Steinle/Dienemann. c = critical point. The notation 8.84.–4 signifies 8.84×10^{-4}.

TABLE 2-286 Saturated Neon*

T, K	P, bar	v_f, m^3/kg	v_g, m^3/kg	h_f, kJ/kg	h_g, kJ/kg	s_f, kJ/(kg·K)	s_g, kJ/(kg·K)	c_{pf}, kJ/(kg·K)	μ_f, 10^{-4} Pa·s	k_f, W/(m·K)
10		6.654.–4		0.75		0.0992		0.278		
20		6.823.–4		6.78		0.4906		0.945		
24.6^m		6.696.–4		11.96		0.7257		1.345		
24.6^m	0.434	8.012.–4	0.2266	28.22	117.0	1.388	5.006	1.802	1.57	0.146
26	0.718	8.172.–4	0.1429	30.90	118.1	1.494	4.846	1.868	1.37	0.132
28	1.321	8.413.–4	0.0817	34.75	119.3	1.634	4.653	1.955	1.16	0.124
30	2.238	8.687.–4	0.0501	38.80	120.1	1.771	4.483	2.052	1.00	0.115
32	3.552	9.001.–4	0.0323	43.06	120.6	1.905	4.329	2.163	0.84	0.106
34	5.352	9.370.–4	0.0217	47.57	120.6	2.036	4.184	2.302	0.71	0.097
36	7.728	9.820.–4	0.0149	52.34	119.9	2.166	4.043	2.506	0.59	0.088
38	10.78	1.039.–3	0.0104	57.52	118.4	2.297	3.900	2.825	0.48	0.078
40	14.62	1.116.–3	0.0073	63.33	115.8	2.435	3.749	3.436	0.38	0.069
42	19.39	1.232.–3	0.0050	69.82	111.8	2.582	3.582	5.26	0.31	0.059
44	25.22	1.538.–3	0.0031	80.83	103.0	2.812	3.316	25.0	0.25	
44.4^c	26.53	2.070.–3	0.0021	92.50	92.5	3.062	3.062	∞		∞

*Values extracted and in some cases rounded off from those cited in Rabinovich (ed.), *Thermophysical Properties of Neon, Argon, Krypton and Xenon,* Standards Press, Moscow, 1976. m = melting point; c = critical point. The notation 6.654.–4 signifies 6.654×10^{-4}. This source contains values for the compressed state up to 1000 bar, etc. This book was published in English translation by Hemisphere, New York 1988 (604 pp.).

Saturation and superheat tables and a diagram to 200 bar, 320 K are given by Reynolds, W. C., *Thermodynamic Properties in S.I.,* Stanford Univ. publ., 1979 (173 pp.). Saturation and superheat tables to 60,000 psia, 900°R and a chart to 4000 psia, 560°R appear in Stewart, R. B., R. T. Jacobsen, et al., *Thermodynamic Properties of Refrigerants,* ASHRAE, Atlanta, GA, 1986 (521 pp.). For specific heat, thermal conductivity, and viscosity, see *Thermophysical Properties of Refrigerants,* ASHRAE, 1993.

TABLE 2-287 Compressed Neon*

Temperature, K		Pressure, bar											
		1	10	20	40	60	80	100	200	400	600	800	1000
100	v	0.4117	0.0410	0.0204	0.0102	6.76.–3	5.08.–3	4.09.–3	2.22.–3	1.42.–3	1.18.–3	1.06.–3	9.74.–4
	h	195.4	194.0	192.4	189.4	186.6	184.0	181.6	174.1	173.3	180.0	189.2	199.2
	s	6.129	5.168	4.869	4.556	4.363	4.221	4.106	3.739	3.386	3.197	3.066	2.964
200	v	0.8243	0.0828	0.0416	0.0210	0.0142	0.0107	8.69.–3	4.61.–3	2.61.–3	1.95.–3	1.63.–3	1.43.–3
	h	298.5	298.4	298.4	298.2	298.2	298.2	298.3	299.4	304.6	312.4	321.8	332.1
	s	6.844	5.893	5.605	5.315	5.143	5.020	4.924	4.620	4.308	4.124	3.994	3.893
300	v	1.236	0.1241	0.0624	0.0315	0.0212	0.0160	0.0129	6.77.–3	3.71.–3	2.69.–3	2.18.–3	1.87.–3
	h	401.6	401.8	402.2	402.8	403.5	404.1	404.9	408.8	417.8	427.8	438.5	449.7
	s	7.262	6.312	6.026	5.739	5.570	5.450	5.357	5.065	4.769	4.593	4.469	4.372
400	v	1.648	0.1654	0.0830	0.0418	0.0281	0.0212	0.0171	8.88.–3	4.77.–3	3.40.–3	2.72.–3	2.30.–3
	h	504.6	505.0	505.4	506.4	507.4	508.3	509.3	514.4	525.3	536.7	548.4	560.2
	s	7.558	6.609	6.323	6.037	5.896	5.750	5.657	5.369	5.078	4.907	4.785	4.690
500	v	2.060	0.2066	0.1036	0.0521	0.0350	0.0264	0.0213	0.0110	5.82.–3	4.10.–3	3.24.–3	2.73.–3
	h	607.6	608.1	608.6	609.7	610.8	611.9	613.0	618.8	630.7	642.9	655.2	667.5
	s	7.788	6.839	6.553	6.267	6.100	5.981	5.889	5.601	5.313	5.144	5.023	4.929
600	v	2.472	0.2478	0.1242	0.0625	0.0419	0.0316	0.0254	0.0130	6.85.–3	4.80.–3	3.77.–3	3.15.–3
	h	710.6	711.1	711.7	712.9	714.1	715.3	716.5	722.5	735.0	747.8	760.5	773.2
	s	7.975	7.027	6.741	6.455	6.288	6.169	6.077	5.791	5.504	5.335	5.215	5.122
700	v	2.884	0.2890	0.1449	0.0728	0.0487	0.0367	0.0295	0.0151	7.89.–3	5.49.–3	4.29.–3	3.57.–3
	h	813.5	814.1	814.7	816.0	817.2	818.5	819.7	826.0	838.9	851.9	865.0	878.1
	s	8.134	7.186	6.900	6.614	6.447	6.328	6.236	5.950	5.664	5.496	5.376	5.284
800	v	3.296	0.3302	0.1655	0.0831	0.0556	0.0419	0.0336	0.0172	8.92.–3	6.18.–3	4.81.–3	3.98.–3
	h	916.5	917.1	917.7	919.0	920.3	921.6	922.9	929.3	942.4	955.7	969.0	982.2
	s	8.272	7.323	7.038	6.752	6.585	6.466	6.374	6.088	5.802	5.634	5.515	5.423
900	v	3.708	0.3714	0.1861	0.0934	0.0625	0.0470	0.0378	0.0192	9.96.–3	6.87.–3	5.32.–3	4.40.–3
	h	1020	1020	1021	1022	1023	1025	1026	1033	1046	1059	1073	1086
	s	8.393	7.444	7.159	6.873	6.706	6.588	6.496	6.210	5.924	5.756	5.637	5.545
1000	v	4.120	0.4126	0.2067	0.1037	0.0693	0.0522	0.0419	0.0213	0.0110	7.56.–3	5.84.–3	4.81.–3
	h	1123	1123	1124	1125	1126	1128	1129	1136	1149	1163	1176	1190
	s	8.502	7.553	7.267	6.982	6.815	6.696	6.604	6.318	6.032	5.856	5.746	5.654

*Values extracted and in some cases rounded off from those cited in Rabinovich (ed.), *Thermophysical Properties of Neon, Argon, Krypton and Xenon,* Standards Press, Moscow, 1976. This source contains an exhaustive tabulation of values. v = specific volume, m^3/kg; h = specific enthalpy, kJ/kg; s = specific entropy, kJ/(kg·K). The notation 6.76.–3 signifies 6.76×10^{-3}. This book was published in English translation by Hemisphere, New York, 1988 (604 pp.).

TABLE 2-288 Saturated Nitrogen (R728)*

T, K	P, bar	v_f, 10^{-3} m^3/kg	v_g, m^3/kg	h_f, kJ/kg	h_g, kJ/kg	s_f, kJ/(kg·K)	s_g, kJ/(kg·K)	c_{pf}, kJ/(kg·K)	μ_f, 10^{-4} Pa·s	k_f, W/(m·K)
63.15^t	0.1253	1.155	1477	−148.5	64.1	2.459	5.826	1.928		0.170
65	0.1743	1.165	1091	−144.9	65.8	2.516	5.757	1.930	2.74	0.160
70	0.3859	1.193	525.6	−135.2	70.5	2.657	5.595	1.937	2.17	0.151
75	0.7609	1.224	281.8	−125.4	74.9	2.789	5.460	1.948	1.77	0.141
77.35	1.0133	1.239	216.9	−120.8	76.8	2.849	5.404	1.955	1.60	0.136
80	1.369	1.258	164.0	−115.6	78.9	2.913	5.345	1.964	1.48	0.132
85	2.287	1.297	101.7	−105.7	82.3	3.032	5.244	1.989	1.27	0.123
90	3.600	1.340	66.28	−95.6	85.0	3.147	5.152	2.028	1.10	0.114
95	5.398	1.390	44.87	−85.2	86.8	3.256	5.067	2.086	0.97	0.105
100	7.775	1.447	31.26	−74.5	87.7	3.363	4.985	2.176	0.87	0.097
105	10.83	1.514	22.23	−63.8	87.4	3.469	4.904	2.319	0.79	0.088
110	14.67	1.597	15.98	−51.4	85.6	3.575	4.820	2.566	0.71	0.080
115	19.40	1.714	11.47	−38.1	81.8	3.687	4.729	3.063	0.60	0.071
120	25.15	1.892	8.031	−21.4	74.3	3.821	4.619		0.48	0.063
125	32.05	2.324	5.016	5.1	57.2	4.024	4.444		0.32	0.052
126.25^c	33.96	3.289	3.289	34.8	34.8	4.252	4.252	∞		∞

*Reproduced and converted from Vasserman and Rabinovich, *Thermophysical Properties of Liquid Air and Its Components,* Standartov, Moscow, 1968; and Israel Program for Scientific Translations, TT 69-55092, 1970. t = triple point; c = critical point.

Other extensive tables are given by Angus, S., *International Thermodynamic Tables of the Fluid State—6. Nitrogen,* Pergamon, 1977 (244 pp.); Hanley, H. J. M., R. D. McCarty, et al., *J. Phys. Chem. Ref. Data,* **3** (1974): 979–1019.

Saturation and superheat tables to 30,000 psia and a chart to 10,000 psia, all to 860°R, appear in Stewart, R. B., R. T. Jacobsen, et al., *Thermodynamic Properties of Refrigerants,* ASHRAE, Atlanta, GA, 1986 (521 pp.). For specific heat, thermal conductivity, and viscosity, see *Thermophysical Properties of Refrigerants,* ASHRAE, 1993.

The 1993 ASHRAE *Handbook—Fundamentals* (SI ed.) has a thermodynamic chart for pressures from 0.1 to 800 bar and temperatures from 80 to 500 K.

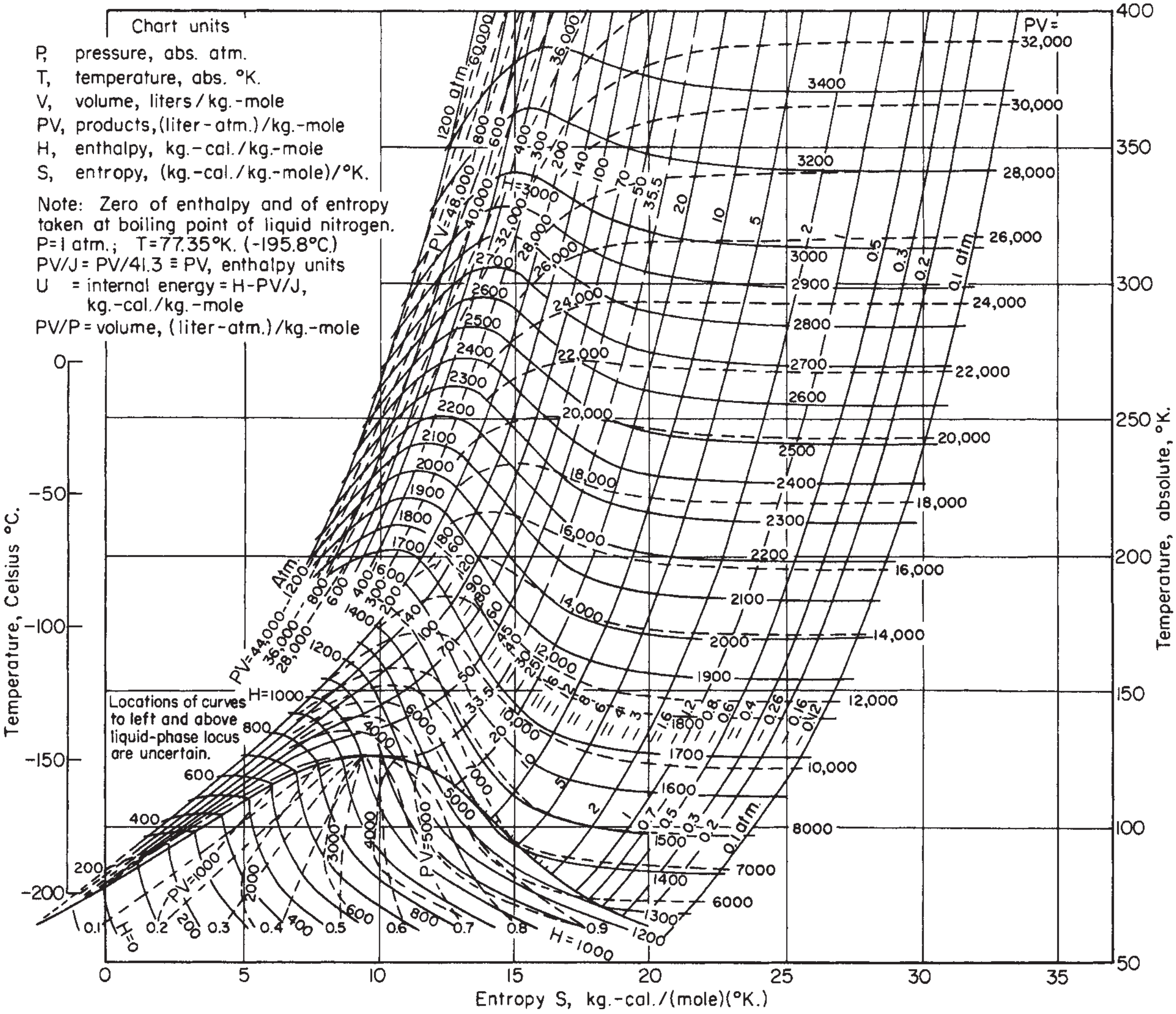

FIG. 2-13 Temperature-entropy diagram for nitrogen. Section of *T-S* diagram for nitrogen by E. S. Burnett, 1950. (*Reprinted from U.S. Bur. Mines Rep. Invest. 4729.*)

TABLE 2-289 Thermophysical Properties of Nitrogen (R728) at Atmospheric Pressure

T (K)	77.4^b	80	100	120	140	160	180	200	220	240
v (m^3/kg)	0.2164	0.2252	0.2871	0.3474	0.4071	0.4664	0.5255	0.5845	0.6434	0.7023
h (kJ/kg)	76.7	80.0	101.9	123.1	144.2	165.2	186.1	207.0	227.8	248.7
s (kJ/kg·K)	5.403	5.446	5.690	5.884	6.046	6.186	6.309	6.419	6.519	6.609
c_p (kJ/kg·K)	1.341	1.196	1.067	1.056	1.050	1.047	1.045	1.043	1.043	1.042
Z	0.9545	0.9610	0.9801	0.9883	0.9927	0.9952	0.9967	0.9977	0.9984	0.9990
$\bar{v}_s$ (m/s)	172	177	202	222	240	257	273	288	302	316
η (10^{-6} Pa·s)	5.0	5.2	6.7	8.0	9.3	10.6	11.8	12.9	14.0	15.0
k (W/m·K)	0.0074	0.0077	0.0098	0.0117	0.0136	0.0154	0.0171	0.0187	0.0203	0.0218
N_{Pr}	0.913	0.811	0.728	0.727	0.723	0.721	0.720	0.719	0.718	0.717

T (K)	260	280	300	320	340	360	380	400	420	440
v (m^3/kg)	0.7611	0.8199	0.8786	0.9371	0.9960	1.0546	1.1134	1.1719	1.2305	1.2892
h (kJ/kg)	269.5	290.3	311.2	332.0	352.8	373.7	394.5	411.5	436.3	457.3
s (kJ/kg·K)	6.693	6.770	6.842	6.909	6.972	7.032	7.088	7.142	7.193	7.242
c_p (kJ/kg·K)	1.042	1.041	1.041	1.042	1.042	1.043	1.044	1.045	1.047	1.048
Z	0.9994	0.9997	0.9998	0.9999	1.0000	1.0001	1.0002	1.0002	1.0002	1.0003
$\bar{v}_s$ (m/s)	329	341	359	365	376	387	397	408	417	427
η (10^{-6} Pa·s)	16.0	17.0	17.9	18.8	19.7	20.5	21.4	22.2	23.0	23.8
k (W/m·K)	0.0232	0.0247	0.0260	0.0273	0.0286	0.0299	0.0311	0.0324	0.0336	0.0347
N_{Pr}	0.717	0.716	0.716	0.717	0.717	0.717	0.717	0.717	0.717	0.717

T (K)	460	480	500	600	700	800	900	1000	1500	2000
v (m^3/kg)	1.3481	1.4065	1.4654	1.758	2.052	2.344	2.636	2.931	4.396	5.862
h (kJ/kg)	478.3	499.3	520.4	626.9	735.6	846.6	960.0	1075.7	1680.5	2313.5
s (kJ/kg·K)	7.288	7.333	7.376	7.570	7.738	7.886	8.019	8.141	8.630	8.995
c_p (kJ/kg·K)	1.051	1.053	1.056	1.075	1.098	1.122	1.146	1.167	1.244	1.284
Z	1.0003	1.0004	1.0004	1.000	1.000	1.000	1.000	1.001	1.001	1.001
$\bar{v}_s$ (m/s)	437	446	455	496	534	568	601	631	765	879
η (10^{-6} Pa·s)	24.5	25.3	26.0	29.5	32.8	35.9	38.8	41.6		
k (W/m·K)	0.0359	0.0371	0.0383	0.0440	0.0496	0.0551	0.0606	0.658		
N_{Pr}	0.718	0.718	0.718	0.722	0.726	0.730	0.734	0.737		

b = normal boiling point.

TABLE 2-290 Saturated Nitrogen Tetroxide

Pressure, bar	Temperature, K	v_f, m^3/kg	v_g, m^3/kg	M_f	M_g
1.0133	299.32	0.000 694	0.2996	91.857	79.157
2	309.57	0.000 711	0.1630	91.886	76.503
4	326.66	0.000 733	0.0876	91.766	73.538
6	337.43	0.000 749	0.0608	91.625	71.748
8	345.45	0.000 762	0.0469	91.488	70.480
10	351.88	0.000 774	0.0382	91.346	69.483
15	364.09	0.000 800	0.0262	90.979	67.742
20	373.17	0.000 822	0.0199	90.601	66.547
30	386.57	0.000 863	0.0133	89.823	64.997
40	396.52	0.000 903	0.0098	89.018	64.099
50	404.50	0.000 945	0.00761	88.191	63.532
60	411.20	0.000 993	0.00607	87.344	63.181
80	422.07	0.001 129	0.00394	85.602	62.959
100	430.76	0.001 577	0.00209	83.817	63.366

Condensed from McCarty, R. D., H-U. Steurer, et al., NBS IR 86 - 3054, 1986 (106 pp.). M = mol wt for the reaction N_2O_4 **A** $2NO_2$ **A** $2NO + O_2$. No derived thermodynamic functions were tabulated due to unduly large differences in literature values, but 92 references are given.

TABLE 2-291 Saturated Nitrous Oxide

Temp., °F	Pressure, psia	v_f, ft^3/lb$_m$	v_g, ft^3/lb$_m$	h_f, Btu/lb$_m$	h_g, Btu/lb$_m$	s_f, Btu/lb$_m$°R	s_g, Btu/lb$_m$°R
−127.2	14.70	0.01310	5.069	0.0	161.7	0.0000	0.4864
−100	33.68	0.01358	2.374	11.7	165.9	0.0304	0.4591
−80	56.79	0.01398	1.463	20.8	168.8	0.0534	0.4433
−60	90.29	0.01444	0.939	30.2	171.5	0.0782	0.4315
−40	136.68	0.01495	0.648	40.3	173.7	0.1044	0.4222
−20	198.62	0.01555	0.450	50.6	175.3	0.1296	0.4133
0	278.97	0.01625	0.316	60.5	176.2	0.1518	0.4036
20	380.88	0.01711	0.227	70.2	176.2	0.1718	0.3928
40	507.51	0.01819	0.164	80.3	175.0	0.1920	0.3815
60	662.69	0.01968	0.117	91.9	172.1	0.2145	0.3687
80	851.5	0.0222	0.0792	105.7	165.0	0.2382	0.3480
90	961.0	0.0247	0.0611	114.7	157.5	0.2523	0.3302
97.6^c	1052.2	0.0354	0.0354	136.4	136.4	0.2890	0.2890

Rounded and condensed from Couch, E. J. and K. A. Kobe, Univ. Texas Rep., Cont. DAI-23-072-ORD-685, June 1, 1956. c = critical point.

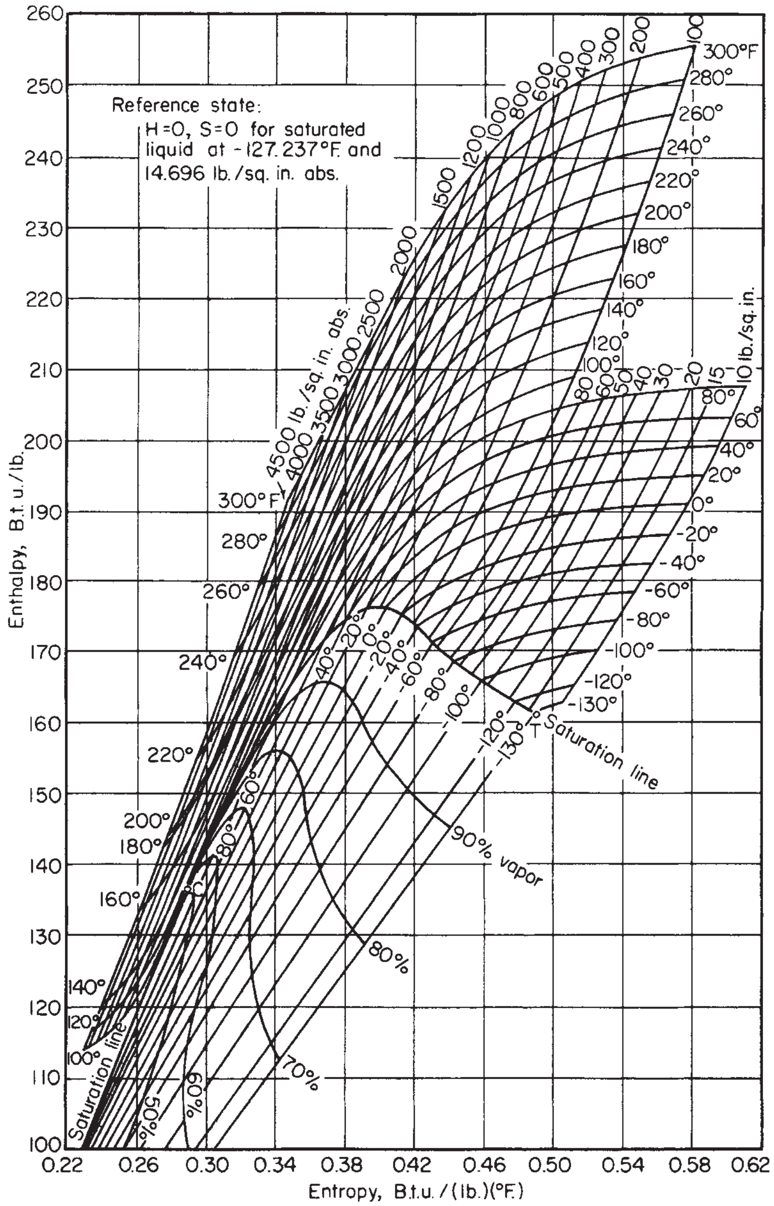

FIG. 2-14 Mollier diagram for nitrous oxide. (*Fig. 9, Univ. Texas Rep., Cont. DAI-23-072-ORD-685, June 1, 1956, by Couch and Kobe. Reproduced by permission.*) Some irregularity in the compressibility factors from 80 to 160 atm, 50 to 100°C exists (*Couch, private communication, 1967*). See Couch et al., *J. Chem. Eng. Data,* **6,** (1961) for PVT data.

TABLE 2-292 Nonane*

T, K	P, bar	v_f, m^3/kg	v_g, m^3/kg	h_f, kJ/kg	h_g, kJ/kg	s_f, kJ/(kg·K)	s_g, kJ/(kg·K)	c_{pf}, kJ/(kg·K)	μ_f, 10^{-4} Pa·s	k_f, W/(m·K)
219.7^t	2.6.–6			358.4		2.424		2.07	33.5	0.150
220	2.7.–6			359.2		2.427		2.07	33.0	0.150
240	3.74.–5			400.6		2.607		2.08	17.9	0.145
260	2.97.–4			442.2	828.7	2.774	4.210	2.10	12.1	0.140
280	1.61.–3			484.8	859.4	2.932	4.243	2.16	8.7	0.134
300	6.40.–3	1.404.–3	30.35	528.6	891.7	3.083	4.282	2.22	6.53	0.129
320	0.0203	1.436.–3	10.19	573.8	925.6	3.229	4.324	2.30	5.13	0.123
340	0.0547	1.471.–3	4.00	622.0	961.1	3.370	4.368		4.16	0.118
360	0.1279	1.508.–3	1.80	671.3	998.2	3.511	4.419		3.44	0.112
380	0.2678	1.548.–3	0.894	722.5	1036.5	3.650	4.476		2.91	0.107
400	0.513	1.591.–3	0.485	776.7	1076.0	3.788	4.536		2.50	0.101
420	0.911	1.637.–3	0.286	833.3	1116.6	3.927	4.601		2.18	0.096
440	1.521	1.690.–3	0.161	890.2	1157.1	4.053	4.660			0.092
460	2.401	1.748.–3	0.104	950.3	1199.2	4.186	4.727			0.089
480	3.639	1.815.–3	0.069	1012.1	1241.3	4.316	4.794			0.085
500	5.309	1.895.–3	0.045	1076.2	1282.9	4.444	4.857			0.082
520	7.437	2.00.–3	0.030	1141.3	1324.5	4.569	4.921			
540	10.20	2.13.–3	0.021	1207.7	1363.8	4.691	3.980			
560	13.76	2.35.–3	0.013	1275.4	1338.7	4.811	5.029			
580	18.02	2.78.–3	0.008	1342.9	1318.1	4.927	5.056			
594.6^c	22.90	4.23.–3	0.004	1305.2	1305.2	5.032	5.032			

*Values of p and v interpolated and converted from tables in Vargaftik, *Handbook of Thermophysical Properties of Gases and Liquids,* Hemisphere, Washington, and McGraw-Hill, New York, 1975. Values of h and s calculated from API tables published by Texas A&M University, College Station. t = triple point; c = critical point.

TABLE 2-293 Octane*

T, K	P, bar	v_f, m^3/kg	v_g, m^3/kg	h_f, kJ/kg	h_g, kJ/kg	s_f, kJ/(kg·K)	s_g, kJ/(kg·K)	c_{pf}, kJ/(kg·K)	μ_f, 10^{-3} Pa·s	k_f, W/(m·K)
216.4^t	1.49.–5			365.9		2.487		2.033	2.25	0.149
220	2.41.–5			373.2		2.520		2.035	2.01	0.148
240	2.18.–4	1.353.–3	700	414.1	811.4	2.698	4.207	2.059	1.24	0.143
260	0.0014	1.368.–3	125	455.8	842.1	2.865	4.259	2.105	0.87	0.138
280	0.0061	1.384.–3	31.9	498.4	873.5	3.023	4.312	2.165	0.65	0.133
300	0.0207	1.420.–3	10.7	542.4	906.2	3.175	4.366	2.231	0.504	0.128
320	0.0575	1.457.–3	4.01	589.8	939.8	3.325	4.419		0.405	0.123
340	0.1384	1.495.–3	1.752	637.9	974.6	3.471	4.461		0.334	0.118
360	0.3000	1.536.–3	0.844	687.1	1010.4	3.611	4.509		0.282	0.112
380	0.5856	1.582.–3	0.448	737.7	1047.3	3.747	4.562		0.244	0.107
400	1.0507	1.632.–3	0.252	790.1	1084.8	3.881	4.617		0.200	0.102
420	1.758	1.685.–3	0.155	843.1	1123.6	4.010	4.677		0.167	0.099
440	2.797	1.747.–3	0.100	897.5	1162.5	4.137	4.740		0.143	0.095
460	4.246	1.818.–3	0.066	954.8	1202.0	4.264	4.802		0.121	0.091
480	6.201	1.904.–3	0.045	1013.5	1241.8	4.388	4.864		0.103	0.087
500	8.785	2.013.–3	0.031	1072.8	1281.2	4.508	4.924		0.086	0.083
520	12.15	2.16.–3	0.021	1136.0	1318.6	4.629	4.980		0.072	
540	16.46	2.37.–3	0.014	1201.5	1352.4	4.749	5.028		0.058	
560	21.98	2.81.–3	0.008	1276.7	1370.4	4.880	5.048		0.044	
568.8^c	24.97	4.26.–3	0.004	1331.7	1331.7	4.977	4.977			

*Values of p and v interpolated and converted from tables in Vargaftik, *Handbook of Thermophysical Properties of Gases and Liquids,* Hemisphere, Washington, and McGraw-Hill, New York, 1975. Values of h and s calculated from API tables published by Texas A&M University, College Station. t = triple point; c = critical point. Saturation and superheat tables and a diagram to 100 bar, 680 K are given by Reynolds, W. C., *Thermodynamic Properties in S.I.,* Stanford Univ. publ., 1979 (173 pp.).

TABLE 2-294 Saturated Oxygen (R732)*

T, K	P, bar	v_f, 10^{-3} m^3/kg	v_g, 10^{-3} m^3/kg	h_f, kJ/kg	h_g, kJ/kg	s_f, kJ/(kg·K)	s_g, kJ/(kg·K)	c_{pf}, kJ/(kg·K)	μ_f, 10^{-4} Pa·s	k_f, W/(m·K)
54.35^t	0.0015	0.776	93980	−189.8	48.9	2.156	6.548			
55	0.0018	0.778	77920	−188.9	49.5	2.172	6.507			
60	0.0073	0.790	21240	−181.1	53.8	2.308	6.223			
65	0.0233	0.802	7200	−173.3	58.1	2.432	5.992			
70	0.0624	0.816	2894	−165.5	62.4	2.545	5.801			
75	0.1448	0.827	1330	−159.2	66.6	2.631	5.642	1.570	3.04	0.170
80	0.3003	0.845	680.7	−149.7	70.8	2.754	5.510	1.589	2.54	0.164
85	0.5677	0.862	379.7	−141.7	74.9	2.849	5.397	1.607	2.16	0.157
90	0.9943	0.880	227.1	−133.7	78.8	2.940	5.301	1.625	1.88	0.151
90.18	1.0133	0.881	223.2	−133.4	78.9	2.943	5.297	1.626	1.87	0.151
95	1.634	0.899	143.9	−125.4	82.4	3.045	5.216	1.645	1.66	0.144
100	2.547	0.920	95.46	−117.1	85.7	3.113	5.141	1.672	1.51	0.138
105	3.794	0.944	65.81	−108.6	88.5	3.196	5.073	1.706	1.34	0.131
110	5.443	0.970	46.81	−99.9	90.8	3.276	5.009	1.752	1.20	0.125
115	7.559	0.998	34.15	−90.0	92.6	3.354	4.950	1.814	1.07	0.118
120	10.21	1.031	25.42	−81.6	93.6	3.432	4.892	1.896	0.97	0.111
125	13.48	1.070	19.21	−71.8	93.9	3.510	4.836	2.004	0.86	0.103
130	17.44	1.116	14.67	−61.5	93.3	3.588	4.779	2.148	0.78	0.096
135	22.19	1.170	11.25	−50.6	91.6	3.667	4.720	2.341	0.70	0.088
140	27.82	1.237	8.612	−38.9	88.4	3.748	4.657	2.629	0.60	0.080
145	34.45	1.332	6.499	−25.9	82.9	3.833	4.583	3.141	0.52	0.072
150	42.23	1.487	4.705	−10.8	73.1	3.928	4.487	3.935		
154.77^c	50.87	2.464	2.464	35.2	35.2	4.219	4.219	∞		∞

*Reproduced and converted from Vasserman and Rabinovich, *Thermophysical Properties of Liquid Air and Its Components,* Standartov, Moscow, 1968; and Israel Program for Scientific Translations, TT 69-55092, 1970. t = triple point; c = critical point.

Other tables are given by Sytchev, V. V., A. A. Vasserman, et al., *Thermodynamic Properties of Oxygen,* Hemisphere, New York, 1987 (307 pp.); Stewart, R. B., R. T. Jacobsen, et al., *J. Phys. Chem. Ref. Data,* **20,** 5 (1991): 917–1021; For fps units, see *Thermodynamic Properties of Refrigerants,* ASHRAE, Atlanta, GA, 1986 (521 pp.). For specific heat, thermal conductivity, and viscosity, see *Thermophysical Properties of Refrigerants,* ASHRAE, 1993. See also Roder, H. M., *Transport Properties of Oxygen,* NASA Ref. Publ. 1102, 1983 (87 pp.); Laesecke, A., K. Krauss, et al., *J. Phys. Chem. Ref. Data,* **19,** 5 (1990): 1089–1122.

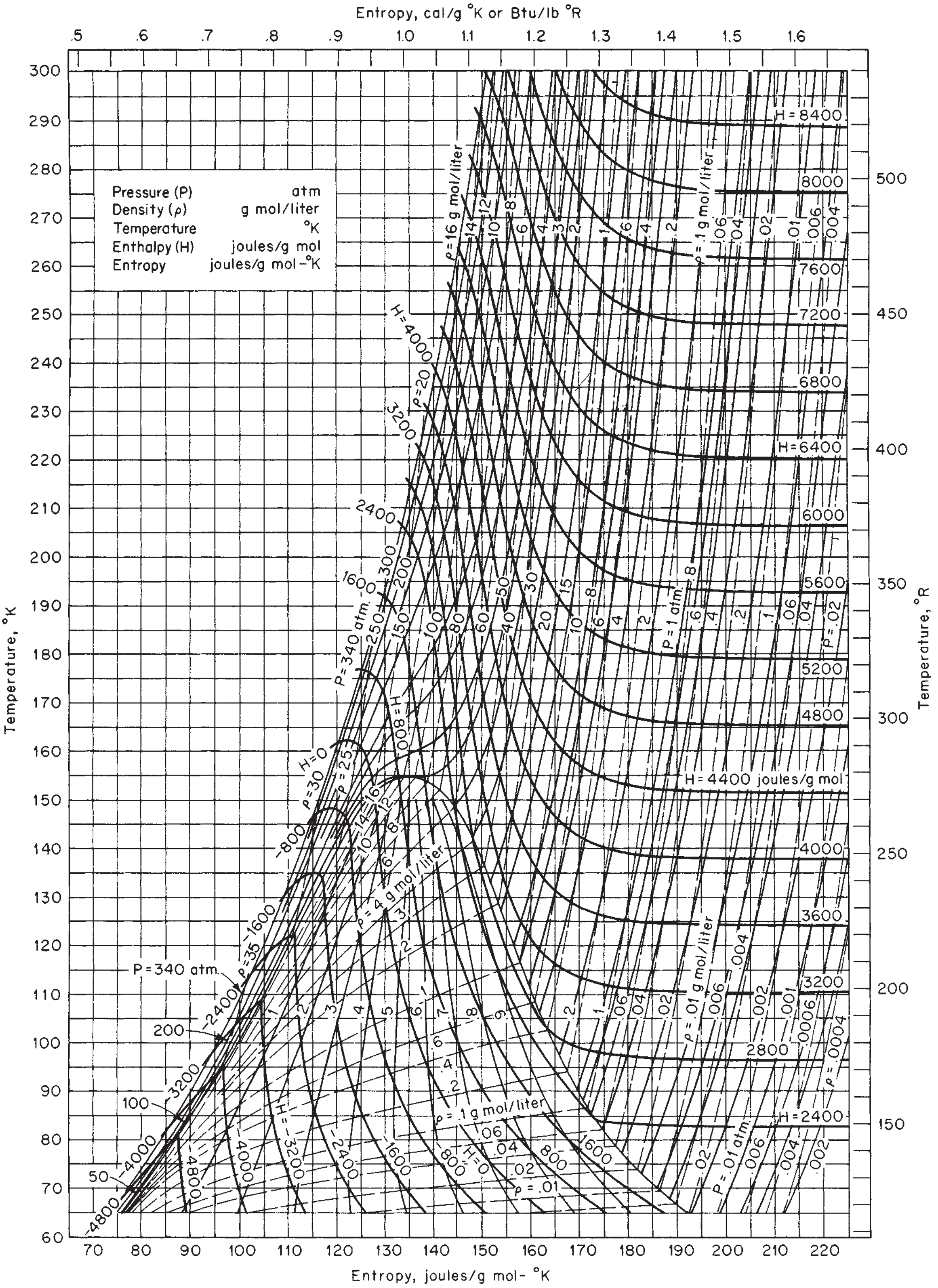

FIG. 2-15 Temperature-entropy chart for oxygen. Pressure *P,* atm; density ρ, (g·mol)/L; temperature, K; enthalpy *H,* J/(g·mol); entropy, J/(g·mol·K). (*NBS Chart D-56. Reproduced by permission.*)

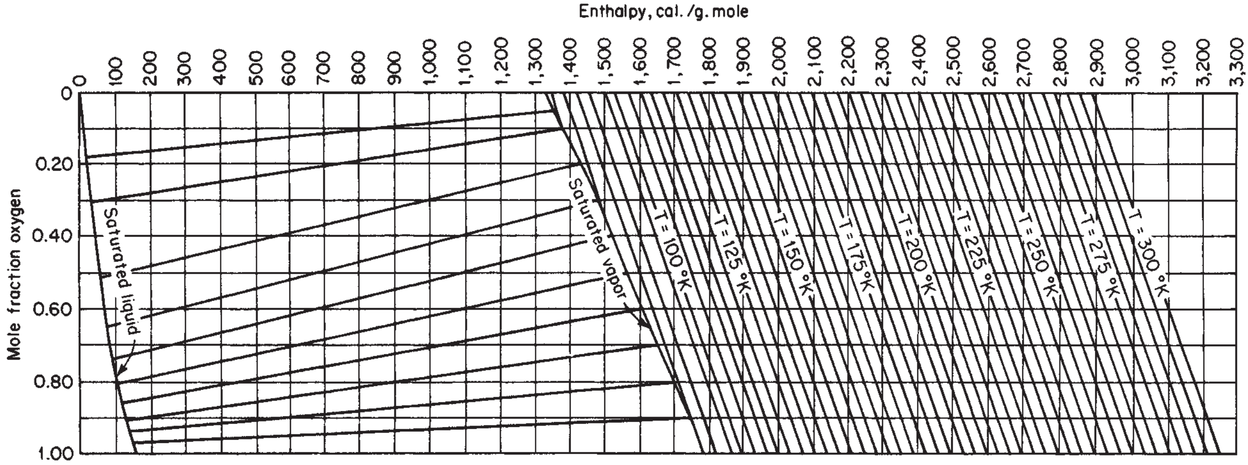

FIG. 2-16 Enthalpy-concentration diagram for oxygen-nitrogen mixture at 1 atm. Reference states: Enthalpies of liquid oxygen and liquid nitrogen at the normal boiling point of nitrogen are zero. (*Dodge,* Chemical Engineering Thermodynamics, *McGraw-Hill, New York, 1944.*) Wilson, Silverberg, and Zellner, AFAPL TDR 64-64 (AD 603151), 1964, p. 314, present extensive vapor-liquid equilibrium data for the three-component system argon-nitrogen-oxygen as well as for binary systems including oxygen-nitrogen.

TABLE 2-295 Pentane

Canjar and Manning (*Thermodynamic Properties and Reduced Correlations for Gases,* Gulf, Houston, 1967) give extensive tables and an enthalpy–log-pressure diagram, based upon Brydon, Walen, and Canjar [*Chem. Eng. Prog. Symp. Ser.,* **49,** 7, (1951): 151–157]. For isopentane, Arnold, Liou, and Eldridge [*J. Chem. Eng. Data,* **10,** 88 (1965)] used the Benedict-Webb-Rubin equation to generate information to 600°F and 60 atm. Das and Kuloor used the same equation in *Ind. J. Technol.,* **5,** 46 (1967) to calculate information up to 1500 K and 1000 atm. Saturation and superheat tables and a diagram to 200 bar, 600 K are given by Reynolds, W. C., *Thermodynamic Properties in S.I.,* Stanford Univ. publ., 1979 (173 pp.). For equations, see Grigoryev, B. A., Yu. L. Rastorguyev, et al., *Int. J. Thermophys.,* **11,** 3 (1990): 487–502.

TABLE 2-296 Saturated Potassium*

T, K	P, bar	v_f, m^3/kg	v_g, m^3/kg	h_f, kJ/kg	h_g, kJ/kg	s_f, kJ/(kg·K)	s_g, kJ/(kg·K)	c_{pf}, kJ/(kg·K)
336.4^m	1.37.–9	0.001208		93.8	2327	1.928	8.567	0.822
400	1.84.–7	0.001229	4.64.+6	145.5	2342	2.068	7.559	0.805
500	3.13.–5	0.001266	3.39.+4	225.1	2390	2.246	6.576	0.785
600	9.26.–4	0.001304	3164	302.7	2433	2.388	5.937	0.771
700	0.01022	0.001346	142.3	379.4	2468	2.506	5.490	0.762
800	0.06116	0.001389	26.75	455.5	2498	2.608	5.161	0.761
1000	0.7322	0.001488	2.691	609.7	2552	2.780	4.722	0.792
1200	3.913	0.001605	0.584	773.5	2610	2.929	4.459	0.846
1400	12.44	0.001742	0.207	948.0	2679	3.063	4.299	0.899
1500	20.0	0.001816	0.132	1040.0	2718	3.123	4.209	0.924

*Converted from tables in Vargaftik, *Tables of the Thermophysical Properties of Liquids and Gases,* Nauka, Moscow, 1972; and Hemisphere, Washington, 1975. m = melting point. The notation 1.37.–9 signifies 1.37×10^{-9}.

Many of the Vargaftik values also appear in Ohse, R. W., *Handbook of Thermodynamic and Transport Properties of Alkali Metals,* Blackwell Sci. Pubs., Oxford, 1985 (1020 pp.). This source contains superheat data. Saturation and superheat tables and a diagram to 30 bar, 1650 K are given by Reynolds, W. C., *Thermodynamic Properties in S.I.,* Stanford Univ. publ., 1979 (173 pp.). For a Mollier diagram from 0.1 to 250 psia, 1300 to 2700°R, see Weatherford, W. D., J. C. Tyler, et al., WADD-TR-61-96, 1961. An extensive review of properties of the solid and the saturated liquid is given by Alcock, C. B., M. W. Chase, et al., *J. Phys. Chem. Ref. Data,* **23,** 3 (1994): 385–497.

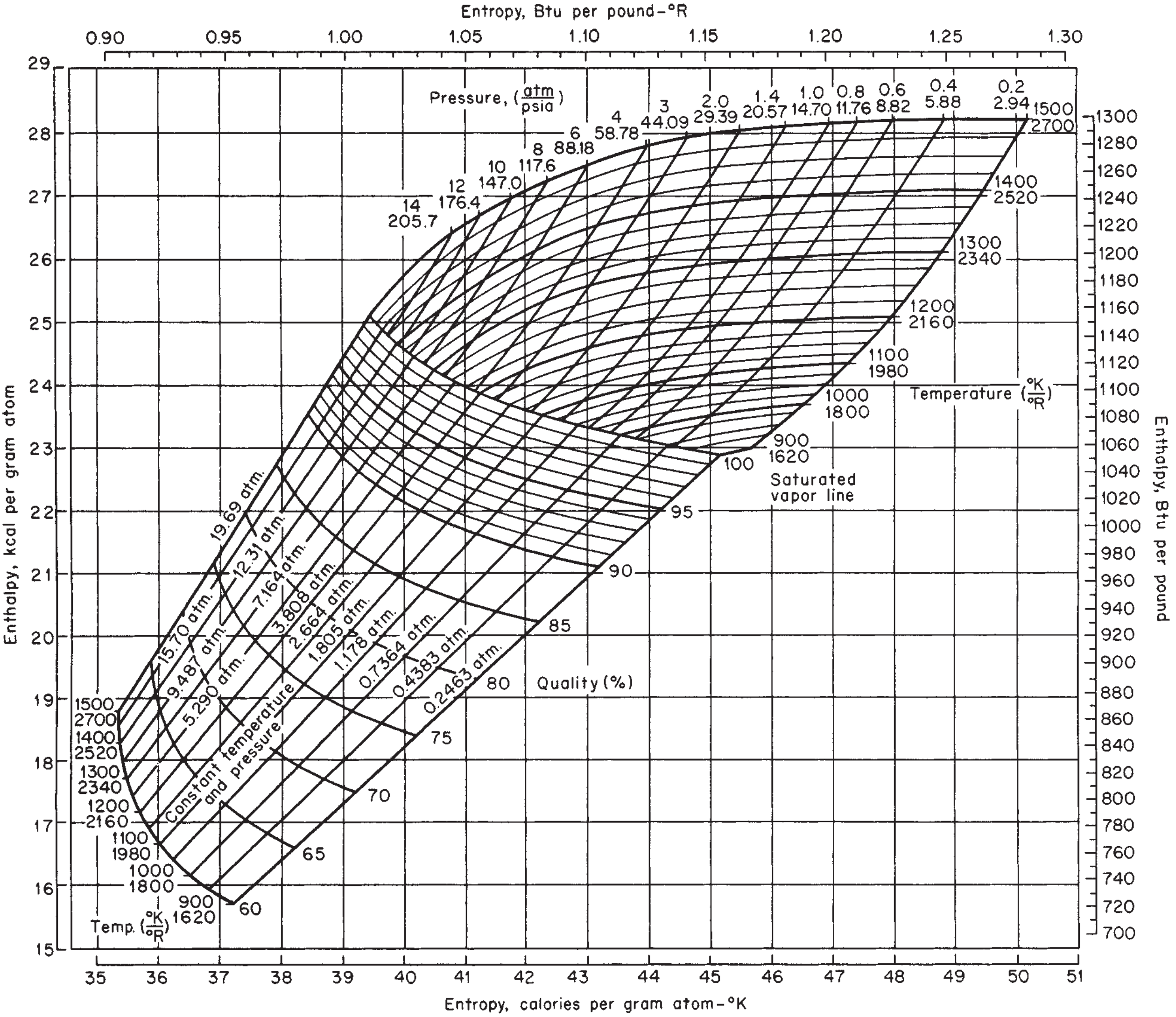

FIG. 2-17 Mollier diagram for potassium. Basis: enthalpy = 0.0 cal/g atom at 298 K; entropy = 15.8 cal/(g atom·K) at 298 K. (*Aerojet-General Rep. AGN8194, vol. 2, 1967. Reproduced by permission.*)

TABLE 2-297 Saturated Propane (R290)*

T, K	P, bar	v_f, m^3/kg	v_g, m^3/kg	h_f, kJ/kg	h_g, kJ/kg	s_f, kJ/(kg·K)	s_g, kJ/(kg·K)	c_{pf}, kJ/(kg·K)	μ_f, 10^{-4} Pa·s	k_f, W/(m·K)
85.5^t	3.0.–9	1.364.–3	5.37.+7	124.92	690.02	1.8738	8.3548	1.92		
90	1.5.–8	1.373.–3	1.12.+7	133.56	693.58	1.9723	8.0953	1.92		
100	3.2.–7	1.392.–3	5.85.+5	152.74	702.23	2.1743	7.6163	1.93		
110	3.9.–6	1.412.–3	53275	172.03	711.71	2.3581	7.2377	1.94		
120	3.1.–5	1.432.–3	7350	191.46	721.78	2.5271	6.9343	1.95		
130	1.8.–4	1.453.–3	1400	211.03	732.27	2.6838	6.6885	1.96		
140	7.7.–4	1.475.–3	344	230.77	743.07	2.8300	6.4881	1.98		
150	2.74.–3	1.497.–3	103	250.67	754.12	2.9674	6.3237	2.00	6.61	0.191
160	8.22.–3	1.521.–3	36.8	270.78	765.37	3.0971	6.1886	2.02	5.54	0.183
170	0.0214	1.545.–3	15.0	291.10	776.80	3.2202	6.0775	2.04	4.67	0.175
180	0.0495	1.570.–3	6.84	311.66	788.40	3.3377	5.9862	2.07	3.97	0.166
190	0.1035	1.597.–3	3.43	332.48	800.15	3.4503	5.9114	2.10	3.27	0.158
200	0.1993	1.625.–3	1.868	353.61	812.03	3.5586	5.8502	2.13	2.98	0.150
210	0.3574	1.654.–3	1.087	375.07	824.01	3.6631	5.8005	2.16	2.65	0.143
220	0.6031	1.686.–3	0.669	396.90	836.04	3.7645	5.7603	2.20	2.36	0.136
230	0.9661	1.719.–3	0.432	419.16	848.08	3.8631	5.7280	2.25	2.07	0.129
240	1.4800	1.754.–3	0.290	442.07	860.07	3.9605	5.7022	2.29	1.86	0.123
250	2.1819	1.792.–3	0.2020	465.58	871.94	4.0563	5.6817	2.34	1.69	0.117
260	3.1118	1.833.–3	0.1445	489.70	883.62	4.1505	5.6656	2.41	1.53	0.111
270	4.3120	1.878.–3	0.1059	514.45	895.02	4.2433	5.6528	2.48	1.40	0.106
280	5.8278	1.927.–3	0.0791	539.88	906.03	4.3349	5.6426	2.56	1.29	0.100
290	7.7063	1.982.–3	0.0600	566.06	916.54	4.4257	5.6343	2.65	1.19	0.096
300	9.9973	2.044.–3	0.0461	593.11	926.41	4.5160	5.6270	2.76	1.10	0.091
310	12.75	2.115.–3	0.0357	621.18	935.45	4.6062	5.6200	2.89	0.93	0.086
320	16.03	2.200.–3	0.0279	650.49	943.38	4.6971	5.6124	3.06	0.82	0.082
330	19.88	2.301.–3	0.0218	681.37	949.79	4.7896	5.6030	3.28	0.72	0.078
340	24.36	2.430.–3	0.0170	714.38	953.92	4.8850	5.5896	3.62	0.62	0.073
350	29.56	2.607.–3	0.0130	750.52	954.23	4.9861	5.5681	4.23	0.52	0.069
360	35.55	2.896.–3	0.0095	792.50	946.56	5.0997	5.5277	5.98	0.40	0.066
369.8^c	42.42	4.566.–3	0.0046	879.20	879.20	5.3300	5.3300	∞	0.29	∞

*Values converted and mostly rounded off from those of Goodwin, NBSIR 77-860, 1977. t = triple point; c = critical point. The notation 3.0.–9 signifies 3.0×10^{-9}. Later tables for the same temperature range for saturation and for the superheat state from 0.1 to 1000 bar, 85.5 to 600 K, were published by Younglove, B. A. and J. F. Ely, *J. Phys. Chem. Ref. Data,* **16,** 4 (1987): 685–721, but the lower temperature saturation tables contain some errors.

Saturation and superheat tables and a chart to 10,000 psia, 800°F appear in Stewart, R. B., R. T. Jacobsen, et al., *Thermodynamic Properties of Refrigerants,* ASHRAE, Atlanta, GA, 1986 (521 pp.).

For thermodynamic properties for 0.1 to 1000 bar, 100 to 700 K, see Sychev, V. V., A. A. Vasserman, et al., *Thermodynamic Properties of Propane,* Hemisphere, New York, NY, 1991 (275 pp.).

Saturation and superheat tables and a diagram to 200 bar, 600 K are given by Reynolds, W. C., *Thermodynamic Properties in S.I.,* Stanford Univ. publ., 1979 (173 pp.).

For specific heat, thermal conductivity, and viscosity, see *Thermophysical Properties of Refrigerants,* ASHRAE, 1993.

TABLE 2-298 Saturated Propylene (Propene, R1270)

T, K	P, bar	v_f, m^3/kg	v_g, m^3/kg	h_f, kJ/kg	h_g, kJ/kg	s_f, kJ/(kg·K)	s_g, kJ/(kg·K)	c_{pf}, kJ/(kg·K)	μ_f, 10^{-6} Pa·s	k_f, W/(m·K)	Pr
87.9[t]	9.54.–9	0.001 301	1.82.+7	−290.1	279.2	−1.923	4.554				
90	2.05.–8	0.001 305	8.66.+6	−285.1	281.1	−1.867	4.424				
100	4.81.–7	0.001 325	411 165	−265.4	290.2	−1.659	3.897	1.695	2017	0.214	15.98
110	6.08.–6	0.001 346	35 753	−247.7	299.6	−1.490	3.488	1.760	1526	0.209	12.85
120	4.88.–5	0.001 367	4 856	−229.8	309.3	−1.335	3.158	1.820	1185	0.204	10.57
130	2.77.–4	0.001 389	927.0	−211.4	319.3	−1.187	2.895	1.875	941	0.198	8.91
140	1.20.–3	0.001 411	230.91	−192.4	329.4	−1.046	2.681	1.923	735	0.193	7.32
150	4.17.–3	0.001 434	71.043	−172.9	339.8	−0.912	2.506	1.964	587	0.188	6.13
160	0.0122	0.001 458	25.903	−153.1	350.4	−0.784	2.363	1.996	478	0.183	5.21
170	0.0309	0.001 483	10.842	−133.1	361.2	−0.663	2.245	2.020	397	0.178	4.50
180	0.0697	0.001 508	5.080	−112.7	372.1	−0.547	2.147	2.044	334.5	0.173	3.95
190	0.1425	0.001 535	2.613	−92.2	383.1	−0.436	2.066	2.067	286.1	0.168	3.52
200	0.2686	0.001 563	1.452	−71.4	394.2	−0.329	1.999	2.094	244.9	0.162	3.17
210	0.4727	0.001 593	0.860	−50.3	405.3	−0.226	1.943	2.128	212.7	0.157	2.88
220	0.7849	0.001 624	0.538	−28.8	416.3	−0.127	1.896	2.162	187.0	0.152	2.66
225.5[b]	1.0133	0.001 642	0.4241	−16.9	422.2	−0.073	1.874	2.182	175.0	0.149	2.56
230	1.2401	0.001 657	0.3515	−7.0	427.1	−0.030	1.857	2.199	166.2	0.147	2.49
240	1.8775	0.001 693	0.2388	15.3	437.8	0.064	1.825	2.243	149.2	0.142	2.36
250	2.7401	0.001 732	0.1674	38.0	448.2	0.157	1.797	2.298	135.0	0.137	2.26
260	3.8737	0.001 774	0.1206	61.3	458.2	0.247	1.774	2.369	123.0	0.131	2.22
270	5.3269	0.001 820	0.0888	85.2	467.8	0.336	1.753	2.418	112.9	0.126	2.17
280	7.1499	0.001 872	0.0666	109.9	476.9	0.425	1.735	2.494	106.6	0.121	2.20
290	9.3954	0.001 929	0.0507	135.3	485.3	0.512	1.719	2.584	100.0	0.116	2.23
300	12.12	0.001 995	0.0390	161.6	492.8	0.600	1.704	2.693	93.0	0.112	2.24
310	15.38	0.002 071	0.0303	189.0	499.3	0.688	1.688	2.842	85.6	0.109	2.23
320	19.23	0.002 162	0.0236	217.7	504.3	0.776	1.672	3.007	77.8	0.104	2.25
330	23.75	0.002 273	0.0184	248.2	507.4	0.867	1.652	3.335	69.6	0.097	2.39
340	29.01	0.002 418	0.0142	280.9	507.6	0.961	1.627	3.723	61.0	0.090	2.52
350	35.12	0.002 628	0.0107	317.6	502.8	1.062	1.592	4.669		0.082	
360	42.20	0.003 038	0.0075	364.1	486.0	1.188	1.527				
365.6[c]	46.65	0.004 476	0.0045	433.3	433.3	1.374	1.374				

t = triple point; b = normal boiling point; c = critical point. The notation 9.54.–9 signifies 9.54×10^{-9}. $h_f = s_f = 0$ at 233.15 K = −40°C. Converted from Angus, S., B. Armstrong, et al., *Intnl. Thermodynamic Properties of the Fluid State—7. Propylene (Propene) R1270*, Pergamon Press, Oxford, 1980 (401 pp.).

TABLE 2-299 Compressed Propylene (Propene, R1270)

Pressure, bar		Temperature, K									
		225	250	275	300	325	350	375	400	425	450
1	v (m^3/kg)	0.00164	0.4817	0.5334	0.5846	0.6354	0.6858	0.7361	0.7861	0.8361	0.8859
	h (kJ/kg)	−17.9	455.5	491.2	529.1	569.1	611.4	656.0	702.8	751.9	803.2
	s (kJ/kg·K)	−0.0779	2.0169	2.1530	2.2847	2.4128	2.5380	2.6610	2.7821	2.9010	3.0183
10	v (m^3/kg)	0.00164	0.00173	0.00184	0.04986	0.05670	0.06295	0.06889	0.07460	0.08014	0.08557
	h (kJ/kg)	−17.2	38.5	97.6	501.2	547.0	593.2	640.8	689.7	740.6	793.3
	s (kJ/kg·K)	−0.0810	0.1535	0.3788	1.7631	1.9653	2.0466	2.1774	2.3042	2.4273	2.5480
20	v (m^3/kg)	0.00163	0.00172	0.00184	0.00198	0.02324	0.02773	0.03149	0.03489	0.03803	0.04104
	h (kJ/kg)	−16.3	39.3	98.1	161.5	512.7	568.2	621.5	673.5	726.5	781.5
	s (kJ/kg·K)	−0.0841	0.1497	0.3736	0.5941	1.6920	1.8567	2.0024	2.1381	2.2674	2.3923
40	v (m^3/kg)	0.00163	0.00172	0.00182	0.00196	0.00216	0.00256		0.01465	0.01682	0.01872
	h (kJ/kg)	−14.4	40.8	99.0	161.3	230.0	313.3		633.6	695.4	755.6
	s (kJ/kg·K)	−0.0908	0.1419	0.3638	0.5806	0.8001	1.0466		1.9256	2.0758	2.2131
60	v (m^3/kg)	0.00162	0.00171	0.00181	0.00194	0.00211	0.00240		0.00743	0.00944	0.01126
	h (kJ/kg)	−12.6	42.3	100.1	161.5	228.2	303.8		575.4	656.7	726.1
	s (kJ/kg·K)	−0.0970	0.1345	0.3546	0.5684	0.7816	1.0055		1.7272	1.9250	2.0832
80	v (m^3/kg)	0.00162	0.00170	0.00180	0.00192	0.00208	0.00231		0.00402	0.00605	0.00757
	h (kJ/kg)	−10.7	44.0	101.3	162.0	227.2	299.0		499.7	607.7	693.3
	s (kJ/kg·K)	−0.1031	0.1274	0.3458	0.5570	0.7657	0.9781		1.5107	1.7795	1.9693
100	v (m^3/kg)	0.00161	0.00169	0.00179	0.00190	0.00204	0.00224	0.00256	0.00316	0.00426	0.00551
	h (kJ/kg)	−8.8	45.6	102.6	162.7	226.7	296.1	373.5	464.9	567.8	660.1
	s (kJ/kg·K)	−0.1091	0.1202	0.3374	0.5466	0.7514	0.9570	1.1704	1.4061	1.6456	1.8669
150	v (m^3/kg)	0.00160	0.00167	0.00176	0.00186	0.00198	0.00214	0.00234	0.00262	0.00300	0.00354
	h (kJ/kg)	−4.1	49.9	106.1	165.0	227.0	292.8	362.9	438.5	519.5	604.6
	s (kJ/kg·K)	−0.1236	0.1038	0.3180	0.5228	0.7214	0.9163	1.1100	1.3049	1.5021	1.6958
200	v (m^3/kg)	0.00159	0.00166	0.00174	0.00183	0.00194	0.00207	0.00222	0.00242	0.00266	0.00296
	h (kJ/kg)	0.8	54.4	110.0	167.9	228.7	292.3	359.2	429.9	504.4	581.4
	s (kJ/kg·K)	−0.1371	0.0884	0.3004	0.5021	0.6963	0.8852	1.0701	1.2521	1.4319	1.6086
300	v (m^3/kg)	0.00157	0.00163	0.00170	0.00178	0.00187	0.00197	0.00208	0.00221	0.00236	0.00253
	h (kJ/kg)	10.9	63.8	118.5	175.2	234.2	295.5	359.3	425.7	494.4	565.6
	s (kJ/kg·K)	−0.1625	0.0601	0.2688	0.4660	0.6549	0.8367	1.0127	1.1839	1.3507	1.5133
400	v (m^3/kg)	0.00155	0.00161	0.00167	0.00174	0.00182	0.00190	0.00199	0.00209	0.00220	0.00232
	h (kJ/kg)	21.2	73.6	127.7	183.6	241.5	301.5	363.7	428.0	494.4	562.9
	s (kJ/kg·K)	−0.1863	0.0347	0.2407	0.4351	0.6207	0.7985	0.9705	1.1362	1.2972	1.4536
500	v (m^3/kg)	0.00153	0.00159	0.00165	0.00171	0.00178	0.00185	0.00193	0.00201	0.00210	0.00220
	h (kJ/kg)	31.6	83.7	137.3	192.6	249.8	309.0	370.1	433.3	498.7	565.4
	s (kJ/kg·K)	−0.2082	0.0112	0.2155	0.4080	0.5910	0.7664	0.9351	1.0981	1.2559	1.4092

Converted and interpolated from Angus, S., B. Armstrong, et al., *International Thermodynamic Tables of the Fluid State—7. Propylene,* Pergamon, Oxford, 1980 (401 pp.).

The 1993 ASHRAE *Handbook—Fundamentals* (SI ed.) has a thermodynamic chart for pressures from 0.1 to 1000 bar for temperatures up to 580 K. Saturation and superheat tables and a diagram to 30,000 psia, 580°F appear in Stewart, R. B., R. T. Jacobsen, et al., *Thermodynamic Properties of Refrigerants,* ASHRAE, Atlanta, GA, 1986 (521 pp.). For specific heat, thermal conductivity, and viscosity, see *Thermophysical Properties of Refrigerants,* ASHRAE, 1993.

TABLE 2-300 Saturated Refrigerant 11*

T, K	P, bar	v_f, m^3/kg	v_g, m^3/kg	h_f, kJ/kg	h_g, kJ/kg	s_f, kJ/(kg·K)	s_g, kJ/(kg·K)	c_{pf}, kJ/(kg·K)	μ_f, 10^{-4} Pa·s	k_f, W/(m·K)
200	0.0043	5.901.–4	28.06	–14.37	186.30	–0.0651	0.9431	0.815	1.674	0.115
220	0.0417	6.061.–4	6.272	–8.20	195.89	–0.0361	0.8925	0.828	1.142	0.110
240	0.0768	6.225.–4	1.882	4.97	205.85	0.0210	0.8581	0.842	0.831	0.104
260	0.2215	6.398.–4	0.703	21.01	216.06	0.0851	0.8353	0.856	0.635	0.098
270	0.3514	6.491.–4	0.458	29.53	221.23	0.1172	0.8272	0.863	0.563	0.095
280	0.5364	6.587.–4	0.309	38.25	226.40	0.1489	0.8209	0.870	0.504	0.093
290	0.7917	6.688.–4	0.216	47.10	231.58	0.1799	0.8160	0.878	0.454	0.090
300	1.1341	6.794.–4	0.154	56.06	236.73	0.2102	0.8124	0.887	0.413	0.087
310	1.5821	6.908.–4	0.113	65.10	241.83	0.2397	0.8099	0.897	0.377	0.084
320	2.1556	7.027.–4	0.0847	74.22	246.88	0.2686	0.8081	0.907	0.346	0.081
330	2.876	7.156.–4	0.0645	83.42	251.84	0.2967	0.8071	0.917	0.320	0.079
340	3.764	7.293.–4	0.0500	92.72	256.69	0.3243	0.8065	0.928	0.297	0.076
350	4.845	7.442.–4	0.0392	102.12	261.40	0.3513	0.8064	0.939	0.276	0.073
360	6.142	7.603.–4	0.0311	111.64	265.95	0.3778	0.8065	0.950	0.259	0.070
380	9.487	7.974.–4	0.0201	131.12	274.40	0.4298	0.8069	0.975	0.229	0.065
400	14.02	8.435.–4	0.0134	151.38	281.69	0.4808	0.8066	1.004	0.203	0.059
420	19.98	9.042.–4	0.0090	172.76	287.20	0.5317	0.8041	1.04	0.169	0.053
440	27.65	9.930.–4	0.0059	196.01	289.72	0.5840	0.7970	1.09	0.131	0.048
460	37.36	1.167.–3	0.0036	223.85	285.36	0.6435	0.7773	1.19	0.084	0.037
471.2^c	44.09	1.799.–3	0.0018	258.70	258.70	0.7162	0.7162	∞	0.033	∞

*Values reproduced or converted from Table 1, p. 17.75, *ASHRAE Handbook, 1981: Fundamentals,* American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, 1981. Copyright material. Reproduced by permission of the copyright owner. c = critical point. The notation 5.901.–4 signifies 5.901×10^{-4}. The 1993 ASHRAE *Handbook—Fundamentals* (SI ed.) gives material for integral degrees Celsius with temperatures on the ITS 90 scale. For experimental isochores for the compressed liquid from 12 to 301 bar, 254 to 453 K, see Blanke, W. and R. Weiss, *PTB Bericht W 30,* Braunschweig, Germany, 1992 (54 pp.). Equations and constants approximated to 1985 ASHRAE tables are given by Mecarik, K. and M. Masaryk, *Heat Recovery Systems and CHP,* **11,** 2/3 (1991): 193–197. For tables and a chart to 3000 psia, 460°F, see Stewart, R. B., R. T. Jacobsen, et al., *Thermodynamic Properties of Refrigerants,* ASHRAE, Atlanta, GA, 1986 (521 pp.). For similar material to 80 bar, 650 K, see Reynolds, W. C., *Thermodynamic Properties in S.I.,* Stanford Univ. publ., 1979 (173 pp.). For specific heat at constant pressure, thermal conductivity, and viscosity in both SI and fps units, see Liley, P. E., *Thermophysical Properties of Refrigerants,* ASHRAE, Atlanta, GA, 1993.

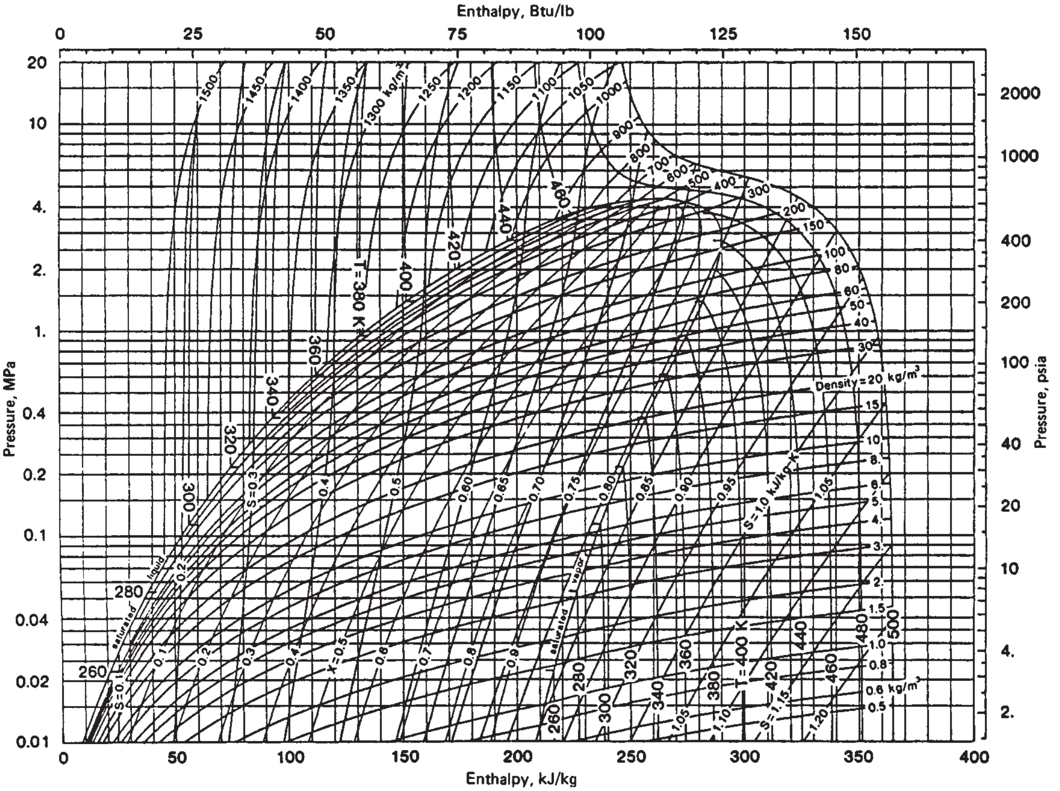

FIG. 2-18 Enthalpy–log-pressure diagram for Refrigerant 11. 1 MPa = 10 bar. (*Copyright 1981 by the American Society of Heating, Refrigerating and Air-Conditioning Engineers and reproduced by permission of the copyright owner.*) This chart, redrawn with a different zero point and temperatures in Celsius, appears in ASHRAE *Handbook—Fundamentals* (SI ed.), Atlanta, GA, 1993.

TABLE 2-301 Saturated Refrigerant 12[*]

T, K	P, bar	v_f, m^3/kg	v_g, m^3/kg	h_f, kJ/kg	h_g, kJ/kg	s_f, kJ/(kg·K)	s_g, kJ/(kg·K)	c_{pf}, kJ/(kg·K)	μ_f, 10^{-4} Pa·s	k_f, W/(m·K)
150	0.00091	5.767.–4	179.12	294.6	496.0	3.492	4.835	0.808	18.9	0.123
160	0.00305	5.849.–4	36.05	302.3	500.2	3.543	4.780	0.817	15.1	0.119
170	0.00871	5.926.–4	13.40	310.3	504.5	3.591	4.734	0.827	12.1	0.116
180	0.02178	6.024.–4	5.666	318.3	508.9	3.637	4.696	0.836	9.69	0.113
190	0.04877	6.118.–4	2.665	326.5	513.5	3.681	4.665	0.845	7.94	0.109
200	0.0996	6.217.–4	1.370	334.8	518.1	3.724	4.640	0.855	6.64	0.105
210	0.1879	6.139.–4	0.7589	343.2	522.7	3.765	4.620	0.864	5.65	0.102
220	0.3317	6.431.–4	0.4476	351.8	527.4	3.805	4.603	0.873	4.88	0.098
230	0.5531	6.549.–4	0.2784	360.6	531.1	3.844	4.590	0.882	4.26	0.094
240	0.8781	6.675.–4	0.1811	369.5	536.8	3.881	4.579	0.891	3.77	0.090
250	1.3359	6.810.–4	0.1225	378.0	541.5	3.918	4.570	0.902	3.37	0.087
260	1.959	6.970.–4	0.08559	387.7	546.1	3.954	4.563	0.913	3.03	0.083
270	2.784	7.112.–4	0.06147	397.0	550.7	3.989	4.558	0.926	2.75	0.080
280	3.825	7.282.–4	0.04543	406.5	555.1	4.023	4.554	0.942	2.52	0.076
290	5.184	7.470.–4	0.03888	416.1	559.4	4.057	4.551	0.959	2.31	0.072
300	6.840	7.678.–4	0.02582	426.0	563.5	4.090	4.548	0.979	2.14	0.069
310	8.860	7.912.–4	0.01992	436.0	567.3	4.122	4.546	1.005	2.00	0.065
320	11.29	8.173.–4	0.01553	446.2	570.9	4.154	4.543	1.041	1.86	0.061
330	14.17	8.478.–4	0.01218	456.8	574.0	4.186	4.541	1.093	1.74	0.058
340	17.58	8.840.–4	0.00957	467.8	576.5	4.218	4.538	1.166	1.60	0.054
350	21.57	9.286.–4	0.00750	479.4	578.2	4.250	4.533	1.264	1.45	0.050
360	26.19	9.868.–4	0.00582	492.1	578.7	4.285	4.525	1.39	1.28	0.046
370	31.56	1.072.–3	0.00439	506.4	577.2	4.322	4.514	1.55	1.06	0.041
380	37.76	1.237.–3	0.00305	524.7	571.2	4.369	4.900		0.75	
385[c]	41.31	1.876.–3	0.00188	551.1	551.1	4.437	4.437	∞	0.31	∞

[*] P, v, h, and s data interpolated from Perelshteyn (ed.), *Tables and Diagrams of the Thermodynamic Properties of Refrigerants 12, 13, and 22,* Moscow, 1971. c_p, μ, and k data interpolated and converted from *Thermophysical Properties of Refrigerants,* American Society of Heating, Refrigerating and Air-Conditioning Engineers, New York, 1976. c = critical point. The notation 5.767.–4 signifies 5.767×10^{-4}.

TABLE 2-302 Saturated Refrigerant 13[*]

T, K	P, bar	v_f, m^3/kg	v_g, m^3/kg	h_f, kJ/kg	h_g, kJ/kg	s_f, kJ/(kg·K)	s_g, kJ/(kg·K)	c_{pf}, kJ/(kg·K)	μ_f, 10^{-4} Pa·s	k_f, W/(m·K)
91	3.817.–6	5.367.–4	19557	238.1	424.9	3.080	5.133			
100	3.418.–5	5.448.–4	2392	243.8	429.0	3.140	4.990			
110	2.563.–4	5.538.–4	347.0	251.1	433.1	3.205	4.860			
120	0.00137	5.635.–4	70.25	258.2	437.2	3.267	4.759			
130	0.00571	5.739.–4	18.15	265.8	441.3	3.327	4.677			
140	0.01895	5.850.–4	5.865	273.7	455.3	3.385	4.610			
150	0.05250	5.969.–4	2.2617	281.7	449.3	3.441	4.558	0.826	6.83	0.114
160	0.1258	6.095.–4	1.0019	290.0	453.5	3.494	4.516	0.845	5.60	0.109
170	0.2680	6.231.–4	0.4962	298.4	457.6	3.545	4.482	0.865	4.59	0.104
180	0.5186	6.380.–4	0.2689	307.1	461.8	3.594	4.454	0.884	3.83	0.099
190	0.9269	6.536.–4	0.1567	315.9	465.9	3.642	4.431	0.898	3.26	0.093
200	1.5507	6.709.–4	9.69.–2	325.0	469.9	3.688	4.413	0.910	2.82	0.088
210	2.456	6.899.–4	6.28.–2	334.3	473.8	3.732	4.397	0.924	2.48	0.083
220	3.712	7.110.–4	4.24.–2	343.8	477.5	3.777	4.385	0.943	2.20	0.078
230	5.396	7.346.–4	2.95.–2	353.6	481.0	3.820	4.374	0.972	1.97	0.072
240	7.589	7.615.–4	2.11.–2	363.5	484.1	3.862	4.364	1.014	1.79	0.067
250	10.37	7.928.–4	1.53.–2	373.9	486.1	3.903	4.355	1.072	1.63	0.062
260	13.85	8.302.–4	1.13.–2	384.7	489.1	3.944	4.346	1.151	1.50	0.057
270	18.13	8.769.–4	8.28.–3	396.2	490.5	3.986	4.336	1.255	1.34	0.051
280	23.32	9.320.–4	6.10.–3	408.8	490.6	4.029	4.323	1.386	1.14	0.045
290	29.57	1.035.–3	4.34.–3	423.6	488.3	4.080	4.303	1.549	0.87	0.038
300	37.05	1.284.–3	2.60.–3	445.3	477.5	4.151	4.257	1.75	0.52	
302.0[c]	38.70	1.808.–3	1.81.–3	463.1	463.1	4.209	4.209	∞	0.29	∞

[*] P, v, h, and s data interpolated from Perelshteyn (ed.), *Tables and Diagrams of the Thermodynamic Properties of Refrigerants 12, 13 and 22,* Moscow, 1971. c_p, μ, and k data interpolated and converted from *Thermophysical Properties of Refrigerants,* American Society of Heating, Refrigerating and Air-Conditioning Engineers, New York, 1976. c = critical point. The notation 3.817.–6 signifies 3.817×10^{-6}. The 1993 ASHRAE *Handbook—Fundamentals* (SI ed.) contains a table at closer temperature increments and also an enthalpy–log-pressure diagram from 0.1 to 70 bar, −100 to 240°C. Equations and constants approximated to 1985 ASHRAE tables are given by Mecarik, K. and M. Masaryk, *Heat Recovery Systems and CHP,* **11,** 2/3 (1991): 193–197. Saturation and superheat tables and a diagram to 60 bar, 600 K are given by Reynolds, W. C., *Thermodynamic Properties in SI,* Stanford Univ. publ., 1979 (173 pp.). For tables and a chart to 1000 psia, 520°F, see Stewart, R. B., R. T. Jacobsen, et al., *Thermodynamic Properties of Refrigerants,* ASHRAE, Atlanta, GA, 1986 (521 pp.). For specific heat, thermal conductivity, and viscosity, see *Thermophysical Properties of Refrigerants,* ASHRAE, 1993.

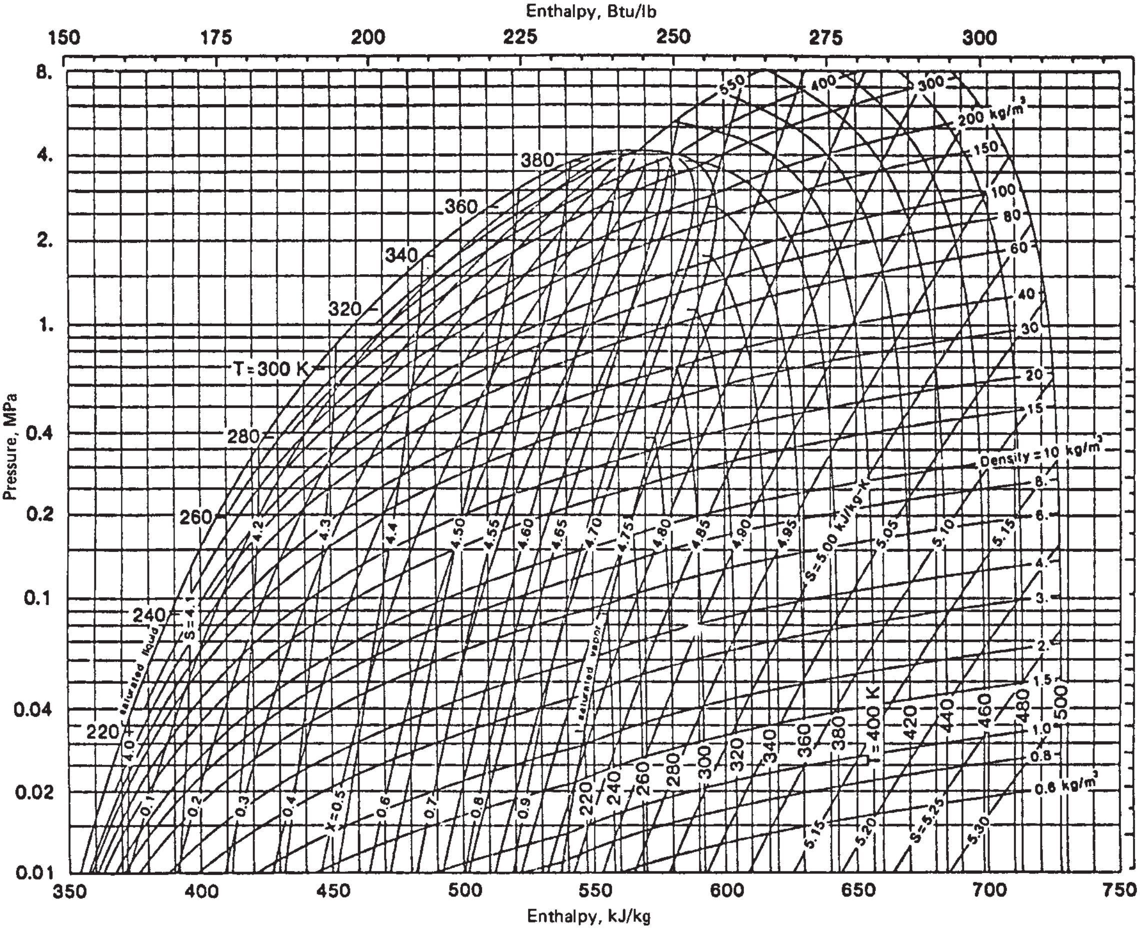

FIG. 2-19 Enthalpy–log-pressure diagram for Refrigerant 12. 1 MPa = 10 bar. (*Copyright 1981 by the American Society of Heating, Refrigerating and Air-Conditioning Engineers and reproduced by permission of the copyright owner.*) This chart, redrawn for integral Celsius temperatures with a different zero point, appears on p. 17.4 of the 1993 ASHRAE *Handbook—Fundamentals* (SI ed.). This handbook gives material for integral degrees Celsius with temperatures on the ITS 90 scale. For experimental isochores for the compressed liquid from 10 to 302 bar, 122 to 462 K, see Blanke, W. and R. Weiss, *PTB Bericht W30,* Braunschweig, Germany, 1992 (54 pp.). Equations and constants approximated to 1985 ASHRAE tables are given by Mecarik, K. and M. Masaryk, *Heat Recovery Systems and CHP,* **11,** 2/3 (1991): 193–197. Tables at 2°C increments to 240°C, 50 bar are given by Watson, J. T. R., *Thermophysical Properties of Refrigerant 12,* H.M.S.O., Edinburgh, Scotland, 1975 (183 pp.). Saturation and superheat tables and a diagram to 40 bar, 620 K are given by Reynolds, W. C., *Thermodynamic Properties in S.I.,* Stanford Univ., 1979 (173 pp.). Tables and a chart to 1100 psia, 480°F are given by Stewart, R. B., R. T. Jacobsen, et al., *Thermodynamic Properties of Refrigerants,* ASHRAE, Atlanta, GA 1986 (521 pp.). For specific heat, thermal conductivity, and viscosity, see *Thermophysical Properties of Refrigerants,* ASHRAE, 1993.

TABLE 2-303 Saturated Refrigerant 13B1*

T, K	P, bar	v_f, m^3/kg	v_g, m^3/kg	h_f, kJ/kg	h_g, kJ/kg	s_f, kJ/(kg·K)	s_g, kJ/(kg·K)	c_{pf}, kJ/(kg·K)	μ_f, 10^{-4} Pa·s	k_f, W/(m·K)
170	0.059	4.594.–4	1.6015	–40.90	90.95	–0.2033	0.5723	0.597	9.54	0.101
180	0.127	4.677.–4	0.7840	–34.75	94.37	–0.1682	0.5491	0.618	7.60	0.096
190	0.250	4.765.–4	0.4190	–28.51	97.83	–0.1345	0.5305	0.634	6.20	0.091
200	0.455	4.860.–4	0.2407	–22.17	101.32	–0.1020	0.5154	0.648	5.13	0.086
210	0.777	4.961.–4	0.1467	–15.68	104.82	–0.0704	0.5033	0.663	4.33	0.082
215.4	1.013	5.020.–4	0.1147	–12.09	106.70	–0.0536	0.4978	0.670	3.97	0.079
220	1.254	5.071.–4	0.0940	–9.02	108.28	–0.0396	0.4936	0.676	3.71	0.077
230	1.933	5.190.–4	0.0628	–2.19	111.68	–0.0094	0.4857	0.690	3.22	0.073
240	2.863	5.321.–4	0.0433	4.83	114.99	0.0202	0.4793	0.703	2.83	0.068
250	4.096	5.466.–4	0.0308	12.03	118.16	0.0494	0.4739	0.721	2.51	0.063
260	5.690	5.627.–4	0.0224	19.44	121.16	0.0781	0.4693	0.742	2.25	0.059
270	7.703	5.809.–4	0.0166	27.06	123.93	0.1064	0.4652	0.767	2.04	0.054
280	10.20	6.018.–4	0.0124	34.94	126.41	0.1345	0.4612	0.800	1.84	0.049
290	13.25	6.264.–4	0.0094	43.11	128.51	0.1625	0.4570	0.842	1.69	0.045
300	16.91	6.562.–4	0.0072	51.68	130.09	0.1908	0.4522	0.891	1.57	0.040
310	21.28	6.940.–4	0.0055	60.81	130.97	0.2197	0.4460	0.951	1.45	0.035
320	26.44	7.458.–4	0.0041	70.80	130.76	0.2503	0.4376	1.09	1.26	0.030
330	32.48	8.295.–4	0.0030	82.42	128.59	0.2845	0.4245	1.29	0.99	0.026
340.2^c	39.64	1.344.–3	0.0013	108.70	108.70	0.3605	0.3605	∞	0.35	∞

*Values reproduced or converted from Table 4, p. 17.83, *ASHRAE Handbook, 1981: Fundamentals,* American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, 1981. Copyright material. Reproduced by permission of the copyright owner. c = critical point. The notation 4.594.–4 signifies 4.594×10^{-4}.

The 1993 ASHRAE *Handbook—Fundamentals* (SI ed.) contains a table at closer temperature increments and also an enthalpy–log-pressure diagram from 0.1 to 35 bar, –80 to 220°C. For tables and a chart to 500 psia, 480°F, see Stewart, R. B., R. T. Jacobsen, et al., *Thermodynamic Properties of Refrigerants,* ASHRAE, Atlanta, GA, 1986 (521 pp.). For specific heat, thermal conductivity, and viscosity, see *Thermophysical Properties of Refrigerants,* ASHRAE, 1993.

Refrigerant 14 (tetrafluoromethane) See Carbon Tetrafluoride (Table 2-245).

Refrigerant 20 See Chloroform (Table 2-248).

TABLE 2-304 Saturated Refrigerant 21

Temperature, K	Pressure, bar	v_f, m^3/kg	v_g, m^3/kg	h_f, kJ/kg	h_g, kJ/kg	s_f, kJ/(kg·K)	s_g, kJ·(kg·K)
250	0.2415	0.000 677	0.8292	16.6	274.8	0.0687	1.1015
260	0.3953	0.000 687	0.5247	26.5	279.9	0.1076	1.0820
270	0.6200	0.000 698	0.3455	36.6	284.9	0.1454	1.0653
280	0.9364	0.000 709	0.2355	46.7	290.0	0.1824	1.0511
290	1.3682	0.000 722	0.1654	57.1	295.0	0.2186	1.0389
300	1.9417	0.000 735	0.1192	67.7	300.0	0.2543	1.0286
310	2.6849	0.000 748	0.0879	78.4	304.8	0.2894	1.0196
320	3.6279	0.000 763	0.0661	89.5	309.5	0.3242	1.0119
330	4.8022	0.000 778	0.0505	100.7	314.1	0.3586	1.0051
340	6.2409	0.000 794	0.0391	112.3	318.4	0.3927	0.9989
350	7.978	0.000 812	0.0307	124.1	322.4	0.4266	0.9932
360	10.049	0.000 830	0.0243	136.2	326.1	0.4602	0.9877
370	12.489	0.000 850	0.0194	148.6	329.3	0.4935	0.9820
380	15.337	0.000 870	0.0155	161.2	331.9	0.5264	0.9758
390	18.630	0.000 893	0.0125	173.9	333.8	0.5587	0.9688
400	22.41	0.000 918	0.01011	186.4	334.8	0.5896	0.9605
410	26.72	0.000 944	0.00820	198.3	334.7	0.6180	0.9506
420	31.60	0.000 972	0.00672	208.7	333.7	0.6418	0.9394
430	37.10	0.001 002	0.00564	216.4	332.4	0.6587	0.9286
440	43.26	0.001 034	0.00491	221.1	332.3	0.6682	0.9208

Reproduced and rounded from unpublished Center for Applied Thermodynamic Studies, Moscow ID report, 1981. For a thermodynamic diagram to 350 bar, 370°C, see Rombusch, U. K., *Allgem. Warme.*, **11,** 3 (1962).

TABLE 2-305 Saturated Refrigerant 22*

T, K	P, bar	v_f, m³/kg	v_g, m³/kg	h_f, kJ/kg	h_g, kJ/kg	s_f, kJ/(kg·K)	s_g, kJ/(kg·K)	c_{pf}, kJ/(kg·K)	μ_f, 10^{-4} Pa·s	k_f, W/(m·K)
150	0.0017	6.209.–4	83.40	268.2	547.3	3.355	5.215	1.059		0.161
160	0.0054	6.293.–4	28.20	278.2	552.1	3.430	5.141	1.058		0.156
170	0.0150	6.381.–4	10.85	288.3	557.0	3.494	5.075	1.057	0.770	0.151
180	0.0369	6.474.–4	4.673	298.7	561.9	3.551	5.013	1.058	0.647	0.146
190	0.0821	6.573.–4	2.225	308.6	566.8	3.605	4.963	1.060	0.554	0.141
200	0.1662	6.680.–4	1.145	318.8	571.6	3.657	4.921	1.065	0.481	0.136
210	0.3116	6.794.–4	0.6370	329.1	576.5	3.707	4.885	1.071	0.424	0.131
220	0.5470	6.917.–4	0.3772	339.7	581.2	3.756	4.854	1.080	0.378	0.126
230	0.9076	7.050.–4	0.2352	350.6	585.9	3.804	4.828	1.091	0.340	0.121
240	1.4346	7.195.–4	0.1532	361.7	590.5	3.852	4.805	1.105	0.309	0.117
250	2.174	7.351.–4	0.1037	373.0	594.9	3.898	4.785	1.122	0.282	0.112
260	3.177	7.523.–4	0.07237	384.5	599.0	3.942	4.768	1.143	0.260	0.107
270	4.497	7.733.–4	0.05187	396.3	603.0	3.986	4.752	1.169	0.241	0.102
280	6.192	7.923.–4	0.03803	408.2	606.6	4.029	4.738	1.193	0.225	0.097
290	8.324	8.158.–4	0.02838	420.4	610.0	4.071	4.725	1.220	0.211	0.092
300	10.956	8.426.–4	0.02148	432.7	612.8	5.113	4.713	1.257	0.198	0.087
310	14.17	8.734.–4	0.01643	445.5	615.1	4.153	4.701	1.305	0.186	0.082
320	18.02	9.096.–4	0.01265	458.6	616.7	4.194	4.688	1.372	0.176	0.077
330	22.61	9.535.–4	9.753.–3	472.4	617.3	4.235	4.674	1.460	0.167	0.072
340	28.03	1.010.–3	7.479.–3	487.2	616.5	4.278	4.658	1.573	0.151	0.067
350	34.41	1.086.–3	5.613.–3	503.7	613.3	4.324	4.637	1.718	0.130	0.062
360	41.86	1.212.–3	4.036.–3	523.7	605.5	4.378	4.605	1.897	0.106	
369.3^c	49.89	2.015.–3	2.015.–3	570.0	570.0	4.501	4.501	∞		

*P, v, h, and s data interpolated from Perelshteyn (ed.), *Tables and Diagrams of the Thermodynamic Properties of Refrigerants 12, 13 and 22,* Moscow, 1971. c_p, μ, and k data interpolated and converted from *Thermophysical Properties of Refrigerants,* American Society of Heating, Refrigerating and Air-Conditioning Engineers, New York, 1976. c = critical point. The notation 6.209.–4 signifies 6.209×10^{-4}. The 1993 ASHRAE *Handbook—Fundamentals* (SI ed.) gives a saturation table from –150 to 96.14°C and an enthalpy–log-pressure diagram from 0.1 to 150 bar, –60 to 200°C. For experimental isochores for the compressed liquid from 12 to 297 bar, 120 to 378 K, see Blanke, W. and R. Weiss, *PTB Bericht W 30,* Braunschweig, Germany, 1992 (54 pp.). Equations and constants approximated to 1985 ASHRAE tables are given by Mecarik, K. and M. Masaryk, *Heat Recovery Systems and CHP,* **11** 2/3 (1991): 193–197. Saturation and superheat tables and a diagram to 100 bar, 620 K are given by Reynolds, W. C., *Thermodynamic Properties in S.I.,* Stanford Univ. publ., 1979 (179 pp.). For tables and a chart to 2000 psia, 480°F, see Stewart, R. B., R. T. Jacobsen, et al., *Thermodynamic Properties of Refrigerants,* ASHRAE, Atlanta, GA, 1986 (521 pp.). For specific heat, thermal conductivity, and viscosity, see *Thermophysical Properties of Refrigerants,* ASHRAE, 1993.

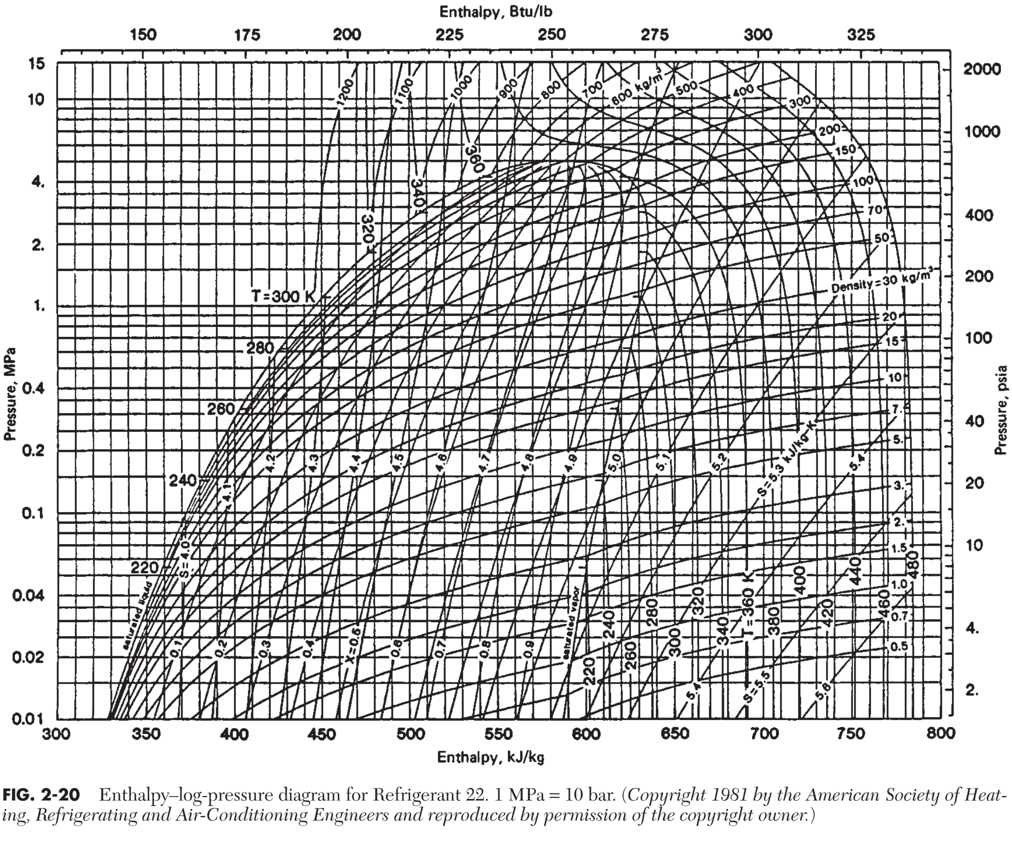

FIG. 2-20 Enthalpy–log-pressure diagram for Refrigerant 22. 1 MPa = 10 bar. (*Copyright 1981 by the American Society of Heating, Refrigerating and Air-Conditioning Engineers and reproduced by permission of the copyright owner.*)

TABLE 2-306 Thermophysical Properties of Compressed R22

Pressure, bar	Property	Temperature, K 275	300	325	350	375	400	425	450
1	c_p (kJ/kg·K)	0.639	0.653	0.689	0.714	0.739	0.758	0.781	0.806
	μ (10^{-6} Pa·s)	11.8	12.8	13.9	14.9	15.8	16.7	17.7	18.7
	k (W/m·K)	0.0091	0.0106	0.0121	0.0136	0.0151	0.0166	0.0181	0.0196
	Pr	0.829	0.793	0.787	0.782	0.773	0.762	0.765	0.769
5	c_p (kJ/kg·K)	0.725	0.728	0.744	0.759	0.766	0.775	0.791	0.816
	μ (10^{-6} Pa·s)	11.8	12.8	13.8	15.0	16.2	17.0	18.0	18.8
	k (W/m·K)	0.0096	0.0107	0.0123	0.0138	0.0153	0.0170	0.0184	0.0199
	Pr	0.887	0.871	0.852	0.839	0.803	0.775	0.773	0.771
10	c_p (kJ/kg·K)	1.166	0.847	0.810	0.799	0.797	0.803	0.814	0.828
	μ (10^{-6} Pa·s)	211	13.7	14.4	15.1	16.1	17.1	18.1	19.0
	k (W/m·K)	0.0954	0.0121	0.0128	0.0144	0.0160	0.0175	0.0190	0.0205
	Pr	2.58	0.959	0.901	0.838	0.802	0.785	0.775	0.767
20	c_p (kJ/kg·K)	0.164	1.237		0.949	0.889	0.865	0.858	0.859
	μ (10^{-6} Pa·s)	211	159		16.5	17.3	18.0	18.8	19.6
	k (W/m·K)	0.0963	0.0849		0.0157	0.0172	0.0184	0.0199	0.0214
	Pr	2.55	2.32		0.997	0.894	0.846	0.811	0.787
40	c_p (kJ/kg·K)	1.152	1.217	1.359		1.373	1.089	0.996	0.956
	μ (10^{-6} Pa·s)	218	164	123		20.7	20.5	20.7	21.2
	k (W/m·K)	0.0980	0.0872	0.0767		0.0219	0.0210	0.0217	0.0233
	Pr	2.56	2.29	2.18		1.30	1.063	0.950	0.870
60	c_p (kJ/kg·K)	1.142	1.191	1.311	1.460		1.767	1.221	1.089
	μ (10^{-6} Pa·s)	221	170	128	94.6		24.7	24.2	23.9
	k (W/m·K)	0.0993	0.0889	0.0786			0.0305	0.0287	0.0268
	Pr	2.54	2.28	2.14			1.431	1.030	0.971
80	c_p (kJ/kg·K)	1.132	1.177	1.277	1.444	1.861		1.396	1.262
	μ (10^{-6} Pa·s)	226	175	133	101	73.6		29.9	27.7
	k (W/m·K)	0.1003	0.0904	0.0803	0.0690	0.0523		0.0374	0.0337
	Pr	2.55	2.28	2.12	2.12	2.62		1.12	1.04
100	c_p (kJ/kg·K)	1.122	1.154	1.247	1.361	1.564	2.073	1.923	1.471
	μ (10^{-6} Pa·s)	230	179	138	108	83.2	55.5	37.6	32.4
	k (W/m·K)	0.1013	0.0916	0.0817	0.0716	0.0607	0.0504	0.0421	0.0378
	Pr	2.55	2.26	2.11	2.04	2.14	2.28	1.72	1.26

Some values are approximate as significant differences exist in the literature.

TABLE 2-307 Saturated Refrigerant 23

Temp., K	Pressure, bar	v_f, m^3/kg	v_g, m^3/kg	h_f, kJ/kg	h_g, kJ/kg	s_f, kJ/(kg·K)	s_g, kJ/(kg·K)	c_{pf}, kJ/(kg·K)	μ_f, 10^{-6} Pa·s	k_f, W/(m·K)	Pr
180	0.510	0.000 678	0.4088	−66.0	181.1	−0.3179	1.0549				
190	0.950	0.000 693	0.2279	−54.4	185.3	−0.2554	1.0062				
191.1^b	1.013	0.000 695	0.2139	−53.1	185.7	−0.2485	1.0011				
200	1.652	0.000 710	0.1353	−42.6	189.1	−0.1948	0.9635				
210	2.709	0.000 729	0.0845	−30.3	192.4	−0.1353	0.9254				
220	4.298	0.000 751	0.0551	−17.5	195.4	−0.0764	0.8913				
230	6.312	0.000 777	0.0372	−4.3	197.8	−0.0182	0.8602	0.710	170.1	0.105	1.15
240	9.091	0.000 807	0.0259	9.4	199.6	0.0392	0.8314	1.043	150.4	0.098	1.56
250	12.69	0.000 844	0.0183	23.6	200.7	0.0957	0.8042	1.289	131.2	0.091	1.85
260	17.25	0.000 889	0.0132	38.1	200.9	0.1512	0.7773	1.497	113.0	0.084	2.00
270	22.94	0.000 948	0.0095	53.5	199.8	0.2071	0.7493				
280	29.98	0.001 031	0.0068	70.5	196.4	0.2665	0.7162				
290	38.68	0.001 169	0.0046	92.0	188.1	0.3387	0.6698				
299.1^c	48.36	0.001 905	0.0019	143.0	143.0	0.5062	0.5062				

b = normal boiling point; c = critical point. $h_f = s_f = 0$ at 233.15 K = −40°C. Interpolated and converted from ASHRAE *Handbook—Fundamentals,* 1993. Experimental P–ρ–T data from 95 to 413 K reported in *J. Phys. Chem.,* **89** (1985): 4637–4646 were used by Rubio, R. G., J. A. Zollweg, et al., *J. Chem. Eng. Data,* **36,** (1991): 171–184, to calculate properties up to 1000 bar from 126 to 332° K.

The 1993 ASHRAE *Handbook—Fundamentals* (SI ed.) gives a saturation table from −100 to 25.92°C and an enthalpy–log-pressure diagram from 0.1 to 80 bar, −100 to 280°C. Equations and constants approximated to the 1985 ASHRAE tables are given by Mecaryk, K. and M. Masaryk, *Heat Recovery Systems and CHP,* **11,** 2/3 (1991): 193–197.

For an enthalpy–log-pressure diagram from 0.005 to 200 bar, −140 to 180°C, see Morsy, T. E., *Kaltetechnik—Klimat.,* **18,** 9 (1966): 347–349. Saturation and superheat tables and a diagram to 100 bar, 600 K are given by Reynolds, W. C., *Thermodynamic Properties in S.I.,* Stanford Univ. publ., 1979 (173 pp.).

For tables and a chart to 1000 psia, 560°F, see Stewart, R. B., R. T. Jacobsen, et al., *Thermodynamic Properties of Refrigerants,* ASHRAE, Atlanta, GA, 1986 (21 pp.). For specific heat, thermal conductivity, and viscosity, see *Thermophysical Properties of Refrigerants,* ASHRAE, 1993.

TABLE 2-308 Thermophysical Properties of Saturated Difluoromethane (R32)

Temp., K	Pressure, bar	v_f, m^3/kg	v_g, m^3/kg	h_f, kJ/kg	h_g, kJ/kg	s_f, kJ/(kg·K)	s_g, kJ/(kg·K)	c_{pf}, kJ/(kg·K)	c_{pg}, kJ/(kg·K)	μ_f, 10^{-6} Pa·s	μ_g, 10^{-6} Pa·s	k_f, W/(m·K)	k_g, W/(m·K)	Pr_f	Pr_g
200	0.2960	7.845.–4	1.0580	–52.340	351.160	–0.2418	1.7757								
210	0.5440	8.025.–4	0.5990	–37.750	356.880	–0.1652	1.7098								
220	0.9384	8.208.–4	0.3593	–20.690	361.970	–0.0909	1.6485	1.557	0.799	283.8	10.30				
230	1.5345	8.402.–4	0.2261	–4.984	366.773	–0.0215	1.5948	1.580	0.839	247.8	10.37				
240	2.3963	8.611.–4	0.1483	10.947	371.129	0.0459	1.5468	1.613	0.894	220.4	10.46				
250	3.5966	8.842.–4	0.1005	27.1778	374.971	0.1117	1.5030	1.642	0.963	198.1	10.66	0.1646	0.0097	1.98	1.06
260	5.2160	9.096.–4	0.07020	43.786	378.224	0.1763	1.4624	1.682	1.043	177.9	10.95	0.1562	0.0106	1.92	1.08
270	7.3423	9.376.–4	0.05009	60.849	380.786	0.2397	1.4247	1.730	1.138	159.1	11.31	0.1487	0.0115	1.85	1.12
280	10.070	9.696.–4	0.03643	78.456	382.525	0.3029	1.3886	1.786	1.244	141.8	11.70	0.1403	0.0125	1.81	1.16
290	13.502	1.006.–3	0.02687	96.713	383.262	0.3654	1.3534	1.863	1.375	126.1	12.21	0.1308	0.0136	1.80	1.23
300	17.749	1.049.–3	0.02001	115.754	382.737	0.4283	1.3182	1.955	1.560	112.0	12.82	0.1228	0.0149	1.78	1.34
310	22.931	1.100.–3	0.01497	135.801	380.576	0.4919	1.2815	2.084	1.810	98.8	13.71	0.1155	0.0165	1.78	1.50
320	29.186	1.166.–3	0.01117	157.212	376.163	0.5574	1.2415	2.282	2.16	86.1	14.4	0.1073	0.0184	1.83	1.69
330	36.675	1.243.–3	0.00822	180.724	368.357	0.6264	1.1950	2.620	2.62	75.1	15.3	0.0990	0.0205	1.99	1.96
340	45.603	1.394.–3	0.00581	208.262	354.460	0.7047	1.1347	3.560	4.21	65.4	17.3		0.0236		3.10
350	56.336		0.00317	274.640	337.933	0.8927	1.0735								
351.4^c	57.927	0.00237	0.00237	286.675	286.675	0.9269	0.9269								

c = critical point. The notation 7.845.–4 signifies 7.845×10^{-4}. P, v, T, h, s, and c_p converted and extrapolated from Defibaugh, D. R., G. Morrison, et al., *J. Chem. Eng. Data,* **39** (1994): 333–340. Saturated liquid and vapor viscosities from smooth curve fits of Oliveira, C. M. B. P. and W. A. Wakeham, *Int. J. Thermophys.,* **14,** 6 (1993): 1131–1143. Thermal conductivity values based upon papers by Geller, V. Z. and M. E. Perlaitis, and by Gross, *Proc. 10th Symp. Thermophys. Props.,* Boulder, CO, 1994.

The 1993 ASHRAE *Handbook—Fundamentals* (SI ed.) gives a saturation table to 78.41°C and a diagram to 200 bar, 200°C.

TABLE 2-309 Specific Heat at Constant Pressure, Thermal Conductivity, Viscosity, and Prandtl Number of R32 Gas

Temp., K	Property	*P*, bar							
		1	5	10	15	20	25	30	40
250	c_p (kJ/kg·K)	0.805							
	μ (10^{-6} Pa·s)	10.55							
	k (W/m·K)	0.0094							
	Pr	0.908							
260	c_p (kJ/kg·K)	0.810	1.025						
	μ (10^{-6} Pa·s)	11.00	10.96						
	k (W/m·K)	0.0100	0.0104						
	Pr	0.890	1.080						
270	c_p (kJ/kg·K)	0.818	0.991						
	μ (10^{-6} Pa·s)	11.42	11.37						
	k (W/m·K)	0.0107	0.0111						
	Pr	0.873	1.015						
280	c_p (kJ/kg·K)	0.825	0.969	1.238					
	μ (10^{-6} Pa·s)	11.82	11.77	11.68					
	k (W/m·K)	0.0116	0.0118	0.0125					
	Pr	0.860	0.967	1.157					
290	c_p (kJ/kg·K)	0.837	0.959	1.161					
	μ (10^{-6} Pa·s)	12.28	12.22	12.17					
	k (W/m·K)	0.0121	0.0125	0.0131					
	Pr	0.849	0.938	1.079					
300	c_p (kJ/kg·K)	0.849	0.951	1.118	1.370				
	μ (10^{-6} Pa·s)	12.70	12.69	12.66	12.62				
	k (W/m·K)	0.0128	0.0132	0.0138	0.0144				
	Pr	0.842	0.914	1.026	1.201				
310	c_p (kJ/kg·K)	0.861	0.945	1.084	1.279	1.560			
	μ (10^{-6} Pa·s)	13.12	13.10	13.08	13.07	13.09			
	k (W/m·K)	0.0135	0.0139	0.0144	0.0150	0.0159			
	Pr	0.878	0.891	0.985	1.114	1.284			
320	c_p (kJ/kg·K)	0.873	0.944	1.059	1.207	1.400	1.704		
	μ (10^{-6} Pa·s)	13.54	13.54	13.55	13.56	13.60	13.75		
	k (W/m·K)	0.0142	0.0146	0.0150	0.0156	0.0164	0.0173		
	Pr	0.836	0.875	0.957	1.049	1.161	1.354		
330	c_p (kJ/kg·K)	0.885	0.942	1.038	1.158	1.301	1.508	1.837	
	μ (10^{-6} Pa·s)	13.96	13.96	13.98	14.01	14.15	14.28	14.52	
	k (W/m·K)	0.0148	0.0152	0.0156	0.0162	0.0169	0.0177	0.0187	
	Pr	0.834	0.865	0.930	1.001	1.089	1.217	1.426	
340	c_p (kJ/kg·K)	0.897	0.937	1.020	1.135	1.242	1.388	1.612	2.488
	μ (10^{-6} Pa·s)	14.38	14.40	14.43	14.47	14.53	14.65	14.85	16.00
	k (W/m·K)	0.0155	0.0159	0.0163	0.0168	0.0175	0.0182	0.0190	0.0217
	Pr	0.832	0.849	0.903	0.978	1.031	1.117	1.260	1.834
350	c_p (kJ/kg·K)	0.910	0.934	1.004	1.118	1.200	1.308	1.440	1.914
	μ (10^{-6} Pa·s)	14.80	14.82	14.84	14.87	14.92	15.06	15.21	16.16
	k (W/m·K)	0.0162	0.0165	0.0169	0.0174	0.0180	0.0186	0.0194	0.0216
	Pr	0.831	0.839	0.882	0.955	0.995	1.060	1.130	1.432

Some values read from charts may be approximate. c_p values interpolated and converted from *Thermodynamic Properties of KLEA 32*, I.C.I., 1993 (47 pp.). Viscosity interpolated from Takahashi, M., C. Yokoyama, et al., *Proc. 14th Symp. Thermophys. Props.*, Japan, 1993 (pp. 427–430). Thermal conductivities are taken from Geller, V. Z. and M. E. Perlaitis, and from Gross, *Proc. 10th Symp. Thermophys. Props.*, Boulder, CO, 1994.

TABLE 2-310 Saturated SUVA MP 39

Temp., °C	P_f, bar	P_g, bar	v_f, m^3/kg	v_g, m^3/kg	h_f, kJ/kg	h_g, kJ/kg	s_f, kJ/(kg·K)	s_g, kJ/(kg·K)	c_{pf}, kJ/(kg·K)	μ_f, 10^{-6} Pa·s	k_f, W/(m·K)	Pr_f
−40	0.733	0.533	0.000 712	0.3778	154.0	385.0	0.8188	1.8244	1.078	351	0.1209	3.13
−30	1.155	0.871	0.000 728	0.2391	164.9	390.6	0.8647	1.8059	1.109	323	0.1154	3.06
−20	1.748	1.361	0.000 744	0.1576	176.2	396.3	0.9099	1.7907	1.137	291	0.1107	2.99
−10	2.553	2.043	0.000 762	0.1075	188.6	401.8	0.9577	1.7781	1.165	266	0.1057	2.93
0	3.615	2.965	0.000 781	0.0755	200.0	407.3	1.0000	1.7675	1.197	241	0.1012	2.85
10	4.984	4.177	0.000 803	0.0544	212.7	412.6	1.0454	1.7587	1.233	221	0.0967	2.82
20	6.712	5.733	0.000 826	0.0399	225.3	417.6	1.0884	1.7510	1.277	202	0.0922	2.80
30	8.857	7.697	0.000 851	0.0298	238.3	422.2	1.1316	1.7439	1.329	186	0.0877	2.83
40	11.475	10.133	0.000 878	0.0225	252.0	426.5	1.1752	1.7372	1.392	170	0.0830	2.85
50	14.628	13.112	0.000 909	0.0172	266.4	430.1	1.2194	1.7304	1.468	157	0.0781	2.95
60	18.378	16.711	0.000 944	0.01313	281.6	433.0	1.2647	1.7228	1.564	143	0.0737	3.04
70	22.79	21.01	0.000 988	0.01005	297.9	434.9	1.3118	1.7138	1.652	131	0.0684	3.16
80	27.92	26.12	0.001 028	0.00764	315.9	435.4	1.3616	1.7022	1.802	122	0.0631	3.48
90	33.83	32.13	0.001 084	0.00570	336.2	433.5	1.4163	1.6858	1.958	115	0.0577	3.90
100	40.53	39.22	0.001 140	0.00403	361.4	426.9	1.4820	1.6584	2.16	110	0.0533	4.46
108.0^c	46.04	46.04	0.001 96	0.00196	397	397						

c = critical point. SUVA MP 39 = R401A = $CHClF_2$ (R22) 53% wt + CH_3CHF_2 (R 152a) 13% wt + $CHClFCF_3$ (R124) 34% wt, near-azeotropic blend. Some values read from charts are approximate. Material used by permission of DuPont Fluoroproducts.

TABLE 2-311 SUVA MP 39 at Atmospheric Pressure

Temp., °C	−27.01	−20	0	20	40	60	80	100	120	140
v (m^3/kg)	0.2102	0.2167	0.2351	0.2534	0.2715	0.2896	0.3076	0.3256	0.3435	0.3613
h (kJ/kg)	351.7	396.9	410.4	424.5	439.2	454.4	470.3	486.6	503.5	521.2
s (kJ/kg·K)	1.8009	1.8193	1.8706	1.9204	1.9689	2.0161	2.0623	2.1073	2.1513	2.1943
c_p (kJ/kg·K)	0.648	0.669	0.698	0.727	0.757	0.787	0.811	0.836	0.859	0.883
μ (10^{-6} Pa·s)	10.17	10.43	11.18	11.93	12.68	13.42	14.17	14.89	15.61	16.32
k (W/m·K)	0.00878	0.00921	0.01041	0.01161	0.01282	0.01404	0.01536	0.01668	0.01796	0.01929
Pr	0.750	0.758	0.750	0.749	0.749	0.748	0.748	0.748	0.747	0.747
Z	0.9829	0.9852	0.9906	0.9949	0.9979	1.0005	1.0025	1.0043	1.0056	1.0060

For composition see footnote to Table 2-310. Some values read from charts are approximate. Material used by permission of DuPont Fluoroproducts.

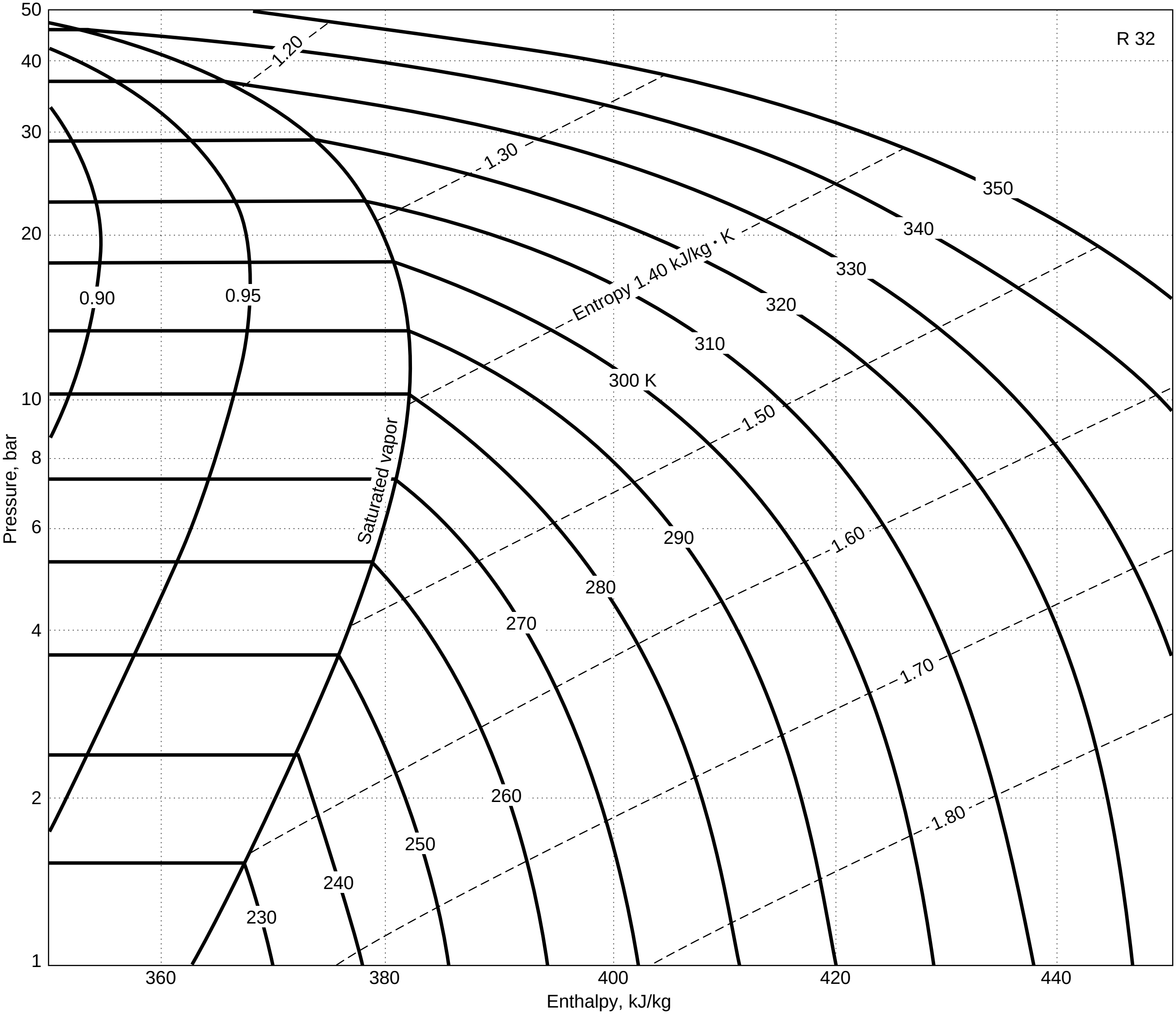

FIG. 2-21 Enthalpy–log-pressure diagram for Refrigerant 32.

TABLE 2-312 Thermodynamic Properties of Saturated KLEA 60

Pressure, bar	T_f, K	T_g, K	v_f, m^3/kg	v_g, m^3/kg	h_f, kJ/kg	h_g, kJ/kg	s_f, kJ/(kg·K)	s_g, kJ/(kg·K)
1	227.3	234.0	0.000 7118	0.2097	–7.80	229.64		0.9965
1.5	236.1	242.5	0.000 7263	0.1433	3.92	235.02		0.9833
2	242.8	249.1	0.000 7381	0.1093	12.89	239.07		0.9744
2.5	248.3	254.5	0.000 7483	0.0885	20.27	242.35		0.9679
3	253.0	259.1	0.000 7573	0.0744	26.57	245.08		0.9629
4	260.7	266.8	0.000 7735	0.0564	37.23	249.54		0.9552
5	267.3	273.1	0.000 7880	0.0442	46.12	253.07		0.9496
6	272.9	278.5	0.000 8012	0.0384	53.84	255.24		0.9450
8	282.1	287.5	0.000 8254	0.0286	67.02	260.70		0.9378
10	289.8	295.0	0.000 8480	0.0228	78.23	263.86		0.9318
12.5	297.9	302.8	0.000 8750	0.01802	90.50	266.95		0.9257
15	304.8	309.5	0.000 9017	0.01481	101.51	269.12		0.9190
17.5	311.0	315.4	0.000 9290	0.01247	111.64	270.58		0.9128
20	316.5	320.7	0.000 9613	0.01069	121.18	271.46		0.9065
22.5	321.4	325.5	0.000 9884	0.00928	130.31	271.79		0.8999
25	326.1	329.8	0.001 023	0.00828	139.17	271.63		0.8927
27.5	330.4	333.9	0.001 063	0.00717	147.89	270.97		0.8850
30	334.5	337.6	0.001 115	0.00635	156.58	269.81		0.8765

$h_f = s_f = 0$ at 233.15 K = –40°C. Converted and interpolated from *Thermodynamic Properties of Klea 60* (British units, 20 pp.), copyright ICI Chemicals and Polymers Limited, 1993. Reproduced by permission. T_f = bubble point temperature; T_g = dew point temperature.

TABLE 2-313 Thermodynamic Properties of Saturated KLEA 61

Pressure, bar	T_f, K	T_g, K	v_f, m^3/kg	v_g, m^3/kg	h_f, kJ/kg	h_g, kJ/kg	s_f, kJ/(kg·K)	s_g, kJ/(kg·K)
1	225.6	230.0	0.000 6852	0.1800	–9.45	191.64		0.8433
1.5	234.3	238.5	0.000 6994	0.1230	2.52	196.90		0.8341
2	241.8	245.0	0.000 7110	0.0937	9.72	200.88		0.8282
2.5	246.4	250.4	0.000 7211	0.0758	16.59	204.10		0.8245
3	251.1	254.9	0.000 7301	0.0637	22.47	206.80		0.8215
4	258.9	262.6	0.000 7463	0.04831	32.43	211.22		0.8172
5	265.4	269.0	0.000 7607	0.03888	40.76	214.74		0.8141
6	270.9	274.4	0.000 7740	0.03249	48.00	217.65		0.8123
8	280.2	283.4	0.000 7985	0.02435	59.82	222.21		0.8080
10	287.8	290.9	0.000 8214	0.01936	70.98	225.63		0.8048
12.5	295.8	298.7	0.000 8491	0.01528	82.59	228.80		0.8010
15	302.8	305.5	0.000 8768	0.01251	93.02	231.08		0.7971
17.5	308.8	311.4	0.000 9053	0.01049	102.67	232.64		0.7929
20	314.3	316.7	0.000 9353	0.00896	111.79	233.60		0.7882
22.5	319.3	321.5	0.000 9680	0.00774	120.55	233.99		0.7829
25	323.9	325.9	0.001 005	0.00674	129.11	233.85		0.7769
27.5	328.1	330.0	0.001 048	0.00590	137.62	233.16		0.7700
30	332.1	333.7	0.001 102	0.00518	146.21	231.84		0.7619

Converted and interpolated from *Thermodynamic Properties of Klea 61* (British units, 20 pp.), copyright ICI Chemicals and Polymers Limited, 1993. Reproduced by permission. T_f = bubble-point temperature; T_g = dew-point temperature. $h_f = s_f = 0$ at 233.15 K = –40 °C.

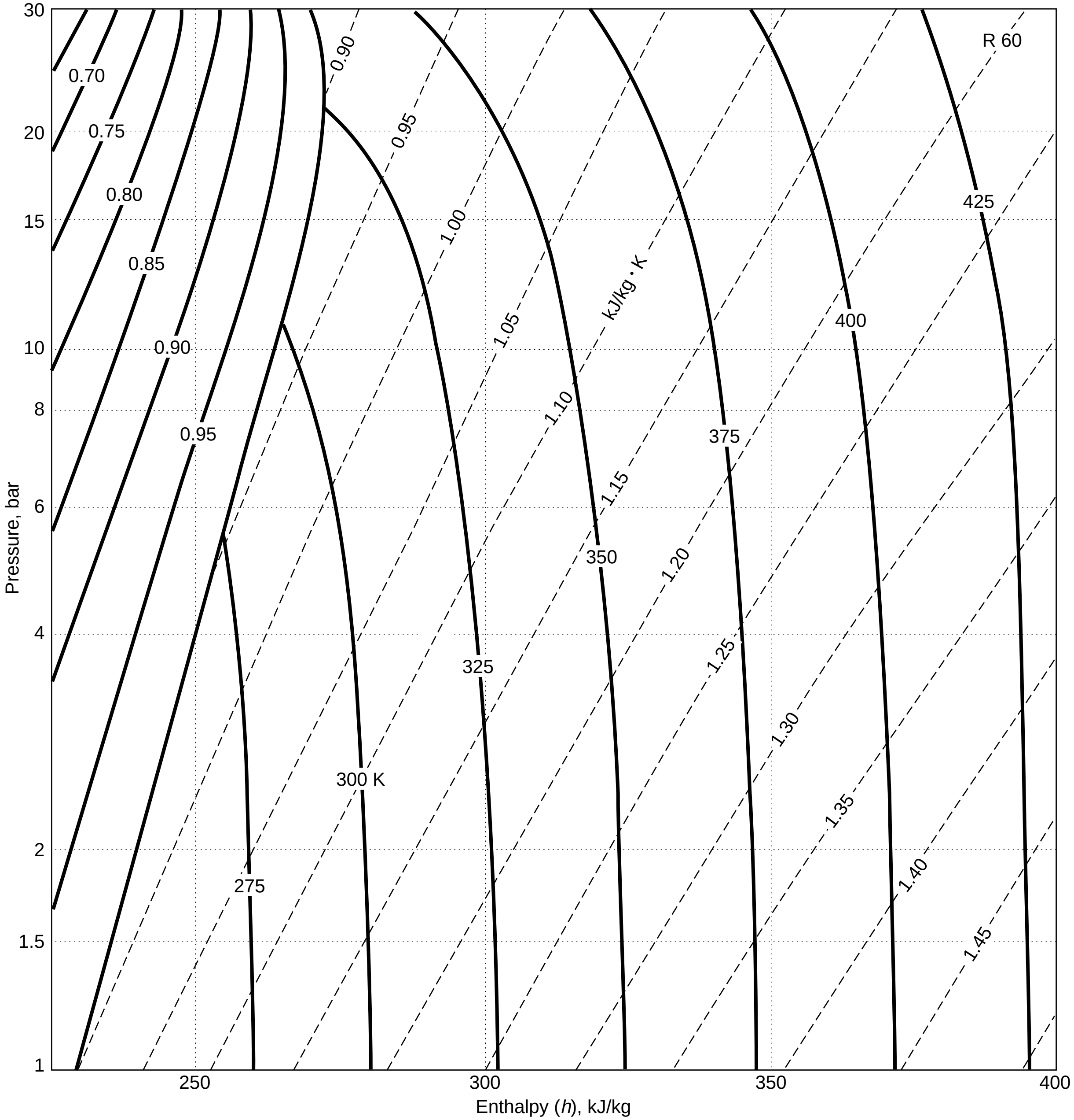

FIG. 2-22 Enthalpy–log-pressure diagram for KLEA 60.

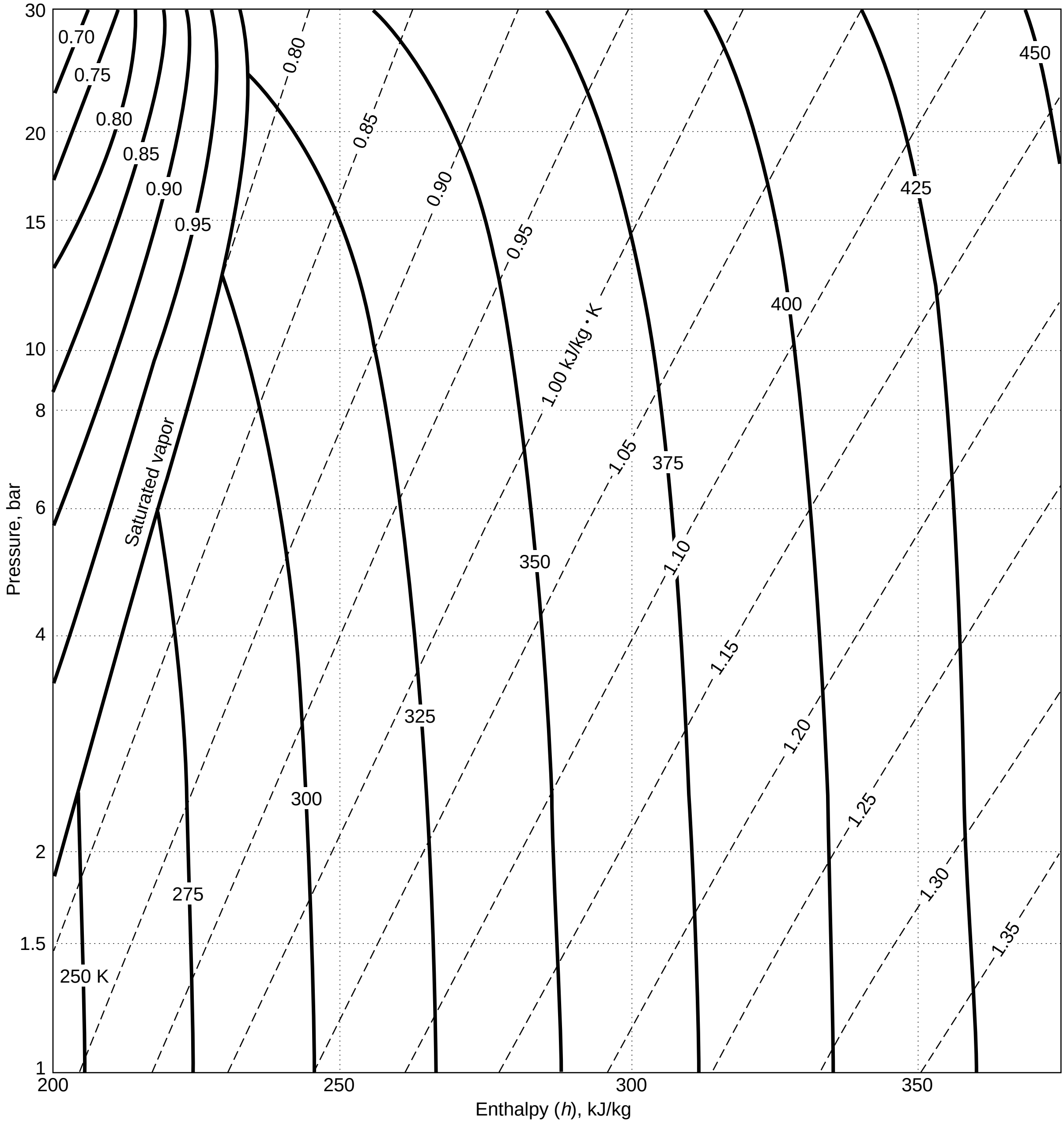

FIG. 2-23 Enthalpy–log-pressure diagram for KLEA 61.

TABLE 2-314 Saturated SUVA HP 62

Temp., °C	P_f, bar	P_g, bar	v_f, m^3/kg	v_g, m^3/kg	h_f, kJ/kg	h_g, kJ/kg	s_f, kJ/(kg·K)	s_g, kJ/(kg·K)	c_{pf}, kJ/(kg·K)	μ_f, 10^{-6} Pa·s	k_f, W/(m·K)	Pr_f
−50	0.852	0.821	0.000 761	0.2244	133.1	337.3	0.7318	1.6487		370	0.0970	
−40	1.367	1.325	0.000 779	0.1434	145.6	343.8	0.7862	1.6380		318		
−30	2.095	2.041	0.000 799	0.0953	159.9	350.3	0.8460	1.6301	1.220	276	0.0868	3.88
−20	3.087	3.018	0.000 820	0.0656	172.8	356.5	0.8975	1.6245	1.260	238	0.0834	3.60
−10	4.404	4.321	0.000 843	0.0463	186.1	362.6	0.9487	1.6202	1.302	207	0.0801	3.37
0	6.111	6.013	0.000 868	0.03338	200.0	368.3	1.0000	1.6188	1.351	181	0.0767	3.19
10	8.278	8.165	0.000 898	0.02444	214.5	373.6	1.0515	1.6138	1.412	158	0.0733	3.04
20	10.977	10.851	0.000 933	0.01809	229.9	378.3	1.1038	1.6106	1.489	138	0.0698	2.94
30	14.287	14.150	0.000 977	0.01348	246.2	382.2	1.1574	1.6065	1.592	122	0.0663	2.93
40	18.292	18.148	0.001 037	0.01003	263.8	385.0	1.2130	1.6005	1.753	106	0.0624	2.98
50	23.08	22.94	0.001 122	0.00739	283.2	386.1	1.2723	1.5910	2.09	91	0.0583	3.26
60	28.75	28.63	0.001 261	0.00527	305.8	384.2	1.3389	1.5742		76	0.0535	
70	35.58			0.00285	339.8	375.9				61		
72.1^c	37.32	37.32	0.002 06	0.00206	361	361						

c = critical point. SUVA HP 62 = CHF_2CF_3 (R125) 44% wt + CH_3CF_3 (R143a) 52% wt + CH_2FCF_3 (R134a) 4% wt, near-azeotropic blend. Material used by permission of DuPont Fluoroproducts. Some values read from charts may be approximate.

TABLE 2-315 SUVA HP 62 at Atmospheric Pressure

Temp., °C	−45.63	−40	−20	0	20	40	60	80	100	120
v (m^3/kg)	0.1866	0.1921	0.2100	0.2278	0.2455	0.2630	0.2805	0.2980	0.3153	0.3325
h (kJ/kg)	336.0	344.4	359.9	376.2	393.1	410.9	429.3	448.4	468.2	488.7
s (kJ/kg·K)	1.6599	1.6636	1.7274	1.7891	1.8491	1.9076	1.9646	2.0203	2.0747	2.1278
c_p (kJ/kg·K)	0.732	0.738	0.781	0.821	0.860	0.897	0.933	0.967	1.000	1.032
μ (10^{-6} Pa·s)	9.47	9.68	10.45	11.22	11.99	12.76	13.53	14.30	15.07	15.84
k (W/m·K)	0.00860	0.00932	0.01059	0.01186	0.01313	0.01440	0.01568	0.01695	0.01827	0.01949
Pr	0.806	0.767	0.771	0.777	0.785	0.795	0.805	0.816	0.827	0.839
Z	0.9755	0.9800	0.9867	0.9919	0.9961	0.9989	1.0014	1.0037	1.0050	1.0060

v,*h*, and *s* from DuPont bull. T—HP62—SI, June 1993 (17 pp.). c_p and *k* from DuPont bull. ART 18, June 1993 (37 pp.). Some values read from charts may be approximate. Material used by permission of DuPont Fluoroproducts.

TABLE 2-316 Thermodynamic Properties of Saturated KLEA 66

Pressure, bar	T_f, K	T_g, K	v_f, m^3/kg	v_g, m^3/kg	h_f, kJ/kg	h_g, kJ/kg	s_f, kJ/(kg·K)	s_g, kJ/(kg·K)
0.69	221.46	228.77	0.000 7122	0.31325	−16.16	241.25		1.0729
1	228.89	236.05	0.000 7237	0.22131	−5.89	245.91		1.0580
1.5	237.69	244.69	0.000 7382	0.15140	6.22	251.38		1.0430
2	244.45	251.33	0.000 7501	0.11537	15.51	255.52		1.0330
2.5	249.99	256.76	0.000 7600	0.09104	23.12	258.95		1.0258
3	254.36	261.39	0.000 7695	0.07855	29.62	261.63		1.0201
4	262.60	269.14	0.000 7857	0.05964	40.60	266.16		1.0114
5	269.12	275.51	0.000 8001	0.04806	49.74	269.74		1.0055
6	274.70	280.98	0.000 8133	0.04021	57.69	272.68		0.9993
8	284.03	290.08	0.000 8375	0.03022	71.22	277.25		0.9913
10	291.74	297.56	0.000 8599	0.02410	82.73	280.64		0.9834
12.5	299.87	305.44	0.000 8867	0.01910	95.32	283.74		0.9770
15	306.87	312.18	0.000 9131	0.01571	106.59	285.93		0.9701
17.5	313.05	318.10	0.000 9400	0.01324	116.97	287.28		0.9633
20	318.60	323.40	0.000 9680	0.01137	126.73	288.26		0.9564
22.5	323.7	328.2	0.000 9981	0.00988	136.0	288.6		0.9493
25	328.3	332.5	0.001 032	0.00883	145.1	288.4		0.9418
27.5	332.7	336.6	0.001 072	0.00766	153.9	287.8		0.9338
30	336.7	340.4	0.001 125	0.00703	162.7	286.6		0.9251

Converted and interpolated from *Thermodynamic Properties of Klea 66* (British units, 22 pp.), copyright ICI Chemicals and Polymers Limited, 1993. Reproduced by permission. T_f = bubble-point temperature; T_g = dew-point temperature. $h_f = s_f = 0$ at 233.15 K = −40°C.

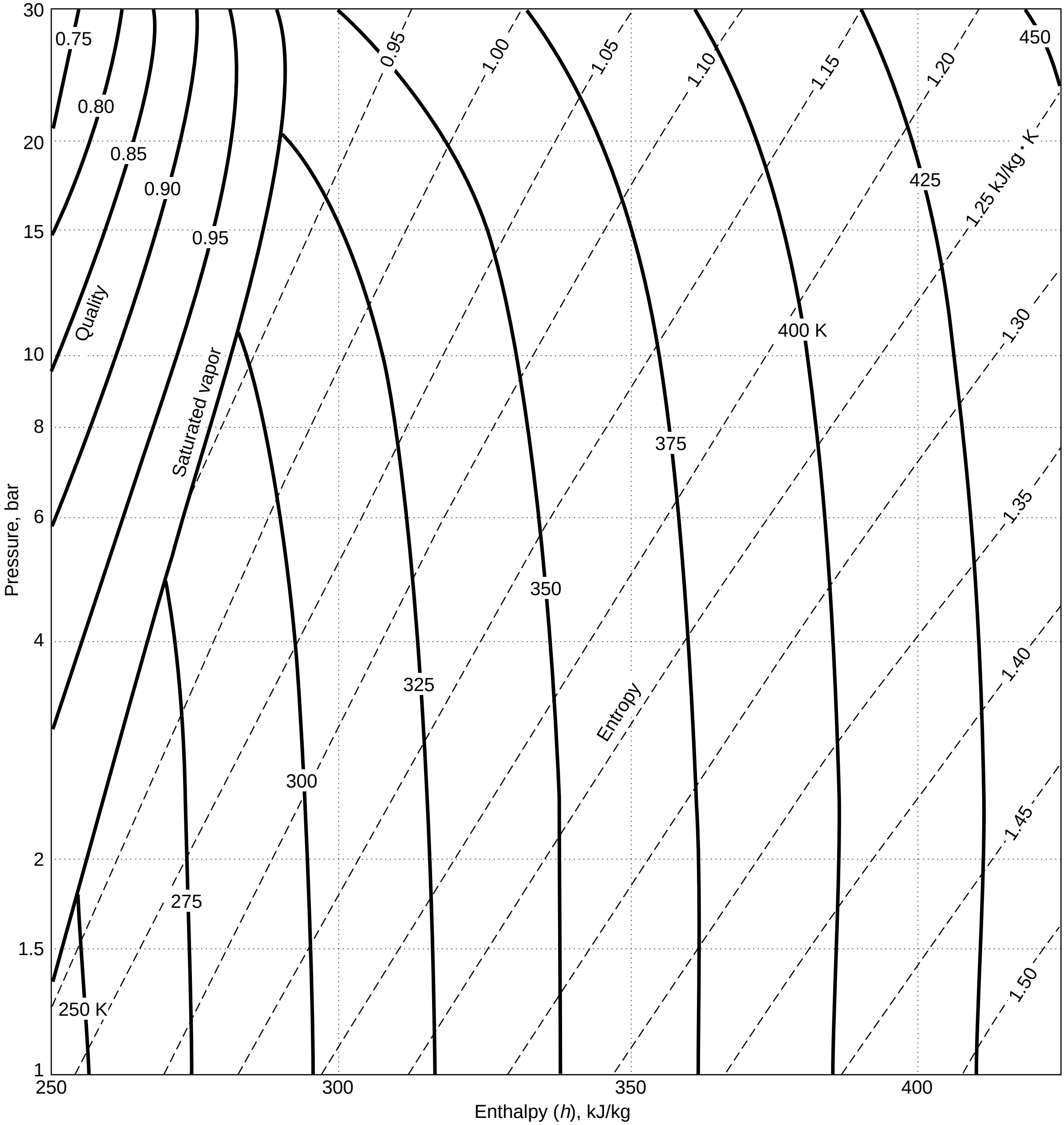

FIG. 2-24 Enthalpy–log-pressure diagram for KLEA 66.

TABLE 2-317 Saturated SUVA MP 66

Temp., °C	P_f, bar	P_g, bar	v_f, m³/kg	v_g, m³/kg	h_f, kJ/kg	h_g, kJ/kg	s_f, kJ/(kg·K)	s_g, kJ/(kg·K)	c_{pf}, kJ/(kg·K)	μ_f, 10^{-6} Pa·s	k_f, W/(m·K)	Pr_f
−40	0.788	0.585	0.000 710	0.3498	153.8	386.0	0.8184	1.8291	1.078	349	0.1209	3.11
−30	1.239	0.952	0.000 725	0.2224	164.8	391.6	0.8643	1.8100	1.109	313	0.1154	3.01
−20	1.872	1.479	0.000 740	0.1471	176.0	397.1	0.9095	1.7940	1.137	282	0.1106	2.90
−10	2.726	2.212	0.000 758	0.1008	188.6	402.6	0.9577	1.7807	1.165	257	0.1057	2.83
0	3.850	3.198	0.000 778	0.0710	200.0	407.8	1.0000	1.7694	1.197	236	0.1012	2.79
10	5.297	4.491	0.000 801	0.05124	212.6	412.9	1.0450	1.7598	1.233	217	0.0967	2.77
20	7.120	6.146	0.000 827	0.03771	225.1	417.7	1.0879	1.7512	1.277	198	0.0922	2.74
30	9.379	8.229	0.000 858	0.02818	238.2	422.1	1.1311	1.7433	1.329	181	0.0877	2.74
40	12.133	10.808	0.000 895	0.02131	251.9	426.1	1.1747	1.7357	1.392	168	0.0830	2.82
50	15.444	13.955	0.000 939	0.01625	266.3	429.4	1.2190	1.7278	1.468	151	0.0781	2.84
60	19.378	17.750	0.000 994	0.01244	281.6	431.9	1.2645	1.7191	1.564	139	0.0737	2.95
70	24.00	22.28	0.001 066	0.00951	298.1	433.4	1.3120	1.7088	1.652	127	0.0684	3.07
80	29.37	27.64	0.001 164	0.00721	316.3	433.2	1.3625	1.6956	1.802	116	0.0631	3.31
90	35.55	33.96	0.001 313	0.00534	337.2	430.4	1.4187	1.6768			0.0577	
100	42.30										0.0533	
106.1^c	46.82	46.82	0.001 95	0.00195	389	389						

c = critical point. SUVA MP 66 = R401 = $CHClF_2$ (R22) 61% wt + CH_3CHF_2 (R152a) 11% wt + $CHClFCF_3$ (R124) 28% wt, near-azeotropic blend. Material used by permission of DuPont Fluoroproducts. Some values read from charts are approximate.

TABLE 2-318 SUVA MP 66 at Atmospheric Pressure

Temp., °C	−28.63^b	−20	0	20	40	60	80	100	120	140
v (m³/kg)	0.2086	0.2177	0.2362	0.2545	0.2727	0.2908	0.3089	0.3269	0.3449	0.3629
h (kJ/kg)	392.2	397.9	411.2	425.1	439.6	454.6	470.1	486.2	502.7	519.4
s (kJ/kg·K)	1.8081	1.8299	1.8804	1.9295	1.9772	2.0237	2.0690	2.1132	2.1564	2.1986
c_p (kJ/kg·K)	0.641	0.652	0.688	0.716	0.744	0.771	0.796	0.822	0.844	0.866
μ (10^{-6} Pa·s)	9.78	10.43	11.18	11.93	12.68	13.42	14.17	14.89	15.61	16.32
k (W/m·K)	0.00817	0.00921	0.01041	0.01161	0.01282	0.01404	0.01536	0.01668	0.01796	0.01929
Pr	0.767	0.738	0.737	0.736	0.735	0.735	0.734	0.734	0.733	0.733
Z	0.9652	0.9730	0.9783	0.9822	0.9852	0.9876	0.9896	0.9912	0.9925	0.9937

v, h, and s from DuPont bull. T—MP 66—SI, Jan. 1993 (17 pp.). c_p, μ, and k from DuPont bull. ART 10, Jan. 1993 (27 pp.). Some values read from charts may be approximate. Material used by permission of DuPont Fluoroproducts. b = normal boiling point.

TABLE 2-319 Saturated SUVA HP 80

Temp., °C	P_f, bar	P_g, bar	v_f, m³/kg	v_g, m³/kg	h_f, kJ/kg	h_g, kJ/kg	s_f, kJ/(kg·K)	s_g, kJ/(kg·K)	c_{pf}, kJ/(kg·K)	μ_f, 10^{-6} Pa·s	k_f, W/(m·K)	Pr_f
−50	0.962	0.872	0.000 679	0.2033	139.6	334.1	0.7578	1.6327		377	0.0970	
−40	1.520	1.403	0.000 695	0.1303	150.8	339.9	0.8070	1.6206		317		
−30	2.305	2.156	0.000 713	0.0869	163.1	345.6	0.8584	1.6110	1.193	283	0.0880	3.84
−20	3.370	3.188	0.000 733	0.0598	174.9	351.1	0.9053	1.6034	1.217	247	0.0849	3.54
−10	4.776	4.560	0.000 757	0.0423	187.6	356.4	0.9541	1.5972	1.236	215	0.0813	3.27
0	6.588	6.336	0.000 785	0.03060	200.0	361.3	1.0000	1.5919	1.253	188	0.0778	3.03
10	8.877	8.592	0.000 819	0.02248	213.0	365.9	1.0461	1.5870	1.286	165	0.0743	2.86
20	11.720	11.404	0.000 860	0.01671	226.7	369.8	1.0927	1.5820	1.340	146	0.0708	2.76
30	15.195	14.855	0.000 911	0.01250	241.2	373.1	1.1403	1.5762	1.412	128	0.0672	2.69
40	19.388	19.034	0.000 977	0.00936	256.8	375.4	1.1897	1.5690	1.512	113	0.0634	2.70
50	24.39	24.04	0.001 070	0.00696	273.9	376.2	1.2420	1.5589	1.64	98	0.0593	2.71
60	30.30	29.97	0.001 212	0.00505	293.6	374.6	1.2998	1.5433	1.81	83	0.0551	2.79
70										68		
75.5^c	41.35	41.35	0.001 850	0.00185	340	340						

c = critical point. SUVA HP 80 = R402 = CHF_2CF_3 (R125) 60% wt + $CH_3CH_2CH_3$ (R290) 2% wt + $CHClF_2$ (R22) 38% wt, near-azeotropic blend. Material used by permission of DuPont Fluoroproducts. Some values, read from charts, may be approximate.

TABLE 2-320 SUVA HP 80 at Atmospheric Pressure

Temp., °C	−46.95[b]	−40	−20	0	20	40	60	80	100	120
v (m^3/kg)	0.1768	0.1827	0.1996	0.2164	0.2331	0.2497	0.2663	0.2828	0.2992	0.3155
h (kJ/kg)	335.9	340.5	354.3	368.6	383.5	398.7	414.9	431.4	448.5	466.1
s (kJ/kg·K)	1.6286	1.6490	1.7055	1.7599	1.8124	1.8633	1.9128	1.9610	2.0081	2.0541
c_p (kJ/kg·K)	0.648	0.654	0.687	0.721	0.749	0.779	0.807	0.836	0.863	0.890
μ (10^{-6} Pa·s)	9.42	9.69	10.45	11.22	11.99	12.75	13.52	14.29	15.06	15.82
k (W/m·K)	0.00888	0.00932	0.01059	0.01186	0.01313	0.01440	0.01568	0.01695	0.01822	0.01949
Pr	0.687	0.680	0.678	0.681	0.685	0.690	0.696	0.703	0.713	0.722
Z	0.9673	0.9697	0.9758	0.9804	0.9840	0.9868	0.9892	0.9910	0.9923	0.9932

b = normal boiling pt. v, h, and s from DuPont bull. T—HP 80—SI, Jan. 1993 (17 pp.). c_p, μ, and k from DuPont bull. ART 18, June 1993 (37 pp.). Some values read from charts may be approximate. Material used by permission of DuPont Fluoroproducts.

TABLE 2-321 Saturated SUVA HP 81

Temp., °C	P_f, bar	P_g, bar	v_f, m^3/kg	v_g, m^3/kg	h_f, kJ/kg	h_g, kJ/kg	s_f, kJ/(kg·K)	s_g, kJ/(kg·K)	c_{pf}, kJ/(kg·K)	μ_f, 10^{-6} Pa·s	k_f, W/(m·K)	Pr_f
−50	0.883	0.787	0.000 687	0.2425	140.3	351.7	0.7606	1.7122		383	0.1031	
−40	1.403	1.273	0.000 702	0.1548	151.4	357.2	0.8092	1.6957		333	0.0983	
−30	2.135	1.967	0.000 719	0.1028	163.3	362.7	0.8589	1.6820	1.178	290	0.0941	3.63
−20	3.132	2.923	0.000 739	0.0707	174.9	368.0	0.9054	1.6706	1.191	253	0.0900	3.35
−10	4.451	4.198	0.000 761	0.0499	187.8	373.0	0.9550	1.6611	1.204	223	0.0863	3.11
0	6.153	5.852	0.000 787	0.03610	200.0	377.8	1.0000	1.6528	1.221	195	0.0818	2.91
10	8.307	7.959	0.000 817	0.02656	212.7	382.2	1.0450	1.6451	1.288	173	0.0790	2.82
20	10.984	10.591	0.000 854	0.01980	226.0	386.0	1.0905	1.6376	1.313	151	0.0753	2.63
30	14.261	13.827	0.000 899	0.01490	240.1	389.3	1.1367	1.6299	1.37	137	0.0715	2.49
40	18.216	17.750	0.000 955	0.01125	255.1	391.5	1.1842	1.6211	1.75	122	0.0676	3.16
50	22.93	22.45	0.001 030	0.00848	271.4	392.8	1.2339	1.6104	2.07	106	0.0633	3.47
60	28.50	28.03	0.001 136	0.00632	289.5	392.2	1.2873	1.5961		91	0.0586	
70	35.01	34.60	0.001 307	0.00456	299.6	390.9	1.3164	1.5866		75	0.0544	
80												
82.6[c]	44.45	44.45	0.001 88	0.00188	351	351						

c = critical point. SUVA HP 81 = R402 (38/2/60) = CHF_2CF_3 (R125) 38% wt + $CH_3CH_2CH_3$ (R290) 2% wt + $CHClF_2$ (R22) 60% wt, near-azeotropic blend. Material used by permission of DuPont Fluoroproducts. Some values read from charts may be approximate.

TABLE 2-322 SUVA HP 81 at Atmospheric Pressure

Temp., °C	−44.87[b]	−40	−20	0	20	40	60	80	100	120
v (m^3/kg)	0.1903	0.1960	0.2142	0.2322	0.2500	0.2678	0.2856	0.3032	0.3209	0.3386
h (kJ/kg)	354.7	357.7	370.8	384.6	398.8	413.6	428.9	444.7	461.0	477.7
s (kJ/kg·K)	1.7032	1.7169	1.7711	1.8232	1.8735	1.9222	1.9696	2.0158	2.0607	2.1047
c_p (kJ/kg·K)	1.187	1.177	1.169	1.159	1.149	1.143	1.134	1.128	1.124	1.120
μ (10^{-6} Pa·s)	10.16	10.33	11.10	11.86	12.62	13.39	14.15	14.78	15.54	16.30
k (W/m·K)	0.00739	0.00768	0.00902	0.01036	0.01170	0.01304	0.01438	0.01572	0.01706	0.01840
Pr	1.632	1.583	1.439	1.327	1.239	1.174	1.124	1.061	1.024	0.992
Z	0.9622	0.9703	0.9766	0.9811	0.9843	0.9870	0.9894	0.9909	0.9926	0.9940

b = normal boiling point. v, h, and s from DuPont bull. T—HP 81—SI, Jan. 1993 (17 pp.). c_p, μ, and k from DuPont bull. ART 18, June 1993 (37 pp.). Some values, read from charts, may be approximate. Material used by permission of DuPont Fluoroproducts.

TABLE 2-323 Saturated Refrigerant 113*

T, K	P, bar	v_f, m^3/kg	v_g, m^3/kg	h_f, kJ/kg	h_g, kJ/kg	s_f, kJ/(kg·K)	s_g, kJ/(kg·K)	c_{pf}, kJ/(kg·K)	μ_f, 10^{-4} Pa·s	k_f, W/(m·K)
240	0.0233	5.908.–4	4.548	5.70	171.97	0.0241	0.7169	0.845	17.9	0.087
250	0.0435	5.986.–4	2.537	14.19	178.06	0.0587	0.7142	0.877	14.8	0.084
260	0.0767	6.066.–4	1.492	22.83	184.22	0.0926	0.7134	0.895	12.3	0.083
270	0.1290	6.150.–4	0.9189	31.65	190.46	0.1259	0.7141	0.916	10.4	0.081
280	0.2076	6.237.–4	0.5893	40.63	196.75	0.1585	0.7161	0.933	8.9	0.079
290	0.3217	6.328.–4	0.3917	49.77	203.08	0.1906	0.7192	0.946	7.6	0.077
300	0.4817	6.422.–4	0.2687	59.07	209.44	0.2221	0.7233	0.958	6.6	0.075
310	0.6999	6.522.–4	0.1895	68.51	215.80	0.2530	0.7281	0.971	5.9	0.073
320	0.9897	6.626.–4	0.1370	78.09	222.17	0.2833	0.7336	0.983	5.2	0.071
330	1.3657	6.737.–4	0.1012	87.80	228.53	0.3131	0.7396	0.992	4.7	0.069
340	1.8347	6.854.–4	0.0762	97.64	234.86	0.3424	0.7460	1.000	4.2	0.066
350	2.4406	6.979.–4	0.0584	107.58	241.16	0.3711	0.7528	1.013	3.8	0.065
360	3.174	7.112.–4	0.0454	117.65	247.41	0.3993	0.7598	1.029	3.4	0.062
370	4.062	7.255.–4	0.0357	127.82	253.59	0.4270	0.7669	1.042	3.2	0.060
380	5.123	7.411.–4	0.0284	138.11	259.70	0.4542	0.7742	1.059	2.9	0.058
390	6.379	7.580.–4	0.0229	148.52	265.71	0.4810	0.7815	1.084	2.7	0.056
400	7.849	7.767.–4	0.0185	159.07	271.59	0.5075	0.7888	1.109	2.46	0.054
410	9.556	7.975.–4	0.0151	169.78	277.31	0.5336	0.7958	1.14	2.28	0.052
420	11.52	8.211.–4	0.0124	180.69	282.83	0.5595	0.8027	1.18	2.10	0.050
430	13.78	8.483.–4	0.0102	191.85	288.09	0.5853	0.8091	1.22	1.93	0.047
440	16.35	8.806.–4	0.0083	203.35	292.98	0.6112	0.8149	1.27	1.75	0.045
450	19.26	9.201.–4	0.0068	215.31	297.38	0.6375	0.8198	1.32	1.58	0.042
460	22.56	9.713.–4	0.0055	227.97	301.03	0.6645	0.8234	1.38	1.33	0.039
470	26.29	1.044.–3	0.0044	241.79	303.41	0.6933	0.8244	1.45	1.07	0.035
480	30.52	1.174.–3	0.0032	258.16	303.00	0.7264	0.8198	1.54	0.77	0.031
487.5^c	34.11	1.754.–3	0.0018	288.10	288.10	0.7828	0.7828	∞	0.30	∞

*Values reproduced or converted from Table 8, p. 17.91, *ASHRAE Handbook, 1981: Fundamentals,* American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, 1981. Copyright material. Reproduced by permission of the copyright owner. c = critical point. The notation 5.908.–4 signifies 5.908×10^{-4}. The 1993 ASHRAE *Handbook—Fundamentals* (SI ed.) gives a saturation table from –30 to 214.4°C and an enthalpy–log-pressure diagram from 0.1 to 60 bar, 0 to 260°C. Equations and constants approximated to the 1985 ASHRAE tables were given by Mecaryk, K. and M. Masaryk, *Heat Recovery Systems and CHP,* **11,** 2/3 (1991): 193–197. For experimental isochores for the compressed liquid from 21 to 304 bar, 266 to 453 K, see Blanke, W. and R. Weiss, PTB Bericht W 30, Braunschweig, Germany, 1992 (54 pp.).

For tables to 300 bar, 460 K, see Geller, V. Z. and V. A. Rabinovich (ed.), *Thermophysical Properties of Substances and Materials,* Standartov, Moscow, **7** (1973): 135–154. Mastroianni, M. J., R. F. Stahl, et al., *J. Chem. Eng. Data,* **23,** 2 (1978): 113–118 give a diagram to 1000 psia, 600°F. Tables and a diagram to 800 psia, 520°F are given by Stewart, R. B., R. T. Jacobsen, et al., *Thermodynamic Properties of Refrigerants,* ASHRAE, Atlanta, GA, 1986 (521 pp.). For specific heat, thermal conductivity, and viscosity, see *Thermophysical Properties of Refrigerants,* ASHRAE, 1993.

TABLE 2-324 Saturated Refrigerant 114*

T, K	P, bar	v_f, m^3/kg	v_g, m^3/kg	h_f, kJ/kg	h_g, kJ/kg	s_f, kJ/(kg·K)	s_g, kJ/(kg·K)	c_{pf}, kJ/(kg·K)	μ_f, 10^{-4} Pa·s	k_f, W/(m·K)
190	0.0058	6.326.–4	15.823	–42.58	125.78	–0.2091	0.6794	0.765	23.9	0.093
200	0.0137	6.344.–4	7.094	–31.87	131.01	–0.1542	0.6648	0.787	18.2	0.090
210	0.029	6.366.–4	3.465	–21.48	136.41	–0.1035	0.6541	0.810	14.3	0.088
220	0.059	6.391.–4	1.822	–11.37	141.95	–0.0565	0.6466	0.831	11.5	0.085
230	0.109	6.421.–4	1.021	–1.50	147.61	–0.0126	0.6419	0.854	9.4	0.082
240	0.190	6.457.–4	0.604	8.18	153.36	0.0286	0.6393	0.877	7.9	0.080
250	0.317	6.500.–4	0.375	17.74	159.18	0.0676	0.6387	0.900	6.61	0.077
260	0.505	6.554.–4	0.2431	27.22	165.05	0.1047	0.6396	0.923	5.66	0.075
270	0.773	6.619.–4	0.1633	36.71	170.95	0.1405	0.6418	0.946	4.96	0.072
280	1.143	6.700.–4	0.1132	46.27	176.85	0.1751	0.6452	0.967	4.30	0.069
290	1.636	6.799.–4	0.0807	55.95	182.75	0.2090	0.6494	0.991	3.80	0.067
300	2.279	6.918.–4	0.0590	65.79	188.61	0.2422	0.6543	1.015	3.35	0.064
310	3.096	7.060.–4	0.0440	75.79	194.44	0.2748	0.6598	1.038	3.02	0.061
320	4.116	7.224.–4	0.0334	85.92	200.19	0.3067	0.6657	1.062	2.69	0.059
330	5.366	7.412.–4	0.0257	96.16	205.84	0.3379	0.6719	1.087	2.48	0.056
340	6.877	7.624.–4	0.0201	106.49	211.37	0.3685	0.6781	1.111	2.27	0.054
350	8.683	7.863.–4	0.0158	116.96	216.71	0.3984	0.6843	1.136	2.07	0.051
360	10.82	8.135.–4	0.0125	127.63	221.82	0.4280	0.6903	1.160	1.91	0.048
370	13.32	8.453.–4	0.0099	138.60	226.57	0.4575	0.6957	1.185	1.76	0.045
380	16.24	8.836.–4	0.0079	149.99	230.84	0.4872	0.7002	1.210	1.59	0.042
390	19.62	9.324.–4	0.0062	162.01	234.36	0.5176	0.7032	1.236	1.39	0.038
400	23.52	1.001.–3	0.0048	175.03	236.61	0.5496	0.7036	1.261	1.17	0.034
410	28.00	1.118.–3	0.0035	190.13	236.20	0.5857	0.6980	1.5	0.87	0.030
419.0^c	32.61	1.795.–3	0.0018	219.90	219.90	0.6559	0.6559	∞	0.34	∞

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Saturation and superheat tables and a diagram to 60 bar, 540 K are given by Reynolds, W. C., *Thermodynamic Properties in S.I.*, Stanford Univ. publ., 1979 (179 pp.). Tables and a chart to 1500 psia, 480°F are given by Stewart, R. B., R. T. Jacobsen, et al., *Thermodynamic Properties of Refrigerants*, ASHRAE, Atlanta, GA, 1986 (521 pp.). For specific heat, thermal conductivity, and viscosity, see *Thermophysical Properties of Refrigerants*, ASHRAE, 1993.

TABLE 2-325 Saturated Refrigerant 115*

Temp., °F	Pressure, lb/in^2 abs.	Volume, ft^3/lb		Enthalpy, Btu/lb		Entropy, Btu/(lb)(°F)	
		Liquid	Vapor	Liquid	Vapor	Liquid	Vapor
–100	2.327	0.00966	10.57	–13.07	45.83	–0.0335	0.1302
–80	4.573	0.00986	5.624	–8.78	48.39	–0.0219	0.1286
–60	8.306	0.01009	3.218	–4.43	50.96	–0.0108	0.1278
–40	14.13	0.01033	1.953	0.00	53.53	0.0000	0.1275
–20	22.74	0.01060	1.245	4.50	56.07	0.0104	0.1277
0	34.94	0.01090	0.8257	9.09	58.56	0.0206	0.1282
20	51.59	0.01123	0.5657	13.76	61.00	0.0305	0.1290
40	73.65	0.01161	0.3979	18.54	63.35	0.0401	0.1298
60	102.1	0.01204	0.2857	23.45	65.60	0.0496	0.1308
80	138.1	0.01255	0.2081	28.54	67.71	0.0591	0.1317
100	182.7	0.01316	0.1530	33.85	69.63	0.0686	0.1325
120	237.3	0.01393	0.1125	39.50	71.24	0.0782	0.1330
140	303.2	0.01496	0.0817	45.67	72.36	0.0884	0.1329
160	382.0	0.01664	0.0567	52.76	72.42	0.0996	0.1314
170	427.0	0.01838	0.0444	56.56	71.33	0.1055	0.1290
175.89^c	457.6	0.0261	0.0261	64.30	64.30	0.1175	0.1175

*Unpublished data of General Chemicals Division, Allied Chemical Company. Used by permission. c = critical temperature.

No material in SI units appears in the 1993 ASHRAE *Handbook—Fundamentals* (SI ed.). Tables and a chart to 50 ata, 200°C are given by Mathias, H. and H. J. Loffler, Techn. Univ. Berlin rept., 1966 (42 pp.). A chart to 1500 psia, 500°F was given by Mears, W. H., E. Rosenthal, et al., *J. Chem. Eng. Data,* **11,** 3 (1966): 338–343.

TABLE 2-326 Thermodynamic Properties of Refrigerant 123

Pressure, bar	Temp., K	v_f, m^3/kg	v_g, m^3/kg	h_f, kJ/kg	h_g, kJ/kg	s_f, kJ/(kg·K)	s_g, kJ/(kg·K)	c_{pf}, kJ/(kg·K)	k_f, W/(m·K)	μ_f, 10^{-6} Pa·s	Pr_f
0.1	249.49	0.000 6315	1.3430	13.25	198.51	0.0548	0.7977	0.849	0.0908	798.7	7.46
0.5	282.87	0.000 6664	0.2993	41.72	218.53	0.1610	0.7863	0.923	0.0811	503.7	5.73
1.0	300.62	0.000 6862	0.1567	58.62	229.20	0.2195	0.7869	1.000	0.0759	409.8	5.40
1.013	300.99	0.000 6868	0.1546	58.99	229.43	0.2208	0.7870	1.001	0.0758	408.1	5.39
1.5	312.25	0.000 7008	0.1070	70.51	236.52	0.2582	0.7892	1.038	0.0726	361.5	5.17
2.0	321.18	0.000 7126	0.08139	79.90	241.76	0.2877	0.7917	1.063	0.0696	329.6	5.03
2.5	328.50	0.000 7230	0.06546	87.76	246.20	0.3118	0.7942	1.079	0.0678	306.1	4.87
3.0	334.79	0.000 7323	0.05525	94.59	249.96	0.3323	0.7965	1.091	0.0660	287.4	4.75
4.0	345.29	0.000 7490	0.03836	106.16	256.17	0.3661	0.8006	1.108	0.0630	259.7	4.57
5.0	353.95	0.000 7640	0.03358	115.83	261.17	0.3935	0.8042	1.120	0.0605	239.1	4.43
6	361.41	0.000 7779	0.02799	124.23	265.34	0.4168	0.8073	1.130			
8	373.92	0.000 8038	0.02090	138.48	272.04	0.4551	0.8124	1.148			
10	384.19	0.000 8280	0.01675	150.35	277.18	0.4860	0.8162	1.168			
15	404.54	0.000 8874	0.01062	174.49	286.01	0.5462	0.8218	1.234			
20	420.30	0.000 9512	0.00751	194.19	291.01	0.5928	0.8232	1.345			
25	433.33	0.001 030	0.00549	212.00	293.05	0.6334	0.8203	1.559			
30	444.10	0.001 136	0.00408	228.26	291.27	0.6692	0.8112	2.005			
36.68*	456.83	0.001 818	0.00182	264.54	264.54	0.7393	0.7393				

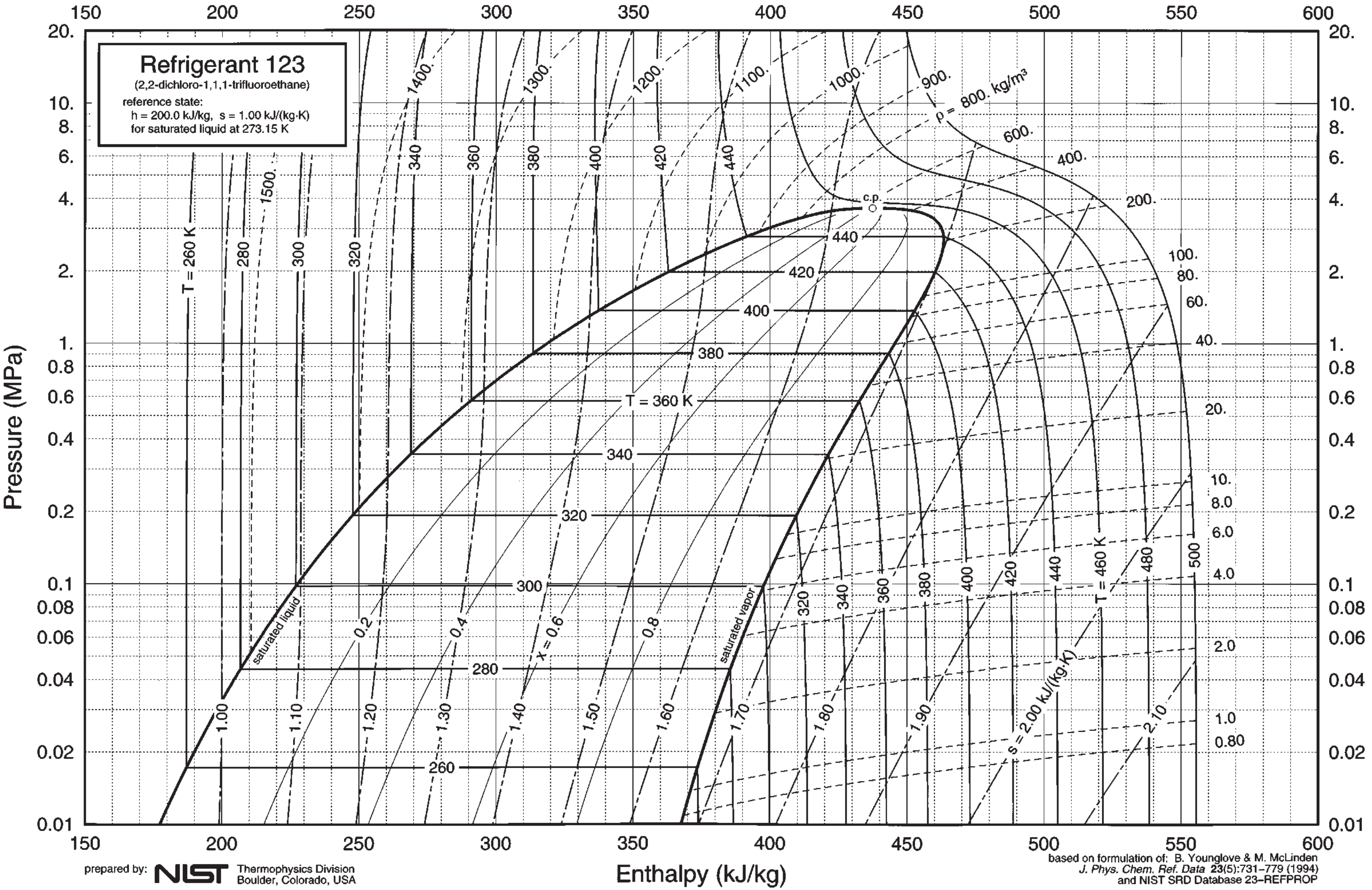
$h_f = s_f = 0$ at −40°C = 233.15 K. s_f, s_g, $c_{p,f}$ units: kJ/kg·K. Interpolated and converted from 1993 ASHRAE *Handbook—Fundamentals* (SI ed.) saturation table from −40 to 183.68°C. This source also contains an enthalpy–log-pressure diagram from 0.1 to 200 bar, −40 to 320°C.

TABLE 2-327 Saturated Refrigerant 124

Temp., °C	Pressure, bar	v_f, m^3/kg	v_g, m^3/kg	h_f, kJ/kg	h_g, kJ/kg	s_f, kJ/(kg·K)	s_g, kJ/(kg·K)
−40	0.2680	0.000 644	0.5173	159.1	334.9	0.8384	1.5927
−30	0.4499	0.000 655	0.3185	169.3	340.6	0.8813	1.5856
−20	0.7197	0.000 668	0.2049	179.5	346.2	0.9222	1.5808
−10	1.1044	0.000 681	0.1369	189.7	351.8	0.9616	1.5777
0	1.6348	0.000 696	0.0945	200.0	357.4	1.0000	1.5762
10	2.3447	0.000 711	0.06703	210.5	363.0	1.0376	1.5760
20	3.2710	0.000 728	0.04867	221.3	368.5	1.0747	1.5768
30	4.4529	0.000 747	0.03604	282.3	373.9	1.1115	1.5785
40	5.9320	0.000 768	0.02713	243.7	379.2	1.1480	1.5808
50	7.7521	0.000 791	0.02069	255.4	384.4	1.1843	1.5836
60	9.9599	0.000 818	0.01594	267.5	389.3	1.2207	1.5864
70	12.605	0.000 849	0.01236	280.1	393.9	1.2572	1.5890
80	15.742	0.000 887	0.00961	293.2	398.0	1.2942	1.5909
90	19.432	0.000 935	0.00744	307.0	401.3	1.3318	1.5915
100	23.749	0.000 999	0.00569	321.9	403.4	1.3710	1.5894
110	28.787	0.001 098	0.00420	338.4	403.0	1.4133	1.5820
120	34.702	0.001 338	0.00269	360.6	394.9	1.4685	1.5558
122.5^c	36.340	0.001 810	0.00181	378.5	378.5		

c = critical point.

Bull. T—124—SI, Jan. 1993 (28 pp.). Used by permission of DuPont Fluoroproducts. The 1993 ASHRAE *Handbook—Fundamentals* (SI ed.) gives a saturation table to 122.47°C and a diagram to 200 bar, 320°C.



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J. Phys. Chem. Ref. Data **23**(5):731–779 (1994)
and NIST SRD Database 23–REFPROP

FIG. 2-25 Enthalpy–log-pressure diagram for Refrigerant 123.

TABLE 2-328 Thermophysical Properties of Saturated Refrigerant 125

Temp., K	Pressure, bar	v_f, m^3/kg	v_g, m^3/kg	h_f, kJ/kg	h_g, kJ/kg	s_f, kJ/(kg·K)	s_g, kJ/(kg·K)	c_{pf}, kJ/(kg·K)	μ_f, 10^{-6} Pa·s
172.5*	0.035	0.000591	3.48						
180	0.064	0.000599	1.958						
190	0.133	0.000611	0.986						
200	0.257	0.000624	0.5312	–30.5	140.8	–0.1386	0.7183		644
210	0.465	0.000638	0.3057	–23.3	146.7	–0.1024	0.7067		531
220	0.794	0.000653	0.1854	–13.9	152.6	–0.0604	0.6981		445.8
224.9†	1.013	0.000660	0.1475	–8.8	155.5	–0.0386	0.6948		411.2
230	1.290	0.000669	0.1175	–3.4	158.4	–0.0147	0.6919	1.077	379.6
240	2.005	0.000686	0.0775	7.7	164.2	0.0324	0.6875	1.139	326.6
250	3.000	0.000705	0.0527	19.3	170.0	0.0800	0.6847	1.184	282.8
260	4.336	0.000725	0.0369	31.3	175.3	0.1274	0.6831	1.221	245.8
270	6.078	0.000749	0.0264	43.7	180.5	0.1743	0.6822	1.257	213.6
280	8.298	0.000776	0.0193	56.5	185.4	0.2206	0.6819	1.299	185.3
290	11.068	0.000809	0.0143	69.7	189.9	0.2666	0.6815	1.356	159.7
300	14.476	0.000848	0.0106	83.5	194.2	0.3126	0.6805	1.437	136.3
310	18.62	0.000898	0.0079	98.1	196.9	0.3597	0.6774	1.57	115.0
320	23.63	0.000969	0.0059	113.9	198.5	0.4079	0.6726	1.82	95.4
330	29.65	0.001088	0.0041	132.2	197.4	0.4621	0.6639		
339.4‡	35.95	0.00175	0.0018	169.0	169.0	0.5699	0.5699		

* = triple point; † = normal boiling point; ‡ = critical point. Converted, extrapolated and interpolated from 1993 ASHRAE *Handbook—Fundamentals* (SI ed.) $h_f = s_f = 0$ at 233.15 K = –40°C. This source also contains an enthalpy–log-pressure diagram from 0.3 to 100 bar, –65 to 175°C. An apparently identical diagram but a different saturation table is contained in Duarte-Garza, H.A., Hwang, C.A. et al., ASHRAE Trans., **99,** 2 (1993): 649–664. R124: The 1993 ASHRAE *Handbook—Fundamentals* (SI ed.) contains a saturation table from –60 to 122.47°C.

TABLE 2-329 Thermophysical Properties of Refrigerant 134a

Pressure, bar	Temp., K	v_f, m^3/kg	v_g, m^3/kg	h_f, kJ/kg	h_g, kJ/kg	s_f, kJ/(kg·K)	s_g, kJ/(kg·K)	c_{pf}, kJ/(kg·K)	μ_f, 10^{-6} Pa·s	k_f, W/(m·K)	Pr_f
0.0039*t*	169.85	0.0006285	35.263	–76.68	186.50	–0.3830	1.1665	1.147	2187		
0.5	232.69	0.0007062	0.3692	–0.57	225.27	–0.0025	0.9669	1.242	506	0.1121	5.61
0.6	236.22	0.0007113	0.3015	3.85	227.52	0.0161	0.9636	1.248	480	0.1105	5.42
0.8	242.04	0.0007199	0.2375	11.15	231.19	0.0467	0.9560	1.258	438	0.1078	5.12
1.0	246.80	0.0007272	0.1924	17.14	234.15	0.0713	0.9507	1.267	408	0.1056	4.90
1.013	247.03	0.0007276	0.1902	17.50	234.33	0.0728	0.9503	1.268	406	0.1054	4.89
1.5	256.03	0.0007421	0.1312	28.96	239.86	0.1181	0.9419	1.288	358.7	0.1013	4.56
2.0	263.09	0.0007543	0.0999	38.13	244.14	0.1533	0.9364	1.306	326.6	0.0980	4.35
2.5	268.88	0.0007648	0.0806	45.75	247.60	0.1819	0.9326	1.322	303.2	0.0954	4.20
3.0	273.82	0.0007743	0.0677	52.33	250.50	0.2059	0.9297	1.337	285.1	0.0931	4.09
4.0	282.08	0.0007912	0.0512	63.50	255.22	0.2458	0.9256	1.363	257.7	0.0893	3.93
5	288.89	0.0008063	0.04116	72.87	258.99	0.2784	0.9232	1.387	237.5	0.0861	3.83
6	294.72	0.0008203	0.03434	81.04	262.09	0.3062	0.9208	1.410	221.6	0.0835	3.74
8	304.47	0.0008460	0.02565	95.00	267.01	0.3522	0.9171	1.454	197.6	0.0790	3.64
10	312.53	0.0008703	0.02035	106.86	270.74	0.3901	0.9144	1.497	179.5	0.0753	3.57
12	319.47	0.0008938	0.01675	117.34	273.65	0.4227	0.9120	1.541	165.1	0.0721	3.53
14	325.57	0.0009170	0.01414	126.80	275.92	0.4515	0.9095	1.589	153.0	0.0693	3.51
16	330.11	0.0009362	0.01247	134.00	277.40	0.4729	0.9073	1.631	144.3	0.0672	3.50
18	336.04	0.0009555	0.01059	143.68	279.01	0.5013	0.9041	1.698	133.2	0.0645	3.51
20	340.63	0.0009894	0.00931	151.39	279.95	0.5236	0.9010	1.764	124.8	0.0623	3.53
25	350.73	0.0010585	0.00695	169.30	280.64	0.5738	0.8913	1.987	106.6	0.0577	3.67
30	359.37	0.001144	0.00528	185.05	278.32	0.6212	0.8807	2.418	90.4	0.0538	4.06
35	366.89	0.001270	0.00399	203.19	273.52	0.6657	0.8574				
40	373.50	0.001606	0.00255	229.24	257.12	0.7292	0.8038				
40.56^c	374.18	0.001948	0.00195	241.22	241.22	0.7620	0.7620				

t = triple point, *c* = critical point. $h_f = s_f = 0$ at –40°C = 233.15 K. *T, v, h,* and *s* interpolated and converted from *Refrigerant 134a—Thermodynamic and Physical Properties,* Int. Inst. Refrig., Paris, France, 1992 (28 pp.).

Other properties from this source and from Oliveira, C. M. B. P. and W. A. Wakeham, *Int. J. Thermophys.,* **14,** 1 (1993): 33–44; Krauss, R., J. Luettmer-Strathmann, et al., *Int. J. Thermophys.,* **14,** 4 (1993): 951–988; ASHRAE *Handbook—Fundamentals,* Atlanta, GA, 1993; ICI KLEA 134a bulletin, 1993 (43 pp.); and *R134a—Thermodynamic and Physical Properties,* Int. Inst. Refrig., Paris, France, 1992 (28 pp.).

Papers giving polynomial curve fits and similar simple equations include Cleland, A. C., *Rev. Int. Froid = Int. J. Refrig.,* **17,** 4 (1994): 245–249; Dobrokhotov, A., A. Grebenkov, et al., *Proc. 14th Japan Symp. Thermophys. Props.,* (1993): 271–274; Huber, M. L. and J. F. Ely, *Rev. Int. Froid = Int. J. Refrig.,* **17,** 1 (1994): 18–31 (includes extensive list of vapor pressure and liquid density sources for many refrigerants); Modic, J., *Proc. 11th Int. Symp. Htg, Refrig and Air-Condg.,* Zagreb, (1991): 174–185; and Kabelac, S., *Int. J. Refrig.,* **14,** (1991): 217–222. The 1993 ASHRAE *Handbook—Fundamentals* (SI ed.) gives saturation data for integral degrees Celsius with temperatures on the ITS 90 scale from –103.03°C to 101.03°C. The thermodynamic diagram from 0.1 to 200 bar extends to 320°C.

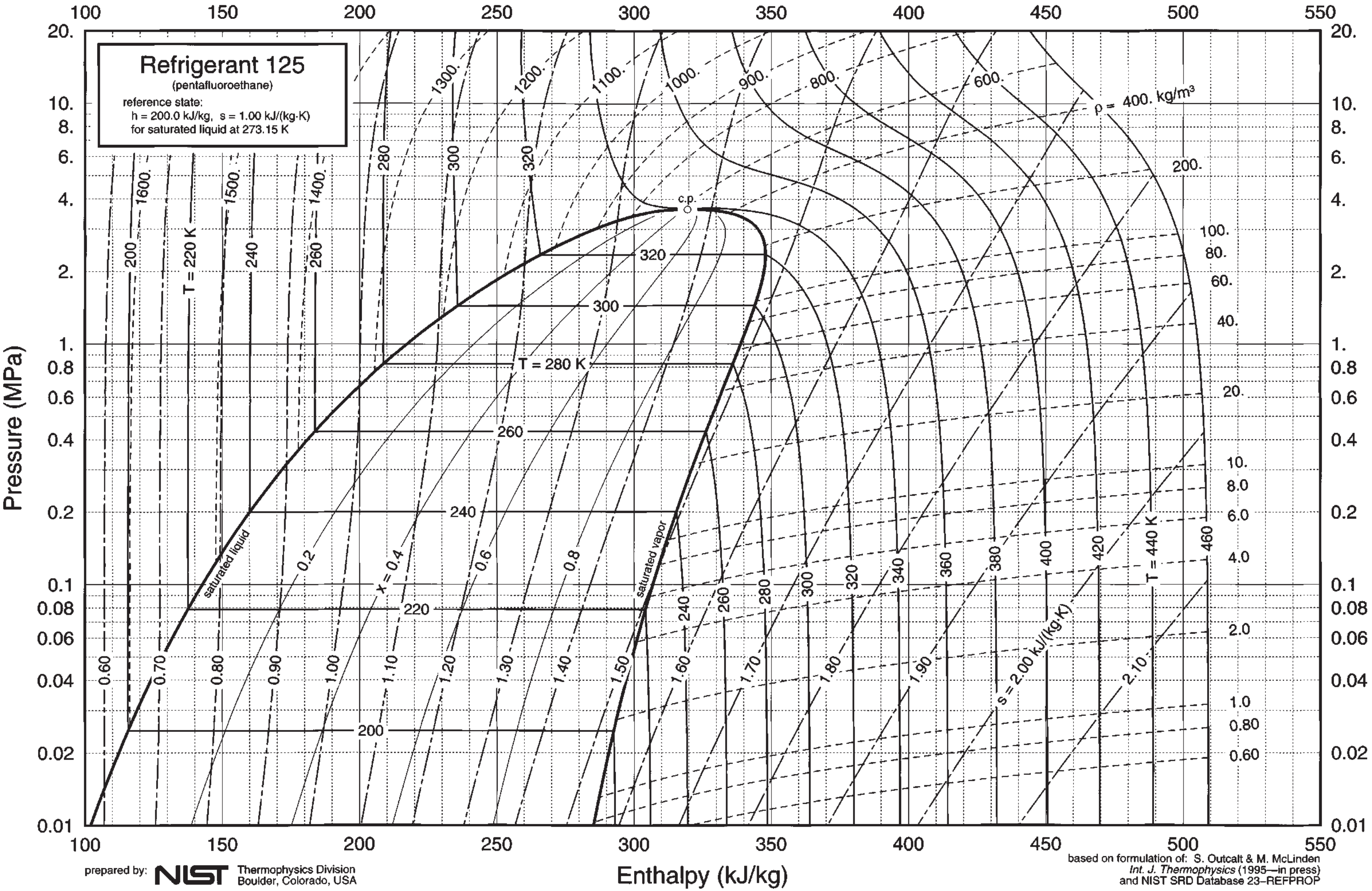


FIG. 2-26 Enthalpy–log-pressure diagram for Refrigerant 125.

TABLE 2-330 Thermophysical Properties of Compressed Gaseous Refrigerant 134*a*

Temp., K		Pressure, bar						
		0	1	2	3	4	5	6
230	c_p (kJ/kg·K)		—	—	—	—	—	—
	μ (10^{-6} Pa·s)		—	—	—	—	—	—
	k (W/m·K)		—	—	—	—	—	—
	Pr		—	—	—	—	—	—
240	c_p (kJ/kg·K)		—	—	—	—	—	—
	μ (10^{-6} Pa·s)		—	—	—	—	—	—
	k (W/m·K)		—	—	—	—	—	—
	Pr		—	—	—	—	—	—
250	c_p (kJ/kg·K)	0.7437	0.7953	—	—	—	—	—
	μ (10^{-6} Pa·s)	10.11	10.15	—	—	—	—	—
	k (W/m·K)	0.0096	0.0097	—	—	—	—	—
	Pr	0.783	0.797	—	—	—	—	—
260	c_p (kJ/kg·K)	0.7627	0.8048	—	—	—	—	—
	μ (10^{-6} Pa·s)	10.47	10.51	—	—	—	—	—
	k (W/m·K)	0.0105	0.0107	—	—	—	—	—
	Pr	0.761	0.790	—	—	—	—	—
270	c_p (kJ/kg)	0.7813	0.8158	0.8557	—	—	—	—
	μ (10^{-6} Pa·s)	10.84	10.88	10.94	—	—	—	—
	k (W/m·K)	0.0117	0.0118	0.0118	—	—	—	—
	Pr	0.724	0.761	0.793	—	—	—	—
280	c_p (kJ/kg·K)	0.7996	0.8283	0.8604		—	—	—
	μ (10^{-6} Pa·s)	11.22	11.26	11.29		—	—	—
	k (W/m·K)	0.0122	0.0123	0.0123		—	—	—
	Pr	0.735	0.757	0.790		—	—	—
290	c_p (kJ/kg·K)	0.8176	0.8412	0.8673	0.8938	0.9335		—
	μ (10^{-6} Pa·s)	11.62	11.65	11.68	11.71	11.74		—
	k (W/m·K)	0.0130	0.0131	0.0131	0.0133			—
	Pr	0.731	0.748	0.773	0.787			—
300	c_p (kJ/kg·K)	0.8354	0.8556	0.8771	0.8972	0.9277	0.9606	0.9976
	μ (10^{-6} Pa·s)	12.05	12.06	12.08	12.10	12.15		
	k (W/m·K)	0.0139	0.0139	0.0140	0.0141	0.0142	0.0143	
	Pr	0.730	0.742	0.757	0.770	0.792	0.816	
310	c_p (kJ/kg·K)	0.8530	0.8703	0.8875	0.9046	0.9292	0.9546	0.9827
	μ (10^{-6} Pa·s)	12.44	12.45	12.47	12.49	12.52	12.54	
	k (W/m·K)	0.0145	0.0146	0.0147	0.0148	0.0149	0.0150	0.0152
	Pr	0.730	0.742	0.753	0.763	0.781	0.798	
320	c_p (kJ/kg·K)	0.8703	0.8843	0.8993	0.9163	0.9356	0.9548	0.9750
	μ (10^{-6} Pa·s)	12.83	12.84	12.86	12.88	12.90	12.93	12.97
	k (W/m·K)	0.0153	0.0153	0.0154	0.0155	0.0156	0.0157	0.0158
	Pr	0.730	0.740	0.751	0.761	0.774	0.786	0.800
330	c_p (kJ/kg·K)	0.8874	0.8996	0.9114	0.9268	0.9398	0.9569	0.9750
	μ (10^{-6} Pa·s)	13.22	13.23	13.25	13.27	13.29	13.32	13.35
	k (W/m·K)	0.0160	0.0161	0.0161	0.0162	0.0163	0.0164	0.0165
	Pr	0.729	0.739	0.750	0.759	0.766	0.777	0.789
340	c_p (kJ/kg·K)	0.9042	0.9152	0.9262	0.9372	0.9502	0.9632	0.9770
	μ (10^{-6} Pa·s)	13.61	13.62	13.64	13.66	13.68	13.70	13.73
	k (W/m·K)	0.0169	0.0169	0.0169	0.0170	0.0170	0.0171	0.0171
	Pr	0.728	0.738	0.748	0.755	0.765	0.772	0.780
350	c_p (kJ/kg·K)	0.9208	0.9307	0.9406	0.9505	0.9607	0.9695	0.9830
	μ (10^{-6} Pa·s)	13.98	13.99	14.01	14.03	14.05	14.07	14.10
	k (W/m·K)	0.0175	0.0176	0.0176	0.0177	0.0177	0.0178	0.0179
	Pr	0.730	0.740	0.749	0.754	0.763	0.767	0.774

Dashes indicate unavailable states; blanks indicate no data.

Note that "profound differences" presently exist in the transport properties of R134a according to *Chemistry International,* **16**(6), 233, Nov. 1994, and **18**(2) 44–47, 1996.

TABLE 2-330 Thermophysical Properties of Compressed Gaseous R134a (*Concluded*)

Temp., K		Pressure, bar						
		8	10	12.5	15	17.5	20	22.5
300	c_p (kJ/kg·K)	—	—	—	—	—	—	—
	μ (10^{-6} Pa·s)	—	—	—	—	—	—	—
	k (W/m·K)	—	—	—	—	—	—	—
	Pr	—	—	—	—	—	—	—
310	c_p (kJ/kg·K)	1.053	—	—	—	—	—	—
	μ (10^{-6} Pa·s)		—	—	—	—	—	—
	k (W/m·K)	0.0155	—	—	—	—	—	—
	Pr		—	—	—	—	—	—
320	c_p (kJ/kg·K)	1.028	1.097	—	—	—	—	—
	μ (10^{-6} Pa·s)	13.05	13.13	—	—	—	—	—
	k (W/m·K)	0.0161		—	—	—	—	—
	Pr	0.833		—	—	—	—	—
330	c_p (kJ/kg·K)	1.015	1.065	1.151	1.276	—	—	—
	μ (10^{-6} Pa·s)	13.41	13.49	13.64	13.86	—	—	—
	k (W/m·K)	0.0168	0.0171	0.0177	0.0184	—	—	—
	Pr	0.810	0.840	0.887	0.961	—	—	—
340	c_p (kJ/kg·K)	1.008	1.049	1.107	1.187	1.319	—	—
	μ (10^{-6} Pa·s)	13.79	13.86	13.98	14.17		—	—
	k (W/m·K)	0.0174	0.0177	0.181	0.0187		—	—
	Pr	0.799	0.821	0.855	0.899		—	—
350	c_p (kJ/kg·K)	1.008	1.040	1.086	1.148	1.225	1.340	1.525
	μ (10^{-6} Pa·s)	14.15	14.22	14.34	14.49		14.97	
	k (W/m·K)	0.0181	0.0183	0.0186	0.0192	0.0198	0.0205	0.0215
	Pr	0.788	0.828	0.837	0.866			

TABLE 2-331 Refrigerant 141b

The 1993 ASHRAE *Handbook—Fundamentals* (SI ed.) gives saturation data to 150°C and a diagram to 20 bar, 150°C. For equation of state including decomposition, see Weber, L. A., paper 69, *Proc. 18th Int. Congr. Refrig.*, Montreal, 1991.

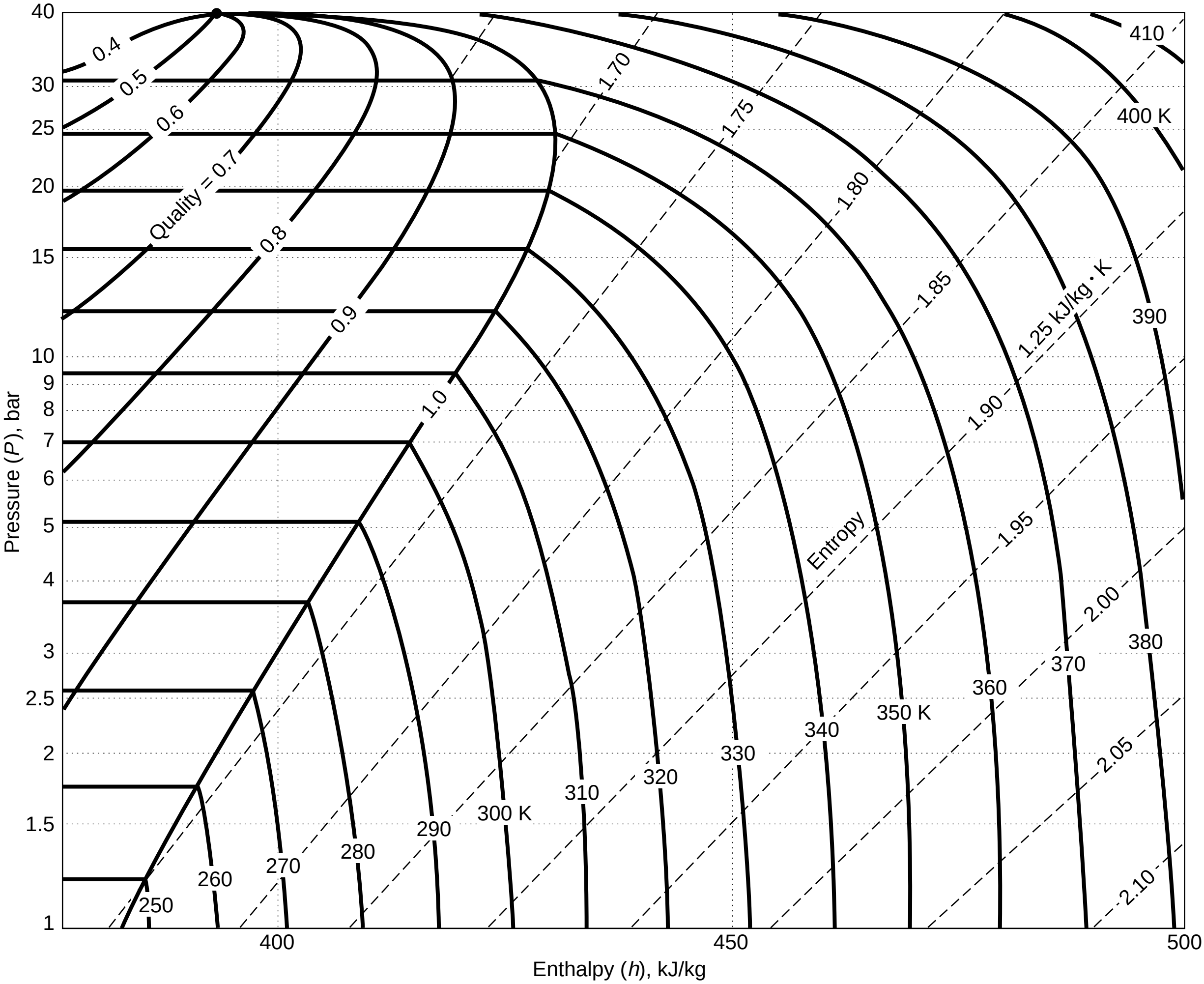


FIG. 2-27 Enthalpy–log-pressure diagram for Refrigerant 134a.

TABLE 2-332 Refrigerant 142b*

T, K	P, bar	v_f, m^3/kg	v_g, m^3/kg	h_f, kJ/kg	h_g, kJ/kg	s_f, kJ/(kg·K)	s_g, kJ/(kg·K)	c_{pf}, kJ/(kg·K)	μ_f, 10^{-4} Pa·s	k_f, W/(m·K)
200	0.0380	7.505.–4	4.337	–24.36	200.49	–0.1123	1.0119			0.123
210	0.0728	7.626.–4	2.374	–17.48	206.82	–0.0788	0.9893	1.15		0.118
220	0.1314	7.751.–4	1.373	–10.21	213.28	–0.0450	0.9708	1.17		0.114
230	0.2252	7.883.–4	0.833	–2.52	219.82	–0.0109	0.9558	1.18		0.111
240	0.3691	8.019.–4	0.527	9.92	229.74	0.0414	0.9387	1.19	0.517	0.109
250	0.5815	8.164.–4	0.346	14.32	233.05	0.0592	0.9341	1.21	0.466	0.103
260	0.8846	8.317.–4	0.234	23.54	239.66	0.0952	0.9264	1.22	0.422	0.099
270	1.3046	8.480.–4	0.162	33.32	246.18	0.1320	0.9204	1.24	0.385	0.095
280	1.8714	8.653.–4	0.115	43.68	252.57	0.1695	0.9155	1.26	0.355	0.091
290	2.6184	8.843.–4	0.0838	54.60	258.77	0.2076	0.9116	1.28	0.329	0.088
300	3.583	9.047.–4	0.0619	66.07	264.69	0.2462	0.9082	1.30	0.305	0.084
310	4.803	9.273.–4	0.0464	78.07	270.26	0.2851	0.9051	1.32	0.285	0.080
320	6.324	9.525.–4	0.0353	90.55	275.40	0.3243	0.9020	1.34	0.267	0.075
330	8.187	9.810.–4	0.0271	103.45	280.01	0.3634	0.8985		0.241	0.072
340	10.44	1.014.–3	0.0210	116.71	283.99	0.4024	0.8943		0.216	0.068
350	13.13	1.052.–3	0.0164	130.30	287.23	0.4409	0.8893		0.192	0.064
360	16.30	1.099.–3	0.0129	144.18	289.61	0.4791	0.8831			0.060
370	20.01	1.157.–3	0.0102	158.45	291.01	0.5170	0.8753			0.056
380	24.29	1.235.–3	0.0080	173.45	291.22	0.5557	0.8656			0.052
390	29.20	1.348.–3	0.0062	190.16	289.77	0.5974	0.8528			0.048
400	34.78	1.541.–3	0.0046	212.57	284.04	0.6521	0.8307			0.044
410[c]	41.5	2.300.–3	0.0023	255.00	255.00					∞

*Values reproduced and converted from Table 10, p. 17.95, *ASHRAE Handbook, 1981: Fundamentals,* American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, 1981. Copyright material. Reproduced by permission of the copyright owner. c = critical point. The notation 7.505.–4 signifies 7.505×10^{-4}.

The 1993 ASHRAE *Handbook—Fundamentals* (SI ed.) gives material for integral degrees Celsius with temperatures on the IPTS 68 scale from –50 to 125°C. The thermodynamic diagram from 0.1 to 35 bar extends to 180°C. For experimental isochores for the compressed liquid from 6 to 298 bar, 147 to 432 K, see Blanke, W. and R. Weiss, *PTB Bericht W 30,* Braunschweig, Germany, 1992 (54 pp.). Tables and a diagram to 500 psia, 400°F are given in Stewart, R. B., R. T. Jacobsen, et al., *Thermodynamic Properties of Refrigerants,* ASHRAE, Atlanta, GA, 1986 (521 pp.). For specific heat, thermal conductivity, and viscosity, see *Thermophysical Properties of Refrigerants,* ASHRAE, 1993.

TABLE 2-333 Saturated Refrigerant R143a*

Temp., K	Pressure, bar	v_f, m^3/kg	v_g, m^3/kg	h_f, kJ/kg	h_g, kJ/kg	s_f, kJ/(kg·K)	s_g, kJ/(kg·K)	c_{pf}, kJ/(kg·K)	μ_f, 10^{-4} Pa·s	k_f, W/(m·K)
161.82[t]	0.01124	0.000752	14.22	53.2	320.5	0.3181	1.970	1.188	6.011	0.1416
170	0.02497	0.000764	6.709	63.0	325.5	0.3774	1.922	1.215	5.366	0.1403
180	0.05914	0.000778	2.991	75.3	331.8	0.4474	1.872	1.235	4.692	0.1372
190	0.126	0.000793	1.474	87.7	338.1	0.5147	1.832	1.252	4.121	0.1331
200	0.2458	0.000809	0.7898	100.3	344.5	0.5792	1.800	1.268	3.636	0.1281
210	0.4455	0.000826	0.4532	113.1	350.8	0.6415	1.774	1.287	3.221	0.1226
220	0.7586	0.000845	0.2754	126.1	357.1	0.7018	1.752	1.308	2.864	0.1168
225.92	1.01325	0.000856	0.2098	133.9	360.8	0.7367	1.741	1.323	2.676	0.1133
230	1.225	0.000865	0.1755	139.3	363.3	0.7604	1.734	1.333	2.556	0.1108
240	1.89	0.000886	0.1164	152.8	369.4	0.8176	1.720	1.362	2.288	0.1047
250	2.806	0.000910	0.07975	166.6	375.3	0.8736	1.708	1.394	2.055	0.09862
260	4.027	0.000936	0.05617	180.8	380.9	0.9287	1.698	1.431	1.852	0.09272
270	5.613	0.000966	0.04045	195.3	386.2	0.983	1.690	1.475	1.673	0.08682
280	7.629	0.000999	0.02964	210.3	391.1	1.037	1.682	1.527	1.496	0.08098
290	10.14	0.001038	0.02200	225.9	395.4	1.091	1.675	1.593	1.334	0.07521
300	13.23	0.001084	0.01646	242.1	399.0	1.144	1.668	1.679	1.192	0.06951
310	16.98	0.001140	0.01234	259.2	401.6	1.199	1.659	1.804	1.067	0.06381
320	21.48	0.001214	0.009182	277.4	402.7	1.255	1.647	2.006	0.9569	0.05803
330	26.85	0.001321	0.006678	297.5	401.0	1.315	1.629	2.421	0.8321	0.05202
340	33.25	0.001514	0.004520	321.8	393.4	1.385	1.595	4.021	0.6560	0.04480
346.75[c]	38.32	0.002311	0.002311	360.6	360.6	1.471	1.471	—	—	—

*Values calculated from NIST Thermodynamic Properties of Refrigerants and Refrigerant Mixtures Database (REFPROP, Version 5). Thermodynamic properties are from 32-term MBWR equation of state; transport properties are from extended corresponding states model. t = triple point; c = critical point.

TABLE 2-334 Saturated Refrigerant R152a*

Temp., K	Pressure, bar	v_f, m^3/kg	v_g, m^3/kg	h_f, kJ/kg	h_g, kJ/kg	s_f, kJ/(kg·K)	s_g, kJ/(kg·K)	c_{pf}, kJ/(kg·K)	μ_f, 10^{-4} Pa·s	k_f, W/(m·K)
154.56*t*	0.000641	0.000839	303.6	14.0	419.8	0.1130	2.738	1.492	10.85	0.1932
160	0.001297	0.000846	155.2	22.2	423.5	0.1647	2.673	1.500	9.614	0.1894
170	0.004145	0.000859	51.59	37.2	430.6	0.2560	2.570	1.510	8.058	0.1822
180	0.01141	0.000873	19.82	52.4	437.9	0.3425	2.484	1.517	6.940	0.1753
190	0.02775	0.000887	8.588	67.6	445.3	0.4247	2.413	1.525	6.012	0.1685
200	0.06088	0.000902	4.110	82.9	452.8	0.5032	2.353	1.535	5.236	0.1618
210	0.1224	0.000918	2.138	98.3	460.4	0.5784	2.303	1.547	4.582	0.1552
220	0.2284	0.000935	1.193	113.8	468.0	0.6507	2.261	1.562	4.028	0.1487
230	0.4004	0.000952	0.7064	129.5	475.6	0.7205	2.225	1.580	3.556	0.1423
240	0.6647	0.000971	0.4397	145.5	483.1	0.7881	2.195	1.600	3.153	0.1361
249.12	1.01325	0.000989	0.2961	160.2	489.8	0.8481	2.171	1.622	2.834	0.1304
250	1.053	0.000991	0.2855	161.6	490.5	0.8538	2.169	1.624	2.805	0.1299
260	1.603	0.001012	0.1922	178.0	497.7	0.9178	2.147	1.651	2.500	0.1239
270	2.354	0.001035	0.1334	194.7	504.7	0.9805	2.129	1.681	2.231	0.1179
280	3.354	0.001060	0.09500	211.7	511.4	1.042	2.112	1.716	1.995	0.1121
290	4.650	0.001087	0.06916	229.1	517.8	1.103	2.098	1.756	1.789	0.1064
300	6.297	0.001118	0.05126	246.9	523.8	1.162	2.085	1.803	1.607	0.1008
310	8.351	0.001152	0.03857	265.2	529.3	1.222	2.073	1.859	1.447	0.09526
320	10.87	0.001190	0.02935	284.1	534.1	1.281	2.062	1.928	1.305	0.08986
330	13.92	0.001235	0.02251	303.7	538.2	1.340	2.051	2.015	1.180	0.08457
340	17.57	0.001289	0.01735	324.2	541.3	1.400	2.038	2.131	1.069	0.07939
350	21.90	0.001355	0.01335	345.7	542.9	1.460	2.024	2.299	1.005	0.07336
360	27.00	0.001440	0.01020	368.8	542.5	1.523	2.006	2.573	0.9225	0.06666
370	32.97	0.001563	0.007603	394.3	538.5	1.591	1.980	3.143	0.8191	0.06032
380	39.97	0.001785	0.005274	425.4	526.2	1.671	1.936	5.407	0.6638	0.05176
386.41^c	45.17	0.002717	0.002717	477.3	477.3	1.778	1.778	—	—	—

*Values calculated from NIST Thermodynamic Properties of Refrigerants and Refrigerant Mixtures Database (REFPROP, Version 5). Thermodynamic properties are from 32-term MBWR equation of state; transport properties are from extended corresponding states model. *t* = triple point; *c* = critical point.

TABLE 2-335 Saturated Refrigerant 216*

Temp., °F	Pressure, lb/in^2 abs.	Volume, ft^3/lb		Enthalpy, Btu/lb		Entropy, Btu/(lb)(°F)	
		Liquid	Vapor	Liquid	Vapor	Liquid	Vapor
−40	0.339	0.00927	59.957	0.000	62.415	0.0000	0.1487
−20	0.713	0.00942	29.749	4.778	65.276	0.0111	0.1487
0	1.382	0.00958	15.986	9.541	68.208	0.0217	0.1493
20	2.497	0.00974	9.184	14.298	71.199	0.0318	0.1504
40	4.247	0.00992	5.582	19.056	74.239	0.0415	0.1520
60	6.862	0.01010	3.558	23.821	77.319	0.0509	0.1538
80	10.612	0.01030	2.361	28.598	80.429	0.0599	0.1559
100	15.797	0.01050	1.6215	33.391	83.559	0.0686	0.1582
120	22.753	0.01073	1.1462	38.205	86.701	0.0770	0.1607
140	31.845	0.01097	0.8304	43.049	89.845	0.0852	0.1632
160	43.468	0.01124	0.6142	47.930	92.981	0.0931	0.1658
180	58.046	0.01153	0.4623	52.861	96.099	0.1009	0.1685
200	76.033	0.01186	0.3529	57.857	99.186	0.1085	0.1712
220	97.913	0.01223	0.2725	62.939	102.225	0.1161	0.1739
240	124.21	0.01266	0.2121	68.132	105.196	0.1235	0.1765
260	155.50	0.01317	0.1660	73.474	108.066	0.1309	0.1790
280	192.40	0.01378	0.1300	79.015	110.789	0.1384	0.1813
300	235.63	0.01458	0.1013	84.835	113.282	0.1460	0.1834
320	286.03	0.01570	0.0776	91.089	115.373	0.1539	0.1851
340	344.81	0.01764	0.0565	98.234	116.538	0.1628	0.1856
355.98^c	399.45	0.02771	0.0277	110.248	110.248	0.1773	0.1773

*From published data, Chemicals Division, Union Carbide Corporation. Used by permission. The paper describing these data is by Shank, *ASHRAE J.*, **7** (1965): 94–101. *c* = critical temperature.

The 1993 ASHRAE *Handbook—Fundamentals* (SI ed.) gives material for integral degrees Celsius with temperatures on the ITS 90 scale from −118.59 to 113.26°C. The thermodynamic diagram from 0.1 to 30 bar extends to 180°C. For tables and a diagram to 400 psia, 360°F, see Stewart, R. B., R. T. Jacobsen, et al., *Thermodynamic Properties of Refrigerants*, ASHRAE, Atlanta, GA, 1986 (521 pp.). For specific heat and viscosity, see *Thermophysical Properties of Refrigerants*, ASHRAE, 1993. Thermal conductivity data as a function of pressure and temperature are reported by Krauss, R. and K. Stephan, *Proc. 12th Symp. Thermophys. Props.*, Boulder, CO, 1994.

TABLE 2-336 Saturated Refrigerant 245*

T, K	P, bar	v_f, m^3/kg	v_g, m^3/kg	h_f, kJ/kg	h_g, kJ/kg	s_f, kJ/(kg·K)	s_g, kJ/(kg·K)
172	0.0034	6.46.–4	31.49	–63.4	133.8	–0.3131	0.8327
180	0.0076	6.57.–4	14.63	–55.9	138.7	–0.2707	0.8099
190	0.0190	6.70.–4	6.20	–46.2	145.1	–0.2182	0.7885
200	0.0425	6.83.–4	2.91	–36.0	151.7	–0.1666	0.7725
210	0.0870	6.97.–4	1.48	–25.7	158.5	–0.1157	0.7612
220	0.1654	7.11.–4	0.822	–14.8	165.4	–0.0654	0.7539
230	0.2946	7.25.–4	0.475	–3.6	172.5	–0.0156	0.7500
240	0.4958	7.40.–4	0.292	8.0	179.6	0.0337	0.7487
250	0.7946	7.55.–4	0.192	19.9	186.8	0.0824	0.7497
260	1.2204	7.72.–4	0.125	32.3	194.0	0.1305	0.7525
270	1.806	7.89.–4	0.0862	44.9	201.1	0.1781	0.7567
280	2.584	8.08.–4	0.0611	57.9	208.3	0.2249	0.7621
290	3.600	8.30.–4	0.0443	71.1	215.3	0.2711	0.7683
300	4.888	8.53.–4	0.0327	84.6	222.2	0.3161	0.7751
310	6.491	8.80.–4	0.0246	98.4	228.9	0.3614	0.7822
320	8.456	9.11.–4	0.0186	112.6	235.3	0.4057	0.7893
330	10.83	9.48.–4	0.0143	127.1	241.4	0.4497	0.7960
340	13.67	9.93.–4	0.0111	142.1	246.9	0.4937	0.8018
350	17.04	0.00105	0.0084	157.2	251.5	0.5382	0.8060
360	21.02	0.00113	0.0063	174.7	254.8	0.5844	0.8071
370	25.71	0.00125	0.0045	193.6	255.2	0.6349	0.8013
375	28.46	0.00137	0.0036	205.2	252.5	0.6649	0.7953
380.1^c	31.37	0.00204	0.0020	231.8	231.8	0.7341	0.7341

*Values converted from tables of Shank, *Thermodynamic Properties of UCON 245 Refrigerant,* Union Carbide Corporation, New York, 1966. See also Shank, *J. Chem. Eng. Data,* **12,** 474–480 (1967). c = critical point. The notation 6.46.–4 signifies 6.46×10^{-4}.

TABLE 2-337 Refrigerant C 318*

T, K	P, bar	v_f, m^3/kg	v_g, m^3/kg	h_f, kJ/kg	h_g, kJ/kg	s_f, kJ/(kg·K)	s_g, kJ/(kg·K)	c_{pf}, kJ/(kg·K)	μ_f, 10^{-4} Pa·s	k_f, W/(m·K)
200	0.0216	5.507.–4	3.810	353.5	498.0	3.909	4.560			
210	0.0449	5.593.–4	1.931	361.0	500.1	3.947	4.564			
220	0.0875	5.683.–4	1.038	369.2	502.2	3.984	4.569			
230	0.1608	5.778.–4	0.588	377.6	504.4	4.022	4.574	0.98	11.7	0.088
240	0.2810	5.879.–4	0.349	386.4	510.9	4.060	4.578	1.00	9.55	0.085
250	0.466	5.988.–4	0.2166	395.6	517.4	4.097	4.584	1.02	7.90	0.082
260	0.741	6.106.–4	0.1401	405.2	524.0	4.133	4.592	1.03	6.63	0.078
270	1.133	6.234.–4	0.0938	415.1	530.7	4.172	4.599	1.05	5.64	0.075
280	1.672	6.375.–4	0.0647	425.8	537.3	4.210	4.609	1.07	4.85	0.071
290	2.392	6.529.–4	0.0458	436.2	543.9	4.247	4.618	1.09	4.22	0.068
300	3.325	6.694.–4	0.0332	447.3	550.4	4.284	4.626	1.12	3.70	0.065
310	4.522	6.893.–4	0.0245	458.7	556.9	4.322	4.638	1.15	3.20	0.061
320	6.007	7.115.–4	0.0184	470.5	563.3	4.359	4.648	1.18	2.94	0.058
330	7.826	7.365.–4	0.0139	482.7	569.4	4.396	4.659	1.23	2.66	0.054
340	10.018	7.666.–4	0.0106	495.2	575.4	4.433	4.669	1.27	2.33	0.051
350	12.632	8.034.–4	0.0082	508.1	581.0	4.469	4.678	1.32	2.00	0.048
360	15.71	8.508.–4	0.0062	521.5	585.8	4.507	4.685	1.39		
370	19.33	9.172.–4	0.0047	535.6	589.9	4.544	4.691			
380	23.59	1.031.–3	0.0033	551.4	591.5	4.585	4.691			
388.5^c	27.83	1.613.–3	0.0016	577.2	577.2	4.651	4.651			

*Values of P, v, h, and s interpolated, extrapolated, and converted from tables of Oguchi, *Reito,* **52** (1977): 869–889. Values of c_p, μ, and k interpolated and converted from tables in *Thermophysical Properties of Refrigerants,* American Society of Heating, Refrigerating and Air-Conditioning Engineers, New York, 1976. c = critical point.

Saturation and superheat tables and a diagram to 80 bar, 580 K are given by Reynolds, W. C., *Thermodynamic Properties in S.I.,* Stanford Univ. publ., 1979 (173 pp.). For equations, see Cipollone, R., *ASHRAE Trans.,* **97,** 2 (1991): 262–267.

TABLE 2-338 Saturated Refrigerant 500[*]

T, K	P, bar	v_f, m^3/kg	v_g, m^3/kg	h_f, kJ/kg	h_g, kJ/kg	s_f, kJ/(kg·K)	s_g, kJ/(kg·K)	c_{pf}, kJ/(kg·K)	μ_f, 10^{-4} Pa·s	k_f, W/(m·K)
200	0.1219	6.966.–4	1.360	–29.56	185.87	–0.1363	0.9408	1.044	6.11	0.113
210	0.2258	7.090.–4	0.766	–21.03	191.25	–0.0948	0.9161	1.018	5.15	0.109
220	0.3936	7.222.–4	0.457	–12.17	196.63	–0.0536	0.8955	0.997	4.42	0.106
230	0.6511	7.361.–4	0.286	–2.97	201.96	–0.0130	0.8782	0.987	3.85	0.102
240	1.0291	7.509.–4	0.187	6.58	207.23	0.0277	0.8638	0.987	3.42	0.098
250	1.5632	7.668.–4	0.1261	16.50	212.40	0.0680	0.8517	0.997	3.04	0.094
260	2.2932	7.839.–4	0.0879	26.78	217.45	0.1082	0.8415	1.017	2.74	0.090
270	3.2624	8.024.–4	0.0628	37.44	222.35	0.1481	0.8329	1.048	2.48	0.086
280	4.5172	8.226.–4	0.0459	48.48	227.06	0.1878	0.8257	1.089	2.26	0.082
290	6.1064	8.450.–4	0.0342	59.91	231.56	0.2275	0.8194	1.140	2.08	0.078
300	8.0809	8.699.–4	0.0259	71.76	235.79	0.2671	0.8139	1.201	1.92	0.074
310	10.49	8.981.–4	0.0198	84.05	239.69	0.3067	0.8088	1.273	1.77	0.070
320	13.40	9.306.–4	0.0154	96.83	243.19	0.3464	0.8038	1.355	1.63	0.066
330	16.86	9.690.–4	0.0119	110.17	246.14	0.3864	0.7985	1.447	1.48	0.062
340	20.93	1.016.–3	0.0093	124.20	248.36	0.4271	0.7922	1.550	1.34	0.058
350	25.70	1.077.–3	0.0072	139.18	249.47	0.4689	0.7841	1.663		
360	31.25	1.162.–3	0.0055	155.66	248.71	0.5135	0.7721	1.919		
370	37.72	1.307.–3	0.0040	175.59	244.26	0.5650	0.7509	2.07		
378.6^c	44.26	2.012.–3	0.0020	219.50	219.50	0.6729	0.6729	∞		

[*] Values reproduced and converted from Table 12, p. 17.99, *ASHRAE Handbook, 1981: Fundamentals,* American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, 1981. Copyright material. Reproduced by permission of the copyright owner. c = critical point. The notation 6.966.–4 signifies 6.966×10^{-4}.

The 1993 ASHRAE *Handbook—Fundamentals* (SI ed.) gives material for integral degrees Celsius with temperatures on the IPTS 68 scale from −70 to 105.60°C. The thermodynamic diagram from 0.1 to 70 bar extends to 240°C. Equations and constants approximated to the 1985 ASHRAE tables were given by Mecaryk, K. and M. Masaryk, *Heat Recovery Systems and CHP,* **11,** 2/3 (1991): 193–197. Saturation and superheat tables and a diagram to 80 bar, 560 K are given by Reynolds, W. C., *Thermodynamic Properties in S.I.,* Stanford Univ. publ., 1979 (173 pp.). Tables and a chart to 1000 psia, 480°F are given by Stewart, R. B., R. T. Jacobsen, et al., *Thermodynamic Properties of Refrigerants,* ASHRAE, Atlanta, GA, 1986 (521 pp.). Specific heat and viscosity appear in *Thermophysical Properties of Refrigerants,* ASHRAE, 1993.

TABLE 2-339 Saturated Refrigerant 502[*]

T, K	P, bar	v_f, m^3/kg	v_g, m^3/kg	h_f, kJ/kg	h_g, kJ/kg	s_f, kJ/(kg·K)	s_g, kJ/(kg·K)	c_{pf}, kJ/(kg·K)	μ_f, 10^{-4} Pa·s	k_f, W/(m·K)
200	0.2274	6.381.–4	0.646	–29.04	153.34	–0.1337	0.7782	1.018	5.72	0.103
210	0.4098	6.507.–4	0.374	–20.83	158.42	–0.0937	0.7599	1.036	4.88	0.099
220	0.6965	6.640.–4	0.228	–12.15	163.49	–0.0534	0.7449	1.055	4.23	0.095
230	1.1251	6.783.–4	0.146	–2.99	168.50	–0.0128	0.7328	1.075	3.71	0.091
240	1.7392	6.938.–4	0.0969	6.66	173.42	0.0280	0.7228	1.097	3.28	0.087
250	2.5867	7.105.–4	0.0665	16.78	178.20	0.0691	0.7148	1.120	2.94	0.083
260	3.7188	7.289.–4	0.0470	27.36	182.81	0.1102	0.7082	1.144	2.65	0.079
270	5.1893	7.492.–4	0.0340	38.36	187.21	0.1514	0.7027	1.170	2.41	0.075
280	7.0530	7.720.–4	0.0251	49.77	191.35	0.1923	0.6980	1.197	2.18	0.072
290	9.3660	7.979.–4	0.0188	61.55	195.16	0.2330	0.6937	1.225	1.99	0.068
300	12.19	8.280.–4	0.0143	73.68	198.56	0.2734	0.6896	1.254	1.79	0.064
310	15.57	8.637.–4	0.0109	86.17	201.43	0.3134	0.6852	1.285	1.59	0.060
320	19.60	9.081.–4	0.0084	99.06	203.57	0.3532	0.6798	1.317	1.40	0.056
330	24.35	9.666.–4	0.0064	112.53	204.62	0.3933	0.6723	1.351	1.23	0.052
340	29.95	1.053.–3	0.0048	127.13	203.71	0.4351	0.6604	1.386	1.07	0.048
350	36.62	1.220.–3	0.0033	145.44	197.82	0.4859	0.6355	1.422	0.93	0.044
355.3^c	40.75	1.786.–3	0.0018	174.00	174.00	0.5634	0.5634			

[*] Values reproduced and converted from Table 13, p. 17.101, *ASHRAE Handbook, 1981: Fundamentals,* American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, 1981. Copyright material. Reproduced by permission of the copyright owner. c = critical point. The notation 6.381.–4 signifies 6.381×10^{-4}.

The 1993 ASHRAE *Handbook—Fundamentals* (SI ed.) gives material for integral degrees Celsius with temperatures on the IPTS 68 scale from −70 to 82.2°C. The thermodynamic diagram from 0.1 to 80 bar extends to 180°C. Equations and constants approximated to 1985 ASHRAE tables are given by Mecaryk, K., and M. Masaryk, *Heat Recovery Systems and CHP,* **11,** 2/3 (1991): 193–197. Saturation and superheat tables and a diagram to 20 bar, 515 K are given by Reynolds, W. C., *Thermodynamic Properties in S.I.,* Stanford Univ. publ., 1979 (173 pp.). Tables and a chart to 1000 psia, 400°F appear in Stewart, R. B., R. T. Jacobsen, et al., *Thermodynamic Properties of Refrigerants,* ASHRAE, Atlanta, GA, 1986 (521 pp.). For specific heat and viscosity, see *Thermophysical Properties of Refrigerants,* ASHRAE, 1993.

TABLE 2-340 Saturated Refrigerant 503*

T, K	P, bar	v_f, m^3/kg	v_g, m^3/kg	h_f, kJ/kg	h_g, kJ/kg	s_f, kJ/(kg·K)	s_g, kJ/(kg·K)	c_{pf}, kJ/(kg·K)	μ_f, 10^{-4} Pa·s	k_f, W/(m·K)
150	0.0750	6.384.–4	1.894	–89.60	111.02	–0.4694	0.8681	0.482	6.12	0.128
160	0.1798	6.478.–4	0.837	–79.73	115.40	–0.4057	0.8139	0.554	5.05	0.123
170	0.3828	6.585.–4	0.414	–69.55	119.70	–0.3441	0.7691	0.620	4.16	0.116
180	0.7395	6.700.–4	0.224	–59.08	123.84	–0.2844	0.7318	0.682	3.43	0.111
190	1.3187	6.850.–4	0.130	–48.36	127.77	–0.2267	0.7003	0.747	2.94	0.105
200	2.1999	7.014.–4	0.0803	–37.45	131.45	–0.1710	0.6735	0.817	2.56	0.099
210	3.4713	7.204.–4	0.0520	–26.36	134.84	–0.1173	0.6503	0.896	2.25	0.094
220	5.2281	7.426.–4	0.0350	–15.10	137.87	–0.0656	0.6298	0.988	1.98	0.088
230	7.5713	7.687.–4	0.0242	–3.65	140.49	–0.0155	0.6112	1.017	1.73	0.082
240	10.61	8.001.–4	0.0172	8.07	142.58	0.0334	0.5939	1.227	1.52	0.076
250	14.46	8.386.–4	0.0124	20.22	143.98	0.0817	0.5767	1.382	1.33	0.070
260	19.25	8.874.–4	0.0090	33.10	144.38	0.1305	0.5585	1.57	1.17	0.065
270	25.13	9.526.–4	0.0064	47.22	143.23	0.1816	0.5373	1.79	1.03	0.059
280	32.27	1.050.–3	0.0045	63.64	139.25	0.2384	0.5085	2.03	0.91	0.054
290	40.87	1.264.–3	0.0028	86.41	127.51	0.3131	0.4548	2.35		
292.6^c	43.57	1.773.–3	0.0018	110.20	110.20	0.3864	0.3864	∞		∞

*P, v, h, and s values reproduced and converted from Table 14, p. 17.103, *ASHRAE Handbook, 1981: Fundamentals*, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, 1981. Copyright material. Reproduced by permission of the copyright owner. c_p, μ, and k values interpolated and converted from *Thermophysical Properties of Refrigerants*, American Society of Heating, Refrigerating and Air-Conditioning Engineers, New York, 1976. c = critical point. The notation 6.384.–4 signifies 6.384×10^{-4}.

Saturation and superheat tables and a diagram to 80 bar, 600 K are given by Reynolds, W. C., *Thermodynamic Properties in S.I.*, Stanford Univ. publ., 1979 (173 pp.). Tables and a chart to 1000 psia, 460°F are given by Stewart, R. B., R. T. Jacobsen, et al., *Thermodynamic Properties of Refrigerants*, ASHRAE, Atlanta, GA, 1986 (521 pp.). For specific heat and viscosity see *Thermophysical Properties of Refrigerants*, ASHRAE, 1993. The 1993 ASHRAE *Handbook—Fundamentals* (SI ed.) gives material for integral degrees Celsius with temperatures on the IPTS 68 scale for saturation conditions from –125 to 19.50°C. The thermodynamic diagram from 0.1 to 80 bar extends to 220°C.

TABLE 2-341 Saturated Refrigerant 504*

Temp., °F	Pressure, lb/in^2 abs.	Volume, ft^3/lb		Enthalpy, Btu/lb		Entropy, Btu/(lb)(°F)	
		Liquid	Vapor	Liquid	Vapor	Liquid	Vapor
–120	2.964	0.01095	15.31	–21.48	86.69	–0.0565	0.2609
–100	6.042	0.01119	7.874	–16.39	89.31	–0.0420	0.2519
–80	11.34	0.01146	4.372	–11.12	91.84	–0.0277	0.2435
–60	19.85	0.01175	2.585	–5.65	94.25	–0.0137	0.2362
–40	32.76	0.01206	1.609	0.00	96.50	0.0000	0.2299
–20	51.44	0.01242	1.045	5.85	98.58	0.0135	0.2244
0	77.41	0.01282	0.7029	11.91	100.45	0.0269	0.2195
20	112.3	0.01328	0.4859	18.22	102.09	0.0401	0.2150
40	158.0	0.01379	0.3431	24.81	103.44	0.0533	0.2107
60	216.2	0.01443	0.2458	31.78	104.41	0.0667	0.2065
80	289.2	0.01522	0.1773	39.25	104.85	0.0804	0.2020
100	379.1	0.01629	0.1274	47.43	104.49	0.0948	0.1968
120	488.3	0.01783	0.0893	56.78	102.72	0.1107	0.1899
140	618.1	0.02083	0.0578	69.97	97.70	0.1322	0.1784
150	692.2	0.02597	0.0394	76.96	89.76	0.1432	0.1642

*Unpublished data of Allied Chemical Company, 1970. Used by permission.

TABLE 2-342 Thermodynamic Properties of Refrigerant 507*

Temp., K	Pressure, bar	v_f, m^3/kg	v_g, m^3/kg	h_f, kJ/kg	h_g, kJ/kg	s_f, kJ/(kg·K)	s_g, kJ/(kg·K)
230.5	1.013	0.000 574	0.1280	–3.1	143.3	–0.015	0.620
240	1.59	0.000 602	0.0826	10.3	150.2	0.042	0.623
250	2.42	0.000 627	0.0546	22.6	154.5	0.092	0.619
260	3.54	0.000 658	0.0377	37.6	159.0	0.149	0.617
270	4.95	0.000 695	0.0270	51.6	163.8	0.202	0.618
280	6.70	0.000 738	0.0198	64.7	169.0	0.250	0.620
290	8.85	0.000 787	0.0148	77.2	174.6	0.295	0.634
300	11.52	0.000 839	0.0112	89.4	180.3	0.336	0.640
310	14.74	0.000 903	0.0084	101.6	185.4	0.378	0.648
320	18.76	0.001 006	0.0062	115.7	188.6	0.422	0.649
330	23.65	0.001 221	0.0042	135.5	189.3	0.481	0.641
340	29.57	0.001 618	0.0025	161.7	179.9	0.557	0.611
341.5^c	32.67	0.001 97	0.0020	172.7	172.7	0.590	0.590

*Azeotropic mixture of R152a and R218. $h_f = s_f = 0$ at 233.15 K = –40°C. Interpolated, extrapolated and converted from Lavrenchenko, G. K., M. G. Khmelnuk, et al., *Int. J. Refrig.*, **17**, 7 (1994): 461. Some values are tentative. This source also gives a ln P–h diagram from 0.6 to 30 bar, –50 to 70°C. Differences exist between the published diagram and tables. c = critical point.

TABLE 2-343 Saturated Rubidium*

T, K	P, bar	v_f, m³/kg	v_g, m³/kg	h_f, kJ/kg	h_g, kJ/kg	s_f, kJ/(kg·K)	s_g, kJ/(kg·K)	c_{pf}, kJ/(kg·K)
312.7^m	2.46.–9	6.75.–4		118.7	1036	0.998	3.932	0.379
400	1.69.–6	6.98.–4	2.3.+5	151.6	1057	1.091	3.355	0.375
500	1.73.–4	7.22.–4	2790	188.8	1078	1.174	2.953	0.369
600	0.0037	7.46.–4	156.6	225.4	1096	1.241	2.692	0.362
700	0.0317	7.73.–4	20.75	261.3	1111	1.296	2.511	0.357
800	0.1584	8.10.–4	4.662	296.8	1124	1.343	2.378	0.353
1000	1.467	8.65.–4	0.605	367.6	1150	1.422	2.205	0.360
1200	6.466	9.40.–4	0.159	440.1	1179	1.490	2.104	0.385
1400	18.6	1.03.–3						
1500	28.5	1.08.–3						

*Converted from tables in Vargaftik, *Tables of the Thermophysical Properties of Liquids and Gases,* Nauka, Moscow, 1972, and Hemisphere, Washington, 1975. m = melting point. The notation 2.46.–9 signifies 2.46×10^{-9}.

Many of the Vargaftik values also appear in Ohse, R. W., *Handbook of Thermodynamic and Transport Properties of Alkali Metals,* Blackwell Sci. Pubs., Oxford, 1985 (1020 pp.). This source contains superheat data.

Saturation and superheat tables and a diagram to 40 bar, 1600 K are given by Reynolds, W. C., *Thermodynamic Properties in S.I.,* Stanford Univ. publ., 1979 (173 pp.).

For a Mollier diagram from 0.1 to 320 psia, 1200 to 2700°R, see Weatherford, W. D., J. C. Tyler, et al., WADD-TR-61-96, 1961. An extensive review of properties of the solid and the saturated liquid was given by Alcock, C. B., M. W. Chase, et al., *J. Phys. Chem. Ref. Data,* **23,** 3 (1994): 385–497.

TABLE 2-344 Thermophysical Properties of Saturated Seawater

Temp., °C	Pressure, bar	v, (m³/kg)10³	c_p, kJ/(kg·K)	μ, Ns/m²	k, W/(m·K)	N_{Pr}	$10^5\kappa$, 1/bar
0	0.005993	1.000158	4.000	0.001884	0.560	13.46	5.06
1	0.006438	1.000099	4.000	0.001827	0.563	12.98	5.02
2	0.006916	1.000057	4.000	0.001772	0.565	12.55	4.98
3	0.007427	1.000033	4.000	0.001720	0.567	12.13	4.95
4	0.007970	1.000025	4.001	0.001669	0.569	11.74	4.92
5	0.008548	1.000033	4.001	0.001620	0.571	11.35	4.89
6	0.009163	1.000057	4.001	0.001574	0.574	10.97	4.86
7	0.009816	1.000096	4.002	0.001529	0.576	10.62	4.83
8	0.010511	1.000149	4.002	0.001486	0.578	10.29	4.80
9	0.011248	1.000261	4.002	0.001445	0.580	9.97	4.78
10	0.01203	1.000298	4.003	0.001405	0.582	9.70	4.76
11	0.01286	1.000392	4.003	0.001367	0.584	9.37	4.74
12	0.01374	1.000500	4.003	0.001330	0.586	9.09	4.72
13	0.01467	1.000620	4.004	0.001294	0.588	8.81	4.70
14	0.01566	1.000727	4.004	0.001259	0.590	8.54	4.68
15	0.01671	1.000899	4.005	0.001226	0.592	8.29	4.66
16	0.01781	1.001055	4.005	0.001195	0.594	8.06	4.65
17	0.01898	1.001224	4.006	0.001165	0.595	7.82	4.63
18	0.02022	1.001404	4.006	0.001136	0.597	7.62	4.62
19	0.02153	1.001595	4.007	0.001107	0.599	7.41	4.60
20	0.02291	1.001796	4.007	0.001080	0.600	7.21	4.59
21	0.02437	1.002009	4.007	0.001054	0.602	7.02	4.57
22	0.02591	1.002232	4.008	0.001029	0.604	6.82	4.56
23	0.02753	1.002465	4.008	0.001005	0.605	6.66	4.55
24	0.02924	1.002708	4.009	0.000981	0.607	6.48	4.54
25	0.03104	1.002961	4.009	0.000958	0.608	6.31	4.53
26	0.03294	1.003224	4.009	0.000936	0.609	6.16	4.52
27	0.03494	1.003496	4.010	0.000915	0.611	6.01	4.51
28	0.03705	1.003778	4.010	0.000895	0.612	5.86	4.50
29	0.03926	1.004069	4.011	0.000875	0.614	5.72	4.49
30	0.04159	1.004369	4.011	0.000855	0.615	5.58	4.48

$\kappa = (-1/V)(\partial v/\partial p)_T \cdot 10^5$. Thus, at 0°C, the compressibility is 5.06×10^{-5}/bar.

For further information see, for instance, Bromley, LeR. A., *J. Chem. Eng. Data,* **12,** 2 (1967): 202–206; **13,** 1 (1968): 60–62 and **13,** 3: 399–402; **15,** 2 (1970): 246–253; and *A.I.Ch.E.J.,* **20,** 2 (1974): 326–335.

Thermal conductivity data sources include Castelli, V. J., E. M. Stanley, et al., *Deep Sea Res.,* **211** (1974): 311–318; Levy, F. L., *Int. J. Refrig.,* **5,** 3 (1982): 155–159.

For velocity of sound, see, for instance, U.S. Naval Oceanographic Office SP 58, 1962 (50 pp.). More recent information is contained in UNESCO technical papers. See *Marine Science* No. 38, 1981 (6 pp.) and No. 44, 1983 (53 pp.).

For sea ice properties, see Fukusako, S., *Int. J. Thermophys.,* **11,** 2 (1990): 353–372.

TABLE 2-345 Saturated Sodium

Temp., K	Pressure, bar	v_f, m^3/kg	v_g, m^3/kg	h_f, kJ/kg	h_g, kJ/kg	s_f, kJ/(kg·K)	s_g, kJ/(kg·K)	c_{pf}, kJ/(kg·K)	c_{pg}, kJ/(kg·K)	μ_f, 10^{-6} Pa·s	μ_g, 10^{-6} Pa·s	k_f, W/(m·K)	k_g, W/(m·K)	Pr_f	Pr_g
371	1.59.–10	0.001 078	8.54.+9	207	4739	2.259	14.475	1.383		688		89.4		0.0106	
400	1.80.–9	0.001 088	8.08.+8	247	4757	2.920	14.195	1.372	0.86	599		87.2		0.0094	
500	8.99.–7	0.001 115	1.99.+6	382	4817	3.222	12.092	1.334	1.25	415		80.1		0.0069	
600	5.57.–5	0.001 144	38022	514	4872	3.462	10.745	1.301	1.80	321		73.7		0.0057	
700	0.00105	0.001 174	2320	642	4921	3.661	10.631	1.277	2.28	264		68.0		0.0050	
800	0.00941	0.001 208	291.5	769	4966	3.830	9.076	1.260	2.59	227	19.6	62.9	0.0343	0.0045	1.48
900	0.05147	0.001 242	58.8	895	5007	3.978	8.547	1.252	2.72	201	20.6	58.3	0.0406	0.0043	1.38
1000	0.1995	0.001 280	16.6	1020	5044	4.110	8.134	1.252	2.70	181	23.0	54.2	0.0455	0.0042	1.36
1100	0.6016	0.001 323	5.95	1146	5079	4.230	7.805	1.261	2.62	166	25.3	50.5	0.0492	0.0042	1.35
1154.7	1.013	0.001 347	3.89	1215	5097	4.290	7.652	1.271	2.56	159	26.5	48.7	0.0522	0.0041	1.30
1200	1.50	0.001 366	2.54	1273	5111	4.340	7.538	1.279	2.51	153	27.5	47.2	0.0547	0.0041	1.26
1300	3.26	0.001 416	1.24	1402	5140	4.444	7.319	1.305	2.43	143	29.9	44.0	0.0570	0.0042	1.27
1400	6.30	0.001 471	0.676	1534	5168	4.542	7.138	1.340	2.39	135	32.2	41.1	0.0592	0.0044	1.30
1500	11.13	0.001 531	0.400	1671	5193	4.636	6.984	1.384	2.36	128	34.6	38.2		0.0046	
1600	18.28	0.001 597	0.253	1812	5217	4.727	6.855	1.437	2.34	122	37.1	35.4		0.0050	
1700	28.28	0.001 675	0.168	1959	5238	4.816	6.745	1.500	2.41	117		32.6		0.0054	
1800	41.61	0.001 761	0.117	2113	5256	4.904	6.650	1.574	2.46	112		29.7		0.0059	
1900	58.70	0.001 862	0.084	2274	5268	4.992	6.568	1.661	2.53	108		26.6		0.0067	
2000	79.91	0.001 984	0.063	2444	5273	5.079	6.494	1.764	2.66	104		23.2		0.0079	
2100	105.5	0.002 174	0.0472	2625	5265			1.926	2.91						
2200	135.7	0.002 320	0.0361	2822	5241			2.190	3.40						
2300	170.6	0.002 584	0.0275	3047	5188			2.690	4.47						
2400	210.3	0.002 985	0.0203	3331	5078			4.012	8.03						
2500	254.7	0.004 19	0.0098	3965	4617			39.3	417.						
2503.7^c	256.4	0.004 57	0.0046	4294	4294										

c = critical point.

s_f values converted from Cordfunke, E. H. P. and R. J. M. Konings, *Thermochemical Data for Reactor Materials and Fission Products,* North Holland Elsevier, NY, 1990. s_g determined as $s_f + (h_g - h_f)/T$. μ_g and k_g values estimated by P. E. Liley. All other values are from Fink, J. K. and L. Leibowitz, Argonne Nat. Lab Rept. ANL/RE-95-2, 1995. The Fink and Leibowitz work also appeared in *High Temp. Materials Sci.,* **35,** 65–103, 1996. Saturation and superheat tables and a diagram to 14 bar, 1700 K are given by Reynolds, W. C., *Thermodynamic Properties in S.I.*, Stanford Univ. publ., 1979 (173 pp.). For a Mollier diagram for 0.1–150 psia, 1500–2700°R, see Weatherford, P. M., J. C. Tyler, et al., WADD-TR-61-96, 1961.

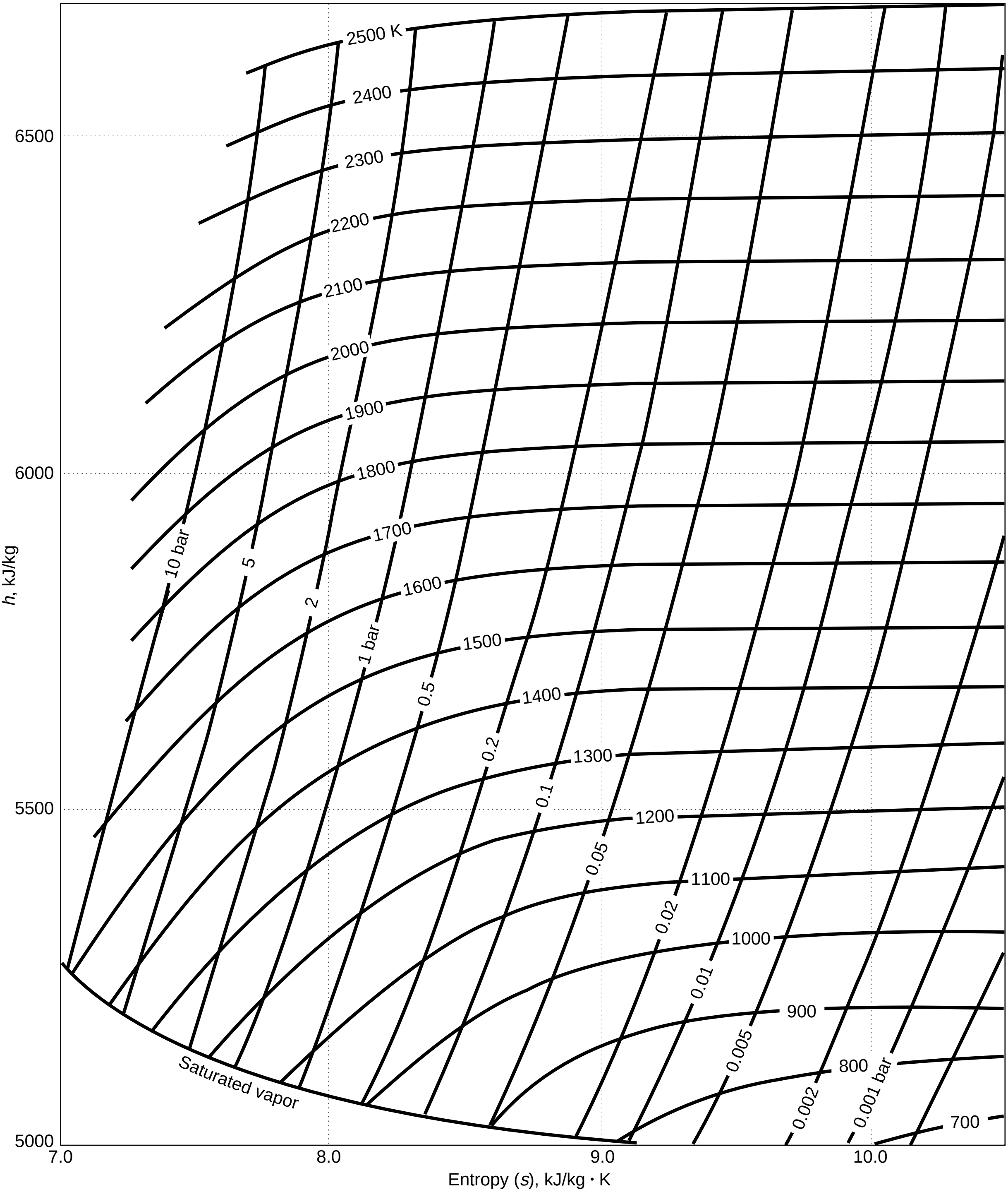


FIG. 2-28 Mollier Diagram for Sodium. Drawn from the Vargaftik et al. values in Ohse, R. W., *Handbook of Thermodynamic and Transport Properties of Alkali Metals,* Blackwell Sci. Pubs., Oxford, UK, 1985. These values are identical with those of Vargaftik, N. B., *Handbook of Thermophysical Properties of Gases and Liquids,* Moscow, 1972, and the Hemisphere translation, pp. 19. An apparent discontinuity exists between the superheat values and the saturation values, not reproduced here. For a Mollier diagram in f.p.s. units from 0.1 to 150 psia, 1500 to 2700°R, see Fig. 3-36, p. 3-232 of the 6th edition of this handbook. An extensive review of properties of the solid and the saturated liquid was given by Alcock, C. B., Chase, M. W. et al., *J. Phys. Chem. Ref. Data,* **23**(3), 385–497, 1994.

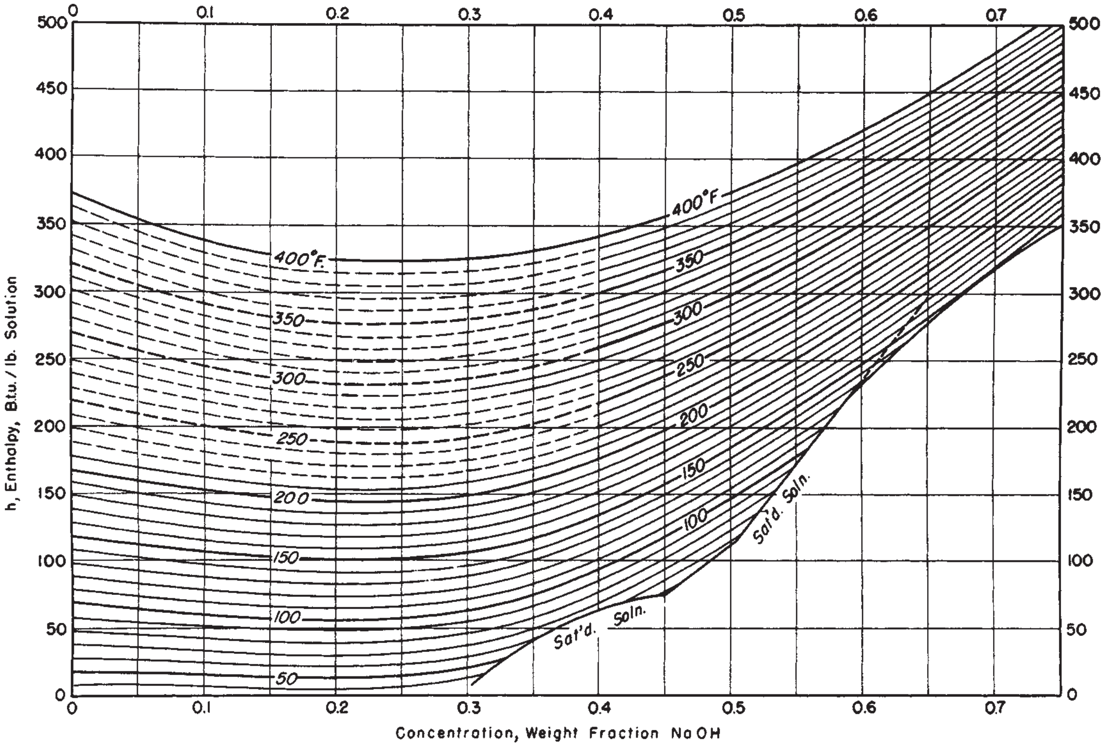


FIG. 2-29 Enthalpy-concentration diagram for aqueous sodium hydroxide at 1 atm. Reference states: enthalpy of liquid water at 32°F and vapor pressure is zero; partial molal enthalpy of infinitely dilute NaOH solution at 64°F and 1 atm is zero. [*McCabe,* Trans. Am. Inst. Chem. Eng., ***31,*** *129 (1935).*]

TABLE 2-346 Saturated Sulfur Dioxide*

T, K	P, bar	v_f, m³/kg	v_g, m³/kg	h_f, kJ/kg	h_g, kJ/kg	s_f, kJ/(kg·K)	s_g, kJ/(kg·K)	c_{pf}, kJ/(kg·K)	μ_f, 10^{-4} Pa·s	k_f, W/(m·K)
200	0.02056	6.189.–4	12.602	7.4	433.3	0.033	2.212	1.280	12.3	
210	0.04569	6.284.–4	5.946	9.1	446.1	0.041	2.159	1.284	10.6	
220	0.09997	6.384.–4	2.876	28.6	453.8	0.123	2.075	1.288	8.37	
230	0.1844	6.488.–4	1.605	43.5	459.5	0.198	2.001	1.293	7.03	
240	0.3202	6.596.–4	0.9602	56.5	464.5	0.254	1.952	1.299	5.97	
250	0.5430	6.707.–4	0.5864	70.0	469.7	0.308	1.906	1.308	5.11	0.262
260	0.8778	6.819.–4	0.3745	85.1	474.5	0.363	1.865	1.317	4.39	0.243
270	1.3634	6.938.–4	0.2479	99.8	479.3	0.425	1.827	1.328	3.78	0.224
280	2.0402	7.057.–4	0.1699	114.8	484.3	0.473	1.793	1.343	3.30	0.206
290	2.9574	7.184.–4	0.1197	129.2	488.5	0.523	1.763	1.363	2.87	0.190
300	4.1675	7.312.–4	0.08647	143.1	492.5	0.568	1.732	1.389	2.51	0.174
310	5.7372	7.447.–4	0.06366	157.1	496.3	0.612	1.706	1.422	2.19	0.162
320	7.8226	7.590.–4	0.04707	170.1	498.9	0.649	1.678	1.459	1.91	0.151
330	10.301	7.847.–4	0.03572	183.0	501.2	0.690	1.654	1.499	1.67	0.139
340	13.229	8.066.–4	0.02792	196.0	502.5	0.731	1.633	1.546	1.46	0.128
350	16.759	8.303.–4	0.02209	211.2	502.9	0.781	1.614	1.603	1.27	0.117
360	21.01	8.571.–4	0.01755	223.7	503.1	0.817	1.593	1.68	1.11	0.108
370	26.01	8.877.–4	0.01399	239.9	502.9	0.862	1.573	1.75	0.96	0.098
380	31.92	9.236.–4	0.01110	257.9	502.7	0.910	1.555	1.84	0.84	0.089
390	38.76	9.671.–4	0.00877	277.7	500.7	0.962	1.534	1.97	0.73	0.081
400	46.67	1.023.–3	0.00685	300.2	496.7	1.020	1.511	2.12	0.63	0.072
410	55.80	1.098.–3	0.00559	326.2	489.5	1.083	1.481		0.53	0.064
420	66.19	1.235.–3	0.00387	355.6	474.1	1.155	1.436		0.44	0.055
425.1[c]	78.81	1.906.–3	0.00191	423.6	423.6	1.304	1.304			

*Values interpolated and converted from tables of Kang, McKetta, et al., Bur. Eng. Res. Repr. 59, University of Texas, Austin, 1961. See also *J. Chem. Eng. Data,* **6** (1961): 220–227; and *Am. Inst. Chem. Eng. J.,* **7** (1961): 418. c = critical point. The notation 6.189.–4 signifies 6.189×10^{-4}. The AIChE publication contains a Mollier diagram to 4500 psia, 480°F, while the reprint contains saturation and superheat tables.

TABLE 2-347 Thermodynamic Properties of Saturated Sulfur Hexafluoride (SF_6)*

Temp., K	Pressure, bar	v_f, m³/kg	v_g, m³/kg	h_f, kJ/kg	h_g, kJ/kg	s_f, kJ/(kg·K)	s_g, kJ/(kg·K)	c_{pf}, kJ/(kg·K)	c_{pg}, kJ/(kg·K)
222.4	2.200	0.0005389	0.05428	–57.55	59.08	–0.2310	0.2935		0.579
225	2.470	0.0005429	0.04861	–54.41	60.49	–0.2171	0.2936		0.583
230	3.045	0.0005507	0.03978	–48.51	63.12	–0.1913	0.2940		0.592
235	3.710	0.0005588	0.03286	–42.67	65.68	–0.1663	0.2947		0.602
240	4.475	0.0005675	0.02737	–36.87	68.18	–0.1421	0.2956		0.613
245	5.346	0.0005768	0.02296	–31.13	70.61	–0.1186	0.2966		0.626
250	6.332	0.0005866	0.01939	–25.47	72.96	–0.0960	0.2977		0.640
255	7.442	0.0005971	0.01647	–19.87	75.22	–0.0741	0.2988		0.656
260	8.684	0.0006085	0.01406	–14.33	77.39	–0.0528	0.2999		0.674
265	10.07	0.0006207	0.01205	–8.85	79.44	–0.0323	0.3009		0.695
270	11.60	0.0006341	0.01035	–3.41	81.38	–0.0123	0.3017		0.720
275	13.30	0.0006488	0.00892	2.00	83.19	0.0071	0.3024		0.748
280	15.18	0.0006652	0.00769	7.42	84.84	0.0262	0.3027		0.783
285	17.25	0.0006836	0.00663	12.88	86.30	0.0451	0.3027		0.827
290	19.52	0.0007047	0.00571	18.45	87.52	0.0639	0.3021	0.409	0.882
295	22.01	0.0007295	0.00490	24.20	88.45	0.0829	0.3008	0.631	0.941
300	24.75	0.0007594	0.00418	30.22	89.00	0.1025	0.2984	0.870	1.070
305	27.76	0.000798	0.00352	36.75	88.97	0.1233	0.2945	1.17	1.26
310	31.05	0.000851	0.00291	44.05	88.06	0.1462	0.2881	1.63	1.63
315	34.67	0.000949	0.00228	53.98	85.22	0.1769	0.2761	2.48	2.40
318.7	37.79	0.001372	0.00137	71.74	71.74	0.2317	0.2317	∞	∞

*See also Oda, A., M. Uematsu, et al., *Bull. JSME*, **26,** 219 (1983): 1590–1596. Ulybin, S.A., *Thermodynamic Properties of Sulfur Hexafluoride,* Moscow, 1977 (53 pp.). For thermal conductivity to 500 bar, see Rastorguev, Yu L., B. A. Grigorev, et al., *Teploenergetika* **24,** 6 (1977): 78–81 and Bakulin, S. S. and S. A. Ulybin, *Teplofiz. Vysok. Temp.*, **16,** 1 (1978): 59–66. For viscosity to 400 bar, see Grigorev, B. A., A. S. Keramidi, et al., *Teploenergetika,* **24,** 9 (1977): 85–87; and Ulybin, S. A. and V. I. Makanushkin, *Teplofiz. Vysok. Temp.*, **15,** 6 (1977): 1195–1201.

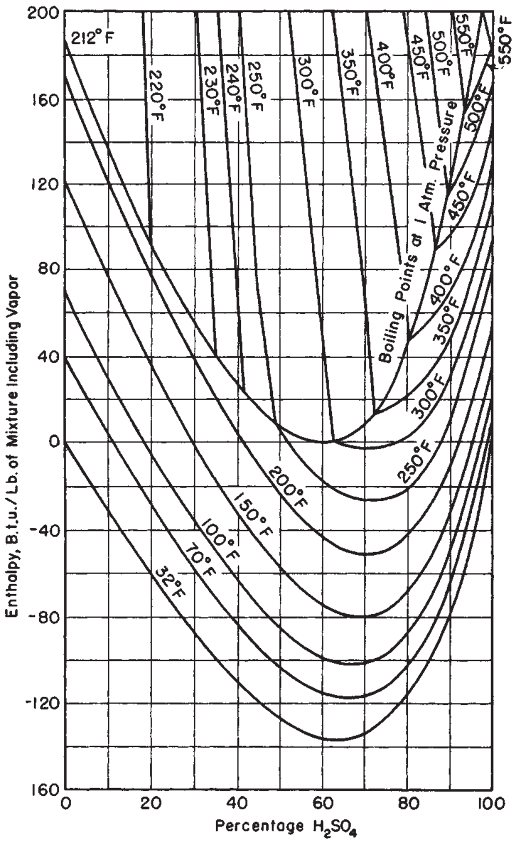


FIG. 2-30 Enthalpy-concentration diagram for aqueous sulfuric acid at 1 atm. Reference states: enthalpies of pure-liquid components at 32°F and vapor pressures are zero. NOTE: It should be observed that the weight basis includes the vapor, which is particularly important in the two-phase region. The upper ends of the tie lines in this region are assumed to be pure water. (*Hougen and Watson,* Chemical Process Principles, *part I, Wiley, New York, 1943.*)

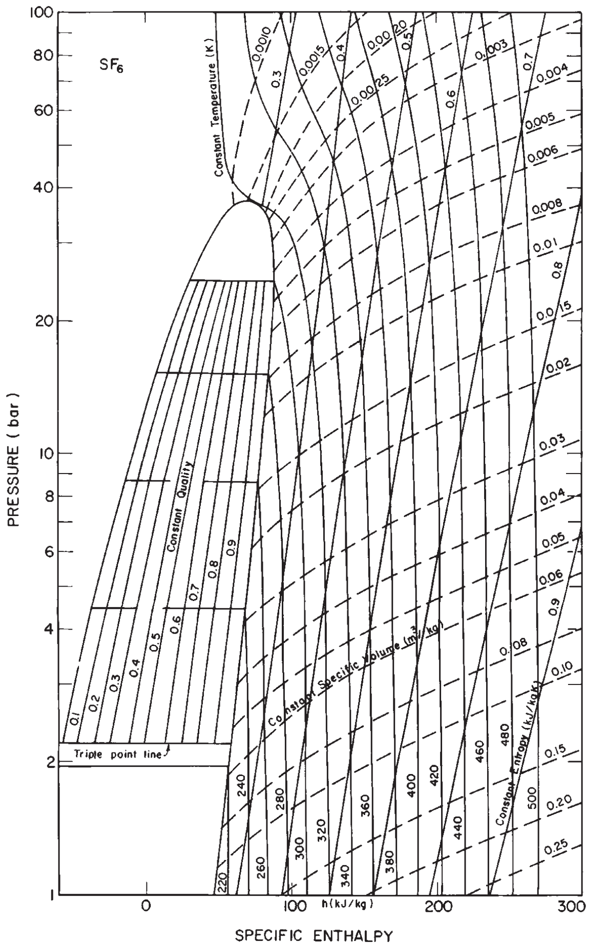


FIG. 2-31 Enthalpy–log-pressure diagram for sulfur hexafluoride.

TABLE 2-348 Saturated SUVA AC 9000

DuPont bulletin T–AC–9000–SI, 1994 (16 pp.) gives tables and a chart to 100 bar, 235°C. With a stated composition of 23% wt CH_2F_2 (R23), 25% wt CHF_2CF_3 (R125), and 52% wt CH_2FCH_3 (R134a) this is apparently identical to KLEA 66, to which the reader is referred.

TABLE 2-349 Saturated Toluene[*]

T, K	P, bar	v_f, m^3/kg	v_g, m^3/kg	h_f, kJ/kg	h_g, kJ/kg	s_f, kJ/(kg·K)	s_g, kJ/(kg·K)	c_{pf}, kJ/(kg·K)	μ_f, 10^{-4} Pa·s	k_f, W/(m·K)
270	0.0076	1.127.–3	34.9	316.7	745.7	2.236	3.825	1.64	8.02	0.141
280	0.0139	1.138.–3	19.1	333.0	756.1	2.295	3.806	1.66	6.96	0.138
290	0.0246	1.150.–3	10.6	349.6	766.8	2.353	3.792	1.68	6.10	0.136
300	0.0418	1.162.–3	6.46	366.5	777.8	2.410	3.782	1.71	5.41	0.133
310	0.0682	1.175.–3	4.08	383.7	789.2	2.467	3.776	1.74	4.83	0.131
320	0.1072	1.188.–3	2.67	401.3	800.9	2.522	3.771	1.78	4.34	0.128
330	0.1633	1.201.–3	1.80	419.6	812.9	2.577	3.771	1.81	3.93	0.126
340	0.2416	1.215.–3	1.25	437.4	825.2	2.632	3.772	1.84	3.58	0.124
350	0.3480	1.230.–3	0.891	456.0	837.8	2.686	3.777	1.88	3.28	0.121
360	0.4894	1.245.–3	0.698	475.1	850.7	2.739	3.783	1.92	3.01	0.119
370	0.6736	1.261.–3	0.481	494.6	863.8	2.792	3.791	1.96	2.78	0.117
380	0.9090	1.277.–3	0.364	514.4	877.2	2.846	3.801	2.01	2.56	0.114
390	1.2049	1.294.–3	0.279	534.7	890.9	2.898	3.811	2.05	2.37	0.112
400	1.5713	1.312.–3	0.218	555.4	904.8	2.950	3.824	2.09	2.19	0.110
420	2.5589	1.350.–3	0.137	598.1	933.1	3.054	3.852	2.17	1.89	0.105
440	3.965	1.393.–3	9.00.–2	642.3	962.0	3.156	3.883	2.24	1.64	0.101
460	5.892	1.443.–3	6.11.–2	688.1	991.3	3.258	3.917	2.31		0.096
480	8.451	1.499.–3	4.26.–2	735.5	1021.1	3.358	3.953	2.38		0.091
500	11.76	1.567.–3	3.03.–2	784.4	1051.3	3.457	3.989	2.45		0.086
520	15.96	1.651.–3	2.19.–2	834.9	1081.4	3.554	4.027	2.53		0.082
540	21.99	1.761.–3	1.58.–2	887.3	1109.6	3.651	4.062	2.65		0.078
560	27.65	1.919.–3	1.13.–2	942.8	1132.1	3.750	4.088	2.82		0.074
580	35.56	2.213.–3	7.59.–3	1005.6	1142.3	3.857	4.093			
590	40.16	2.650.–3	5.28.–3	1050.2	1128.1	3.932	4.063			
591.8^c	41.04	3.432.–3	3.43.–3	1084.9	1084.9	3.989	3.989			

[*] Values converted and mostly rounded off from the tables of Counsell, Lawrenson, and Lees, Nat. Phys. Lab., Teddington (U.K.) Rep. Chem. 52, 1976. c = critical point. The notation 1.127.–6 signifies 1.127×10^{-6}. For other tables, see Goodwin, R. D., *J. Phys. Chem. Ref. Data*, **18,** 4 (1989): 1565–1636.

TABLE 2-350 Saturated Solid/Vapor Water[*]

Temp., °F	Pressure, lb/in^2 abs.	Volume, ft^3/lb		Enthalpy, Btu/lb		Entropy, Btu/(lb)(°F)	
		Solid	Vapor	Solid	Vapor	Solid	Vapor
−160	4.949.–8	0.01722	3.607.+9	−222.05	990.38	−0.4907	3.5549
−150	1.620.–7	0.01723	1.139.+9	−218.82	994.80	−0.4801	3.4387
−140	4.928.–7	0.01724	3.864.+8	−215.49	999.21	−0.4695	3.3301
−130	1.403.–6	0.01725	1.400.+8	−212.08	1003.63	−0.4590	3.2284
−120	3.757.–6	0.01726	5.386.+7	−208.58	1008.05	−0.4485	3.1330
−110	9.517.–6	0.01728	2.189.+7	−204.98	1012.47	−0.4381	3.0434
−100	2.291.–5	0.01729	9.352.+6	−201.28	1016.89	−0.4277	2.9591
−90	5.260.–5	0.01730	4.186.+6	−197.49	1021.31	−0.4173	2.8796
−80	1.157.–4	0.01731	1.955.+6	−193.60	1025.73	−0.4069	2.8045
−70	2.443.–4	0.01732	9.501.+5	−189.61	1030.15	−0.3965	2.7336
−60	4.972.–4	0.01734	4.788.+5	−185.52	1034.58	−0.3862	2.6664
−50	9.776.–4	0.01735	2.496.+5	−181.34	1039.00	−0.3758	2.6028
−45	1.354.–3	0.01736	1.824.+5	−179.21	1041.21	−0.3707	2.5723
−40	1.861.–3	0.01737	1.343.+5	−177.06	1043.42	−0.3655	2.5425
−35	2.540.–3	0.01737	9.961.+4	−174.88	1045.63	−0.3604	2.5135
−30	3.440.–3	0.01738	7.441.+4	−172.68	1047.84	−0.3552	2.4853
−25	4.627.–3	0.01739	5.596.+4	−170.46	1050.05	−0.3501	2.4577
−20	6.181.–3	0.01739	4.237.+4	−168.21	1052.26	−0.3449	2.4308
−15	8.204.–3	0.01740	3.228.+4	−165.94	1054.47	−0.3398	2.4046
−10	1.082.–2	0.01741	2.475.+4	−163.65	1056.67	−0.3347	2.3791
−5	1.419.–2	0.01741	1.909.+4	−161.33	1058.88	−0.3295	2.3541
0	1.849.–2	0.01742	1.481.+4	−158.98	1061.09	−0.3244	2.3297
5	2.396.–2	0.01743	1.155.+4	−156.61	1063.29	−0.3193	2.3039
10	3.087.–2	0.01744	9.060.+3	−154.22	1065.50	−0.3142	2.2827
15	3.957.–2	0.01744	7.144.+3	−151.80	1067.70	−0.3090	2.2600
16	4.156.–2	0.01745	6.817.+3	−151.32	1068.14	−0.3080	2.2555
18	4.581.–2	0.01745	6.210.+3	−150.34	1069.02	−0.3060	2.2466
20	5.045.–2	0.01745	5.662.+3	−149.36	1069.90	−0.3039	2.2378
22	5.552.–2	0.01746	5.166.+3	−148.38	1070.38	−0.3019	2.2291
24	6.105.–2	0.01746	4.717.+3	−147.39	1071.66	−0.2998	2.2205
26	6.708.–2	0.01746	4.311.+3	−146.40	1072.53	−0.2978	2.2119
28	7.365.–2	0.01746	3.943.+3	−145.40	1073.41	−0.2957	2.2034
30	8.080.–2	0.01747	3.608.+3	−144.40	1074.29	−0.2937	2.1950
31	8.461.–2	0.01747	3.453.+3	−143.90	1074.73	−0.2927	2.1908
32	8.858.–2	0.01747	3.305.+3	−143.40	1075.16	−0.2916	2.1867

[*] Condensed from *Fundamentals*, American Society of Heating, Refrigerating and Air-Conditioning Engineers, 1967 and 1972. Reproduced by permission. The validity of many standard reference tables has been critically reviewed by Jancso, Pupezin, and van Hook, *J. Phys. Chem.*, **74** (1970): 2984. This source is recommended for further study. The notation 4.949.–8, 3.607.+9, etc., means 4.949×10^{-8}, 3.607×10^{9}, etc.

TABLE 2-351 Saturated Water Substance—Temperature (fps units)*

Temp., °F	Pressure, lb/in^2 abs.	Volume, ft^3/lb		Enthalpy, Btu/lb		Entropy, Btu/(lb)(°F)	
		Liquid	Vapor	Liquid	Vapor	Liquid	Vapor
32.018	0.08865	0.016022	3302.4	0.000	1075.5	0.0000	2.1872
35	0.09991	0.016020	2948.1	3.002	1076.8	0.0061	2.1767
40	0.12163	0.016019	2445.8	8.027	1079.0	0.0162	2.1594
45	0.14744	0.016020	2037.8	13.044	1081.2	0.0262	2.1426
50	0.17796	0.016023	1704.8	18.054	1083.4	0.0361	2.1262
55	0.21392	0.016027	1432.0	23.059	1085.6	0.0458	2.1102
60	0.25611	0.016033	1207.6	28.060	1087.7	0.0555	2.0946
65	0.30545	0.016041	1022.1	33.057	1089.9	0.0651	2.0794
70	0.36292	0.016050	868.4	38.052	1092.1	0.0745	2.0645
75	0.42964	0.016060	740.3	43.045	1094.3	0.0839	2.0500
80	0.50683	0.016072	633.3	48.037	1096.4	0.0932	2.0359
85	0.59583	0.016085	543.6	53.027	1098.6	0.1024	2.0221
90	0.69813	0.016099	468.1	58.018	1100.8	0.1115	2.0086
95	0.81534	0.016114	404.4	63.008	1102.9	0.1206	1.9954
100	0.94294	0.016130	350.4	67.999	1105.1	0.1295	1.9825
110	1.2750	0.016165	265.39	77.98	1109.3	0.1472	1.9577
120	1.6927	0.016204	203.26	87.97	1113.6	0.1646	1.9339
130	2.2230	0.016247	157.33	97.96	1117.8	0.1817	1.9112
140	2.8892	0.016293	122.98	107.89	1122.0	0.1985	1.8895
150	3.7184	0.016343	97.07	117.95	1126.1	0.2150	1.8686
160	4.7414	0.016395	77.27	127.96	1130.2	0.2313	1.8487
170	5.9926	0.016451	62.06	137.97	1134.2	0.2473	1.8295
180	7.5110	0.016510	50.225	148.00	1138.2	0.2631	1.8111
190	9.340	0.016572	40.957	158.04	1142.1	0.2787	1.7934
200	11.526	0.016637	33.639	168.09	1146.0	0.2940	1.7764
210	14.123	0.016705	27.816	178.15	1149.7	0.3091	1.7600
212	14.696	0.016719	26.799	180.17	1150.5	0.3121	1.7568
220	17.186	0.016775	23.148	188.23	1153.4	0.3241	1.7442
230	20.779	0.016849	19.381	198.33	1157.1	0.3388	1.7290
240	24.968	0.016926	16.321	208.45	1160.6	0.3533	1.7142
250	29.825	0.017066	13.819	218.59	1164.0	0.3677	1.7000
260	35.427	0.017089	11.762	228.76	1167.4	0.3819	1.6862
270	41.856	0.017175	10.060	238.95	1170.6	0.3960	1.6729
280	49.200	0.017264	8.644	249.17	1173.8	0.4098	1.6599
290	57.550	0.01736	7.4603	259.4	1167.8	0.4236	1.6473
300	67.005	0.01745	6.4658	269.7	1179.7	0.4372	1.6351
320	89.643	0.01766	4.9138	290.4	1185.2	0.4640	1.6116
340	117.992	0.01787	3.7878	311.3	1190.1	0.4902	1.5892
360	153.01	0.01811	2.9573	332.3	1194.4	0.5161	1.5678
380	195.73	0.01836	2.3353	353.6	1198.0	0.5416	1.5473
400	247.26	0.01864	1.8630	375.1	1201.0	0.5667	1.5274
420	308.78	0.01894	1.4997	396.9	1203.1	0.5915	1.5080
440	381.54	0.01926	1.2169	419.0	1204.4	0.6161	1.4890
460	466.87	0.01961	0.99424	441.5	1204.8	0.6405	1.4704
480	566.15	0.02000	0.81717	464.5	1204.1	0.6648	1.4518
500	680.86	0.02043	0.67492	487.9	1202.2	0.6890	1.4333
520	812.53	0.02091	0.55956	512.0	1199.0	0.7133	1.4146
540	962.79	0.02146	0.46513	536.8	1194.3	0.7378	1.3954
560	1133.38	0.02207	0.38714	562.4	1187.7	0.7625	1.3757
580	1326.17	0.02279	0.32216	589.1	1179.0	0.7876	1.3550
600	1543.2	0.02364	0.26747	617.1	1167.7	0.8134	1.3330
620	1786.9	0.02466	0.22081	646.9	1153.2	0.8403	1.3092
640	2059.9	0.02595	0.18021	679.1	1133.7	0.8686	1.2821
660	2365.7	0.02768	0.14431	714.9	1107.0	0.8995	1.2498
680	2708.6	0.03037	0.11117	758.5	1068.5	0.9365	1.2086
700	3094.3	0.03662	0.07519	825.2	991.7	0.9924	1.1359
702	3135.5	0.03824	0.06997	835.0	979.7	1.0006	1.1210
704	3177.2	0.04108	0.06300	854.2	956.2	1.0169	1.1046
705.47	3208.2	0.05078	0.05078	906.0	906.0	1.0612	1.0612

*Extracted and condensed from 1967 ASME Steam Tables. Copyright reserved. Reproduced by permission.

TABLE 2-352 Saturated Water Substance—Temperature (SI units)

Temp., K	Pressure, bar*	Volume, m³/kg		Enthalpy, kJ/kg		Entropy, kJ/(kg·K)		Specific heat, C_p, kJ/(kg·K)		Viscosity, Ns/m²		Thermal conductivity, W/(m·K)		Prandtl no.		Surface tension, N/m	Temp., K
		Condensed†	Vapor	Condensed†	Vapor	Condensed†	Vapor	Condensed†	Vapor	Condensed†	Vapor	Condensed†	Vapor	Condensed†	Vapor	Condensed†	
150	6.30.–11	1.073.–3	9.55.+9	–539.6	2273	–2.187	16.54	1.155				3.73					150
160	7.72.–10	1.074.–3	9.62.+8	–525.7	2291	–2.106	15.49	1.233				3.52					160
170	7.29.–9	1.076.–3	1.08.+8	–511.7	2310	–2.026	14.57	1.311				3.34					170
180	5.38.–8	1.077.–3	1.55.+7	–497.8	2328	–1.947	13.76	1.389				3.18					180
190	3.23.–7	1.078.–3	2.72.+6	–483.8	2347	–1.868	13.03	1.467				3.04					190
200	1.62.–6	1.079.–3	5.69.+5	–467.5	2366	–1.789	12.38	1.545				2.91					200
210	7.01.–6	1.081.–3	1.39.+5	–451.2	2384	–1.711	11.79	1.623				2.79					210
220	2.65.–5	1.082.–3	3.83.+4	–435.0	2403	–1.633	11.20	1.701				2.69					220
230	8.91.–5	1.084.–3	1.18.+4	–416.3	2421	–1.555	10.79	1.779				2.59					230
240	3.72.–4	1.085.–3	4.07.+3	–400.1	2440	–1.478	10.35	1.857				2.50					240
250	7.59.–4	1.087.–3	1.52.+3	–381.5	2459	–1.400	9.954	1.935				2.42					250
255	1.23.–3	1.087.–3	956.4	–369.8	2468	–1.361	9.768	1.974				2.38					255
260	1.96.–3	1.088.–3	612.2	–360.5	2477	–1.323	9.590	2.013				2.35					260
265	3.06.–3	1.089.–3	400.4	–351.2	2486	–1.281	9.461	2.052				2.31					265
270	4.69.–3	1.090.–3	265.4	–339.6	2496	–1.296	9.255	2.091				2.27					270
273.15	6.11.–3	1.091.–3	206.3	–333.5	2502	–1.221	9.158	2.116				2.26					273.15
273.15	0.00611	1.000.–3	206.3	0.0	2502	0.000	9.158	4.217	1.854	1750.–6	8.02.–6	0.569	0.0182	12.99	0.815	0.0755	273.15
275	0.00697	1.000.–3	181.7	7.8	2505	0.028	9.109	4.211	1.855	1652.–6	8.09.–6	0.574	0.0183	12.22	0.817	0.0753	275
280	0.00990	1.000.–3	130.4	28.8	2514	0.104	8.980	4.198	1.858	1422.–6	8.29.–6	0.582	0.0186	10.26	0.825	0.0748	280
285	0.01387	1.000.–3	99.4	49.8	2523	0.178	8.857	4.189	1.861	1225.–6	8.49.–6	0.590	0.0189	8.81	0.833	0.0743	285
290	0.01917	1.001.–3	69.7	70.7	2532	0.251	8.740	4.184	1.864	1080.–6	8.69.–6	0.598	0.0193	7.56	0.841	0.0737	290
295	0.02617	1.002.–3	51.94	91.6	2541	0.323	8.627	4.181	1.868	959.–6	8.89.–6	0.606	0.0195	6.62	0.849	0.0727	295
300	0.03531	1.003.–3	39.13	112.5	2550	0.393	8.520	4.179	1.872	855.–6	9.09.–6	0.613	0.0196	5.83	0.857	0.0717	300
305	0.04712	1.005.–3	27.90	133.4	2559	0.462	8.417	4.178	1.877	769.–6	9.29.–6	0.620	0.0201	5.20	0.865	0.0709	305
310	0.06221	1.007.–3	22.93	154.3	2568	0.530	8.318	4.178	1.882	695.–6	9.49.–6	0.628	0.0204	4.62	0.873	0.0700	310
315	0.08132	1.009.–3	17.82	175.2	2577	0.597	8.224	4.179	1.888	631.–6	9.69.–6	0.634	0.0207	4.16	0.883	0.0692	315
320	0.1053	1.011.–3	13.98	196.1	2586	0.649	8.151	4.180	1.895	577.–6	9.89.–6	0.640	0.0210	3.77	0.894	0.0683	320
325	0.1351	1.013.–3	11.06	217.0	2595	0.727	8.046	4.182	1.903	528.–6	10.09.–6	0.645	0.0213	3.42	0.901	0.0675	325
330	0.1719	1.016.–3	8.82	237.9	2604	0.791	7.962	4.184	1.911	489.–6	10.29.–6	0.650	0.0217	3.15	0.908	0.0666	330
335	0.2167	1.018.–3	7.09	258.8	2613	0.854	7.881	4.186	1.920	453.–6	10.49.–6	0.655	0.0220	2.88	0.916	0.0658	335
340	0.2713	1.021.–3	5.74	279.8	2622	0.916	7.804	4.188	1.930	420.–6	10.69.–6	0.660	0.0223	2.66	0.925	0.0649	340
345	0.3372	1.024.–3	4.683	300.7	2630	0.977	7.729	4.191	1.941	389.–6	10.89.–6	0.665	0.0226	2.45	0.933	0.0641	345
350	0.4163	1.027.–3	3.846	321.7	2639	1.038	7.657	4.195	1.954	365.–6	11.09.–6	0.668	0.0230	2.29	0.942	0.0632	350
355	0.5100	1.030.–3	3.180	342.7	2647	1.097	7.588	4.199	1.968	343.–6	11.29.–6	0.671	0.0233	2.14	0.951	0.0623	355
360	0.6209	1.034.–3	2.645	363.7	2655	1.156	7.521	4.203	1.983	324.–6	11.49.–6	0.674	0.0237	2.02	0.960	0.0614	360
365	0.7514	1.038.–3	2.212	384.7	2663	1.214	7.456	4.209	1.999	306.–6	11.69.–6	0.677	0.0241	1.91	0.969	0.0605	365
370	0.9040	1.041.–3	1.861	405.8	2671	1.271	7.394	4.214	2.017	289.–6	11.89.–6	0.679	0.0245	1.80	0.978	0.0595	370
373.15	1.0133	1.044.–3	1.679	419.1	2676	1.307	7.356	4.217	2.029	279.–6	12.02.–6	0.680	0.0248	1.76	0.984	0.0589	373.15
375	1.0815	1.045.–3	1.574	426.8	2679	1.328	7.333	4.220	2.036	274.–6	12.09.–6	0.681	0.0249	1.70	0.987	0.0586	375
380	1.2869	1.049.–3	1.337	448.0	2687	1.384	7.275	4.226	2.057	260.–6	12.29.–6	0.683	0.0254	1.61	0.995	0.0576	380
385	1.5233	1.053.–3	1.142	469.2	2694	1.439	7.218	4.232	2.080	248.–6	12.49.–6	0.685	0.0258	1.53	1.004	0.0566	385
390	1.794	1.058.–3	0.980	490.4	2702	1.494	7.163	4.239	2.104	237.–6	12.69.–6	0.686	0.0263	1.47	1.013	0.0556	390
400	2.455	1.067.–3	0.731	532.9	2716	1.605	7.058	4.256	2.158	217.–6	13.05.–6	0.688	0.0272	1.34	1.033	0.0536	400
410	3.302	1.077.–3	0.553	575.6	2729	1.708	6.959	4.278	2.221	200.–6	13.42.–6	0.688	0.0282	1.24	1.054	0.0515	410
420	4.370	1.088.–3	0.425	618.6	2742	1.810	6.865	4.302	2.291	185.–6	13.79.–6	0.688	0.0293	1.16	1.075	0.0494	420
430	5.699	1.099.–3	0.331	661.8	2753	1.911	6.775	4.331	2.369	173.–6	14.14.–6	0.685	0.0304	1.09	1.10	0.0472	430

440	7.333	1.110.–3	0.261	705.3	2764	2.011	6.689	4.36	2.46	162.–6	14.50.–6	0.682	0.0317	1.04	1.12	0.0451	440
450	9.319	1.123.–3	0.208	749.2	2773	2.109	6.607	4.40	2.56	152.–6	14.85.–6	0.678	0.0331	0.99	1.14	0.0429	450
460	11.71	1.137.–3	0.167	793.5	2782	2.205	6.528	4.44	2.68	143.–6	15.19.–6	0.673	0.0346	0.95	1.17	0.0407	460
470	14.55	1.152.–3	0.136	838.2	2789	2.301	6.451	4.48	2.79	136.–6	15.54.–6	0.667	0.0363	0.92	1.20	0.0385	470
480	17.90	1.167.–3	0.111	883.4	2795	2.395	6.377	4.53	2.94	129.–6	15.88.–6	0.660	0.0381	0.89	1.23	0.0362	480
490	21.83	1.184.–3	0.0922	929.1	2799	2.479	6.312	4.59	3.10	124.–6	16.23.–6	0.651	0.0401	0.87	1.25	0.0339	490
500	26.40	1.203.–3	0.0766	975.6	2801	2.581	6.233	4.66	3.27	118.–6	16.59.–6	0.642	0.0423	0.86	1.28	0.0316	500
510	31.66	1.222.–3	0.0631	1023	2802	2.673	6.163	4.74	3.47	113.–6	16.95.–6	0.631	0.0447	0.85	1.31	0.0293	510
520	37.70	1.244.–3	0.0525	1071	2801	2.765	6.093	4.84	3.70	108.–6	17.33.–6	0.621	0.0475	0.84	1.35	0.0269	520
530	44.58	1.268.–3	0.0445	1119	2798	2.856	6.023	4.95	3.96	104.–6	17.72.–6	0.608	0.0506	0.85	1.39	0.0245	530
540	52.38	1.294.–3	0.0375	1170	2792	2.948	5.953	5.08	4.27	101.–6	18.1.–6	0.594	0.0540	0.86	1.43	0.0221	540
550	61.19	1.323.–3	0.0317	1220	2784	3.039	5.882	5.24	4.64	97.–6	18.6.–6	0.580	0.0583	0.87	1.47	0.0197	550
560	71.08	1.355.–3	0.0269	1273	2772	3.132	5.808	5.43	5.09	94.–6	19.1.–6	0.563	0.0637	0.90	1.52	0.0173	560
570	82.16	1.392.–3	0.0228	1328	2757	3.225	5.733	5.68	5.67	91.–6	19.7.–6	0.548	0.0698	0.94	1.59	0.0150	570
580	94.51	1.433.–3	0.0193	1384	2737	3.321	5.654	6.00	6.40	88.–6	20.4.–6	0.528	0.0767	0.99	1.68	0.0128	580
590	108.3	1.482.–3	0.0163	1443	2717	3.419	5.569	6.41	7.35	84.–6	21.5.–6	0.513	0.0841	1.05	1.84	0.0105	590
600	123.5	1.541.–3	0.0137	1506	2682	3.520	5.480	7.00	8.75	81.–6	22.7.–6	0.497	0.0929	1.14	2.15	0.0084	600
610	137.3	1.612.–3	0.0115	1573	2641	3.627	5.318	7.85	11.1	77.–6	24.1.–6	0.467	0.103	1.30	2.60	0.0063	610
620	159.1	1.705.–3	0.0094	1647	2588	3.741	5.259	9.35	15.4	72.–6	25.9.–6	0.444	0.114	1.52	3.46	0.0045	620
625	169.1	1.778.–3	0.0085	1697	2555	3.805	5.191	10.6	18.3	70.–6	27.0.–6	0.430	0.121	1.65	4.20	0.0035	625
630	179.7	1.856.–3	0.0075	1734	2515	3.875	5.115	12.6	22.1	67.–6	28.0.–6	0.412	0.130	2.0	4.8	0.0026	630
635	190.9	1.935.–3	0.0066	1783	2466	3.950	5.025	16.4	27.6	64.–6	30.0.–6	0.392	0.141	2.7	6.0	0.0015	635
640	202.7	2.075.–3	0.0057	1841	2401	4.037	4.912	26	42	59.–6	32.0.–6	0.367	0.155	4.2	9.6	0.0008	640
645	215.2	2.351.–3	0.0045	1931	2292	4.223	4.732	90		54.–6	37.0.–6	0.331	0.178	12	26	0.0001	645
647.3‡	221.2	3.170.–3	0.0032	2107	2107	4.443	4.443	∞	∞	45.–6	45.0.–6	0.238	0.238	∞	∞	0.0000	647.3‡

*1 bar = 10^5 N/m^2.

†Above the solid line, the condensed phase is solid; below it, liquid.

‡Critical temperature.

NOTE: The notations 6.30.–11, 1.073.–3, 9.55.+9, etc. signify 6.30×10^{-11}, 1.073×10^{-3}, 955×10^{9}, etc.

Tables 2-351 and 2-352 are provided for general use. Tables to higher precision are available over certain ranges and for various properties. The most current internationally accepted tables are found in Haar, L., J. S. Gallagher, and G. S. Kell, *NBS/NRC Steam Tables,* Hemisphere, Washington, DC, 1984 (320 pp.). These do not tabulate certain properties at saturation states. A revised release on the IAPWS Skeleton Tables 1985 for the thermodynamic properties of ordinary water substance, Sept. 1993 (15 pp), is apparently the latest international publication. In *J. Phys. Chem. Ref. Data* **17,** 4 (1988): 1439–1540, H. Sato, M. Uematsu, and others review existing steam tables and present the 1985 formulation of skeleton tables. Property codes and programs include Cheng, S. C. and C. Nguyen, *Modeling and Simulation on Microcomputers 1989* (R. W. Allen, ed.), S.C.S. Intl., San Diego, 1989 (pp. 138–141); Garland, W. J. and B. J. Hand, *Nucl. Engng. & Des.,* **113,** (1989): 21–34; Dickey, D. S., *Chem. Eng.* **98,** 9 (1991): 207–8 and **98,** 11: 235–6; Muneer, T. and S. M. Scott, *Proc. Inst. Mech. Eng.,* **205,** (1991): 25–29; and *Energy Convsn. Mgmt.,* **31,** 4 (1991): 315–325. Useful pictorial representations of 20 properties as a function of both temperature (to 800°C) and pressure (to 1000 bar) are given by Grigull, U., J. Bach, et al., *Warme- u. Stoff.,* **1** (1968): 202–213. Property equations for the saturated liquid for the range 0–300°C are given by Charters, W. W. S. and H. A. Sadafi, *Rev. Int. Froid,* **10,** (Mar. 1987): 105–6. Gordon, S., NASA Tech. Paper 1906, 1982 gives detailed tables for ice from 0 K. Ice and snow properties are reviewed by Fukusako, S., *Int. J. Thermophys.,* **11,** 2 (1990): 353–372. See also Wagner, W., A. Saul, et al., *J. Phys. Chem. Ref. Data,* **23,** 3 (1994): 515–525, and Table 2-358.

TABLE 2-353 Saturated Liquid Water—Miscellaneous Properties

Temperature, °C	$10^4\,\beta$	$10^4\,k_T$/bar	$10^4\,k_s$/bar	v_s, m/s	μ_f, 10^{-6} Pa·s	c_p, kJ/kg·K	k, W/m·K	Pr, bar	σ, N/m
0	–0.681	0.50885	0.50855	1402.4	1.793	4.2176	0.567	13.32	0.07565
1	–0.501	0.50509	0.50493	1407.4	1.732	4.2140	0.569	12.83	0.07551
2	–0.327	0.50151	0.50143	1412.2	1.675	4.2107	0.570	12.37	0.07537
3	–0.160	0.49808	0.49806	1417.0	1.621	4.2077	0.572	11.93	0.07522
4	0.003	0.49481	0.49481	1421.6	1.569	4.2048	0.573	11.51	0.07508
5	0.160	0.49169	0.49167	1426.2	1.520	4.2022	0.575	11.11	0.07494
6	0.312	0.48871	0.48865	1430.6	1.474	4.1999	0.577	10.73	0.07480
7	0.460	0.48587	0.48573	1434.9	1.429	4.1977	0.578	10.38	0.07465
8	0.604	0.48315	0.48291	1439.1	1.387	4.1956	0.580	10.04	0.07451
9	0.744	0.48056	0.48019	1443.3	1.346	4.1938	0.581	9.72	0.07436
10	0.880	0.47809	0.47757	1447.3	1.308	4.1921	0.5828	9.41	0.07422
11	1.012	0.47573	0.47504	1451.2	1.271	4.1906	0.5844	9.11	0.07407
12	1.141	0.47347	0.47260	1455.0	1.236	4.1892	0.5859	8.84	0.07393
13	1.267	0.47133	0.47024	1458.7	1.202	4.1879	0.5875	8.57	0.07378
14	1.389	0.46928	0.46797	1462.4	1.170	4.1867	0.5891	8.32	0.07364
15	1.509	0.46733	0.46578	1465.9	1.139	4.1856	0.5906	8.07	0.07349
16	1.626	0.46548	0.46366	1469.4	1.110	4.1847	0.5922	7.84	0.07334
17	1.740	0.46371	0.46162	1472.7	1.081	4.1838	0.5937	7.62	0.07319
18	1.852	0.46203	0.45966	1476.0	1.054	4.1830	0.5953	7.41	0.07304
19	1.961	0.46043	0.45776	1479.2	1.028	4.1823	0.5968	7.20	0.07289
20	2.068	0.45892	0.45593	1482.3	1.003	4.1817	0.5983	7.01	0.07274
21	2.173	0.45748	0.45417	1485.3	0.979	4.1812	0.5999	6.82	0.07259
22	2.275	0.45612	0.45248	1488.3	0.955	4.1807	0.6014	6.64	0.07244
23	2.376	0.45484	0.45084	1491.2	0.933	4.1802	0.6029	6.47	0.07228
24	2.475	0.45362	0.44927	1493.9	0.911	4.1798	0.6044	6.30	0.07213
25	2.572	0.45247	0.44776	1496.7	0.891	4.1795	0.6059	6.15	0.07198
26	2.667	0.45139	0.44630	1499.3	0.871	4.1792	0.6074	5.99	0.07182
27	2.761	0.45038	0.44490	1501.9	0.852	4.1790	0.6089	5.85	0.07167
28	2.852	0.44943	0.44355	1504.3	0.833	4.1788	0.6104	5.70	0.07151
30	3.032	0.44771	0.44102	1509.1	0.798	4.1785	0.6133	5.44	0.07120
32	3.206	0.44622	0.43869	1513.6	0.765	4.1783	0.6162	5.19	0.07089
34	3.375	0.44496	0.43655	1517.8	0.734	4.1782	0.6190	4.95	0.07058
36	3.539	0.44390	0.43459	1521.7	0.705	4.1783	0.6218	4.74	0.07025
38	3.698	0.44305	0.43280	1525.4	0.679	4.1784	0.6246	4.54	0.06992
40	3.853	0.44239	0.43118	1528.9	0.653	4.1786	0.6273	4.35	0.06960
42	4.004	0.44192	0.42972	1532.1	0.629	4.1789	0.6299	4.17	0.06927
44	4.152	0.44162	0.42842	1535.0	0.607	4.1792	0.6315	4.02	0.06894
46	4.296	0.44149	0.42726	1537.7	0.586	4.1797	0.6351	3.86	0.06861
48	4.438	0.44153	0.42624	1540.3	0.566	4.1801	0.6375	3.71	0.06828
50	4.576	0.44173	0.42535	1542.6	0.547	4.1807	0.6400	3.57	0.06795
55	4.910	0.44290	0.42370	1547.4	0.5043	4.1824	0.6457	3.267	0.06710
60	5.231	0.44496	0.42281	1551.0	0.4668	4.1844	0.6511	3.000	0.06624
65	5.539	0.44788	0.42262	1553.4	0.4338	4.1869	0.6561	2.768	0.06537
70	5.837	0.45162	0.42309	1554.8	0.4045	4.1897	0.6607	2.565	0.06449
75	6.128	0.45614	0.42418	1555.1	0.3784	4.1929	0.6649	2.386	0.06359
80	6.411	0.46143	0.42587	1554.4	0.3550	4.1965	0.6686	2.228	0.06268
85	6.689	0.46748	0.42812	1552.9	0.3340	4.2005	0.6721	2.088	0.06176
90	6.962	0.47429	0.43093	1550.5	0.3150	4.2050	0.6753	1.962	0.06083
95	7.233	0.48185	0.43429	1547.2	0.2979	4.2102	0.6779	1.850	0.05988
100	7.501	0.49019	0.43819	1543.1	0.2823	4.2164	0.6800	1.756	0.05892

Values mostly from Aleksandrov, A. A. and M. S. Trakhtenhertz, *Thermophysical Properties of Water at Atmospheric Pressure,* Standartov, Moscow, 1977 (99 pp.).

TABLE 2-354 Thermodynamic Properties of Compressed Steam*

Temperature, K		Pressure, bar 0.1	0.5	1	5	10	20	40	60	80	100
350	v	16.12	1.027.–3	1.027.–3	1.027.–3	1.027.–3	1.026.–3	1.025.–3	1.024.–3	1.023.–3	1.023.–3
	h	2644	321.7	231.8	322.1	322.5	323.3	324.9	326.4	328.1	329.7
	s	8.327	1.037	1.037	1.037	1.037	1.036	1.035	1.034	1.032	1.031
400	v	18.44	3.67	1.827	1.067.–3	1.067.–3	1.066.–3	1.065.–3	1.064.–3	1.063.–3	1.061.–3
	h	2739	2735	2730	533.1	533.4	534.1	535.4	536.8	538.2	539.6
	s	8.581	7.831	7.502	1.601	1.600	1.599	1.597	1.595	1.593	1.592
450	v	20.75	4.14	2.063	0.410	1.124.–3	1.123.–3	1.121.–3	1.119.–3	1.118.–3	1.116.–3
	h	2835	2833	2830	2804	749.0	749.8	750.8	751.9	753.0	754.1
	s	8.811	8.061	7.736	6.949	2.110	2.107	2.105	2.102	2.099	2.097
500	v	23.07	4.61	2.298	0.452	0.221	0.104	1.201.–3	1.198.–3	1.196.–3	1.193.–3
	h	2932	2931	2929	2912.4	2891.2	2839.4	975.9	976.3	976.8	977.3
	s	9.012	8.261	7.944	7.177	6.823	6.422	2.578	2.575	2.571	2.567
600	v	27.7	5.53	2.76	0.548	0.271	0.133	0.0630	0.0396	0.0276	0.0201
	h	3131	3130	3129	3120	3109	3087	3036	2976	2906	2820
	s	9.374	8.630	8.309	7.560	7.223	6.875	6.590	6.224	5.997	5.775
700	v	32.3	6.46	3.23	0.643	0.319	0.158	0.0769	0.0500	0.0346	0.0283
	h	3335	3335	3334	3328	3322	3307	3278	3247	3214	3179
	s	9.692	8.946	8.625	7.877	7.550	7.215	6.864	6.644	6.431	6.334
800	v	36.9	7.38	3.69	0.736	0.367	0.182	0.0889	0.0589	0.0436	0.0343
	h	3547	3546	3546	3542	3537	3526	3506	3485	3464	3442
	s	9.971	9.228	8.908	8.161	7.837	7.507	7.151	6.965	6.809	6.685
900	v	41.5	8.31	4.15	0.829	0.414	0.206	0.102	0.0674	0.0501	0.0398
	h	3765	3765	3764	3761	3757	3750	3737	3719	3704	3688
	s	10.228	9.485	9.165	8.420	8.097	7.770	7.462	7.237	7.092	6.975
1000	v	46.2	9.23	4.615	0.921	0.460	0.229	0.114	0.0758	0.0564	0.0449
	h	3990	3990	3990	3987	3984	3978	3967	3955	3944	3935
	s	10.466	9.723	9.402	8.659	8.336	8.011	7.682	7.486	7.345	7.233
1500	v	69.2	13.9	6.92	1.385	0.692	0.341	0.1730	0.1153	0.0865	0.0692
	h	5231	5228	5227	5225	5224	5221	5217	5212	5207	5203
	s	11.47	10.77	10.40	9.66	9.34	9.015	8.693	8.503	8.368	8.262
2000	v	93.0	18.6	9.26	1.850	0.925	0.462	0.231	0.1543	0.1157	0.0926
	h	6832	6734	6706	6662	6649	6639	6629	6623	6619	6616
	s	12.38	11.58	11.25	10.48	10.15	9.828	9.503	9.313	9.178	9.073
2500	v	123.7	24.0	11.90	2.35	1.171	0.583	0.291	0.1942	0.1457	0.1166
	h	10417	9330	9046	8621	8504	8413	8342	8307	8285	8269
	s	13.95	12.73	12.28	11.35	10.80	10.62	10.26	10.06	9.920	9.810

*v = specific volume, m^3/kg; h = specific enthalpy, kJ/kg; s = specific entropy, kJ/(kg·K). The notation 1.027.–3 signifies 1.027×10^{-3}.

TABLE 2-354 Thermodynamic Properties of Compressed Steam (*Concluded*)

Temperature, K		Pressure, bar										
		150	200	250	300	400	500	600	700	800	900	1000
350	*v*	1.020.–3	1.018.–3	1.016.–3	1.014.–3	1.009.–3	1.005.–3	1.002.–3	9.977.–4	9.937.–4	9.900.–4	9.865.–4
	h	333.7	337.7	341.7	344.7	353.8	361.8	369.7	377.7	385.7	393.7	401.7
	s	1.028	1.025	1.022	1.019	1.013	1.007	1.001	0.996	0.991	0.985	0.979
400	*v*	1.059.–3	1.056.–3	1.053.–3	1.050.–3	1.045.–3	1.041.–3	1.035.–3	1.031.–3	1.027.–3	1.022.–3	1.018.–3
	h	543.1	546.5	550.1	553.5	560.6	567.8	574.9	582.1	589.3	596.5	603.8
	s	1.587	1.583	1.578	1.574	1.565	1.557	1.549	1.541	1.533	1.526	1.518
450	*v*	1.112.–3	1.108.–3	1.105.–3	1.101.–3	1.094.–3	1.088.–3	1.082.–3	1.076.–3	1.070.–3	1.065.–3	1.059.–3
	h	756.8	759.5	762.3	765.2	771.0	776.9	783.0	789.6	795.3	801.6	807.9
	s	2.088	2.082	2.076	2.070	2.060	2.049	2.039	2.029	2.019	2.010	2.002
500	*v*	1.187.–3	1.181.–3	1.175.–3	1.170.–3	1.160.–3	1.151.–3	1.142.–3	1.134.–3	1.126.–3	1.119.–3	1.112.–3
	h	978.8	980.3	981.9	983.7	987.4	991.5	995.9	1000.5	1005.3	1010.3	1015.4
	s	2.558	2.549	2.541	2.533	2.517	2.502	2.488	2.474	2.461	2.449	2.437
600	*v*	1.519.–3	1.483.–3	1.454.–3	1.428.–3	1.392.–3	1.362.–3	1.337.–3	1.315.–3	1.296.–3	1.280.–3	1.265.–3
	h	1499	1489	1479	1472	1462	1456	1452	1449	1447	1447	1447
	s	3.501	3.469	3.443	3.419	3.379	3.346	3.316	3.290	3.266	3.244	3.223
700	*v*	1.724.–2	1.157.–2	7.986.–3	5.416.–3	2.630.–3	2.038.–3	1.831.–3	1.716.–3	1.639.–3	1.589.–3	1.536.–3
	h	3082	2965	2821	2635	2233	2084	2021	1986	1962	1946	1931
	s	6.037	5.770	5.494	5.179	4.554	4.308	4.192	4.116	4.058	4.012	3.972
800	*v*	2.195.–2	1.575.–2	1.201.–2	9.512.–3	6.391.–3	4.576.–3	3.496.–3	2.866.–3	2.484.–3	2.239.–3	2.072.–3
	h	3386	3325	3261	3193	3047	2895	2734	2648	2567	2508	2465
	s	6.444	6.252	6.086	5.934	5.654	5.397	5.175	4.998	4.864	4.761	4.701
900	*v*	2.590.–2	1.899.–2	1.483.–2	1.207.–2	8.619.–3	6.581.–3	5.257.–3	4.348.–3	3.704.–3	3.454.–3	2.907.–3
	h	3649	3609	3568	3526	3440	3354	3269	3188	3113	3049	2995
	s	6.755	6.587	6.449	6.327	6.119	5.940	5.780	5.637	5.510	5.399	5.305
1000	*v*	2.954.–2	2.186.–2	1.726.–2	1.420.–2	1.038.–2	8.102.–3	6.605.–3	5.557.–3	4.792.–3	4.212.–3	3.763.–3
	h	3904	3874	3845	3816	3756	3697	3640	3584	3532	3482	3435
	s	7.023	6.867	6.741	6.633	6.453	6.302	6.172	6.055	5.951	5.856	5.727
1500	*v*	0.0461	0.0346	0.0277	0.0231	0.0173	0.0139	0.0116	0.00993	0.00871	0.00776	0.00700
	h	5202	5198	5186	5180	5171	5157	5144	5133	5120	5108	5095
	s	8.074	7.936	7.827	7.738	7.597	7.484	7.391	7.310	7.239	7.176	7.118
2000	*v*	0.0619	0.0465	0.0372	0.0311	0.0234	0.0188	0.0157	0.0135	0.0119	0.0106	0.0096
	h	6613	6610	6608	6605	6599	6595	6590	6585	6581	6577	6574
	s	8.883	8.748	8.642	8.555	8.418	8.310	8.222	8.147	8.082	8.024	7.971
2500	*v*	0.0778	0.0584	0.0468	0.0391	0.0294	0.0236	0.0197	0.0170	0.0149	0.0133	0.0120
	h	8269	8269	8269	8268	8267	8265	8261	2856	8250	8244	8240
	s	9.610	9.468	9.358	9.270	9.129	9.020	8.930	8.854	8.788	8.730	8.677

TABLE 2-355 Density, Specific Heats at Constant Pressure and at Constant Volume and Velocity of Sound for Compressed Water, 1–1000 bar, 0–150°C

0°C (ITS-90)

P, bar	density, kg/m^3	C_p, kJ/(kg·K)	C_v, kJ/(kg·K)	w, m/s
1	999.702	4.1923	4.1877	1447.3
50	1002.03	4.174	4.168	1455
100	1004.38	4.156	4.149	1464
150	1006.71	4.139	4.130	1472
200	1009.01	4.123	4.112	1480
250	1011.28	4.108	4.095	1489
300	1013.53	4.093	4.078	1497
400	1017.97	4.065	4.046	1513
500	1022.31	4.040	4.016	1529
600	1026.57	4.018	3.988	1545
800	1034.85	3.979	3.937	1577
1000	1042.83	3.948	3.892	1609

10°C (ITS-90)

P, bar	density, kg/m^3	C_p, kJ/(kg·K)	C_v, kJ/(kg·K)	w, m/s
1	998.207	4.1812	4.1538	1482.3
50	1000.44	4.166	4.137	1491
100	1002.69	4.151	4.119	1499
150	1004.93	4.137	4.103	1507
200	1007.13	4.124	4.087	1516
250	1009.32	4.110	4.071	1524
300	1011.48	4.098	4.056	1532
400	1015.74	4.074	4.027	1548
500	1019.92	4.052	3.999	1565
600	1024.02	4.032	3.974	1581
800	1031.99	3.996	3.926	1613
1000	1039.68	3.967	3.884	1644

20°C (ITS-90)

P, bar	density, kg/m^3	C_p, kJ/(kg·K)	C_v, kJ/(kg·K)	w, m/s
1	995.650	4.1774	4.1148	1509.1
50	997.82	4.164	4.099	1517
100	1000.02	4.151	4.084	1526
150	1002.19	4.139	4.069	1534
200	1004.34	4.127	4.055	1543
250	1006.47	4.115	4.041	1551
300	1008.57	4.104	4.027	1559
400	1012.72	4.083	4.001	1576
500	1016.79	4.063	3.976	1592
600	1020.79	4.044	3.952	1608
800	1028.56	4.011	3.908	1640
1000	1036.06	3.982	3.869	1671

30°C (ITS-90)

P, bar	density, kg/m^3	C_p, kJ/(kg·K)	C_v, kJ/(kg·K)	w, m/s
1	992.217	4.1775	4.0715	1528.9
50	994.36	4.166	4.058	1537
100	996.52	4.154	4.044	1546
150	998.66	4.142	4.031	1554
200	1000.77	4.131	4.018	1563
250	1002.87	4.121	4.005	1571
300	1004.94	4.110	3.993	1579
400	1009.03	4.091	3.969	1596
500	1013.03	4.072	3.946	1612
600	1016.97	4.055	3.924	1628
800	1024.62	4.023	3.884	1660
1000	1032.00	3.995	3.847	1692

40°C (ITS-90)

P, bar	density, kg/m^3	C_p, kJ/(kg·K)	C_v, kJ/(kg·K)	w, m/s
1	988.036	4.1799	4.0248	1542.6
50	990.16	4.169	4.012	1551
100	992.31	4.158	4.000	1560
150	994.44	4.147	3.988	1568
200	996.54	4.137	3.976	1577
250	998.62	4.126	3.965	1585
300	1000.68	4.117	3.954	1594
400	1004.74	4.098	3.932	1610
500	1008.72	4.080	3.911	1627
600	1012.62	4.063	3.892	1643
800	1020.21	4.033	3.854	1676
1000	1027.53	4.005	3.820	1707

50°C (ITS-90)

P, bar	density, kg/m^3	C_p, kJ/(kg·K)	C_v, kJ/(kg·K)	w, m/s
1	983.197	4.1840	3.9755	1551.0
50	985.33	4.173	3.964	1560
100	987.48	4.163	3.953	1568
150	989.61	4.152	3.943	1577
200	991.71	4.142	3.932	1586
250	993.80	4.132	3.922	1594
300	995.86	4.123	3.911	1603
400	999.92	4.105	3.892	1620
500	1003.90	4.087	3.873	1637
600	1007.80	4.071	3.855	1653
800	1015.38	4.041	3.821	1686
1000	1022.69	4.013	3.789	1718

60°C (ITS-90)

P, bar	density, kg/m^3	C_p, kJ/(kg·K)	C_v, kJ/(kg·K)	w, m/s
1	977.766	4.1896	3.9246	1554.8
50	979.92	4.179	3.915	1564
100	982.09	4.169	3.905	1573
150	984.23	4.158	3.895	1582
200	986.36	4.148	3.885	1590
250	988.46	4.139	3.876	1599
300	990.53	4.129	3.867	1608
400	994.62	4.111	3.849	1625
500	998.62	4.094	3.832	1642
600	1002.54	4.078	3.815	1659
800	1010.15	4.048	3.784	1693
1000	1017.48	4.020	3.754	1726

70°C (ITS-90)

P, bar	density, kg/m^3	C_p, kJ/(kg·K)	C_v, kJ/(kg·K)	w, m/s
1	971.791	4.1967	3.8727	1554.5
50	973.98	4.186	3.864	1564
100	976.18	4.176	3.855	1573
150	978.35	4.165	3.846	1582
200	980.51	4.155	3.838	1591
250	982.63	4.146	3.829	1600
300	984.74	4.136	3.821	1609
400	988.87	4.118	3.805	1627
500	992.92	4.101	3.789	1644
600	996.88	4.085	3.774	1662
800	1004.56	4.054	3.745	1696
1000	1011.94	4.027	3.717	1730

Prepared by H. Sato, Keio University, Japan, Oct. 1994. Based upon "An equation of state for the thermodynamic properties of water in the liquid phase including the metastable state," from Properties of Water and Steam," *Proc. 11th Int. Conf. Props. Steam* (M. Pichal and O. Sifner, eds.), Hemisphere, New York, 1990 (551 pp.).

TABLE 2-355 Density, Specific Heats at Constant Pressure and at Constant Volume and Velocity of Sound for Compressed Water, 1–1000 bar, 0–150°C (*Concluded*)

	80°C (ITS-90)				90°C (ITS-90)				100°C (ITS-90)				110°C (ITS-90)			
P, bar	density, kg/m^3	C_p, kJ/(kg·K)	C_v, kJ/(kg·K)	w, m/s	density, kg/m^3	C_p, kJ/(kg·K)	C_v, kJ/(kg·K)	w, m/s	density, kg/m^3	C_p, kJ/(kg·K)	C_v, kJ/(kg·K)	w, m/s	density, kg/m^3	C_p, kJ/(kg·K)	C_v, kJ/(kg·K)	w, m/s
1	965.309	4.2056	3.8206	1550.5	958.348	4.2164	3.7689	1543.1	950.927	4.2296	3.7181	1532.5	943.059	4.2453	3.6684	1519.0
50	967.54	4.195	3.813	1560	960.64	4.205	3.762	1553	953.28	4.218	3.712	1543	945.50	4.233	3.663	1530
100	969.79	4.184	3.805	1569	962.94	4.194	3.755	1563	955.65	4.206	3.706	1553	947.95	4.221	3.657	1540
150	972.00	4.174	3.797	1579	965.21	4.184	3.748	1572	957.99	4.195	3.699	1563	950.36	4.209	3.652	1551
200	974.20	4.164	3.789	1588	967.45	4.173	3.741	1582	960.30	4.184	3.693	1573	952.74	4.198	3.646	1561
250	976.36	4.154	3.782	1597	969.67	4.163	3.734	1592	962.57	4.174	3.687	1583	955.09	4.187	3.641	1572
300	978.50	4.144	3.774	1607	971.85	4.153	3.727	1601	964.82	4.164	3.681	1593	957.40	4.176	3.635	1582
400	982.71	4.126	3.759	1625	976.15	4.135	3.714	1620	969.21	4.144	3.669	1613	961.92	4.155	3.624	1603
500	986.82	4.108	3.745	1643	980.34	4.117	3.701	1639	973.50	4.126	3.657	1632	966.32	4.136	3.613	1623
600	990.83	4.092	3.731	1661	984.43	4.100	3.688	1658	977.69	4.108	3.645	1652	970.61	4.118	3.602	1644
800	998.62	4.061	3.704	1696	992.34	4.068	3.663	1694	985.76	4.076	3.621	1690	978.87	4.084	3.579	1683
1000	1006.08	4.033	3.678	1731	999.92	4.039	3.639	1730	993.47	4.046	3.598	1727	986.73	4.053	3.556	1723

	120°C (ITS-90)				130°C (ITS-90)				140°C (ITS-90)				150°C (ITS-90)			
P, bar	density, kg/m^3	C_p, kJ/(kg·K)	C_v, kJ/(kg·K)	w, m/s	density, kg/m^3	C_p, kJ/(kg·K)	C_v, kJ/(kg·K)	w, m/s	density, kg/m^3	C_p, kJ/(kg·K)	C_v, kJ/(kg·K)	w, m/s	density, kg/m^3	C_p, kJ/(kg·K)	C_v, kJ/(kg·K)	w, m/s
1	934.749	4.2639	3.6201	1502.8	925.997	4.2859	3.5733	1484.1	916.797	4.3114	3.5279	1463.0	907.143	4.3408	3.4848	1439.8
50	937.28	4.251	3.615	1514	928.64	4.271	3.569	1496	919.57	4.296	3.524	1475	910.06	4.324	3.481	1453
100	939.83	4.238	3.610	1525	931.29	4.257	3.564	1508	922.34	4.280	3.520	1488	912.97	4.307	3.477	1467
150	942.33	4.225	3.605	1536	933.90	4.244	3.560	1519	925.06	4.266	3.516	1501	915.82	4.291	3.473	1480
200	944.79	4.213	3.600	1547	936.46	4.231	3.555	1531	927.73	4.251	3.511	1513	918.61	4.276	3.469	1493
250	947.22	4.201	3.595	1558	938.97	4.218	3.550	1543	930.35	4.238	3.506	1525	921.34	4.261	3.464	1507
300	949.61	4.190	3.590	1569	941.45	4.206	3.545	1554	932.92	4.224	3.501	1538	924.03	4.246	3.459	1520
400	954.27	4.168	3.580	1591	946.28	4.183	3.535	1577	937.94	4.199	3.491	1562	929.24	4.219	3.448	1546
500	958.81	4.148	3.569	1612	950.96	4.161	3.525	1600	942.79	4.176	3.480	1586	934.27	4.194	3.436	1572
600	963.22	4.128	3.558	1634	955.51	4.140	3.514	1623	947.48	4.153	3.469	1610	939.13	4.169	3.423	1598
800	971.68	4.092	3.536	1676	964.20	4.101	3.491	1667	956.43	4.112	3.444	1658	948.36	4.124	3.395	1648
1000	979.72	4.059	3.512	1717	972.44	4.066	3.466	1710	964.88	4.073	3.417	1704	957.04	4.081	3.364	1698

TABLE 2-356 Specific Heat and Other Thermophysical Properties of Water Substance*

Pressure, bar		Temperature, K														
		300	350	400	450	500	600	700	800	900	1000	1200	1400	1600	1800	2000
1	μ	8.57.–4	3.70.–4	1.32.–5	1.52.–5	1.73.–5	2.15.–5	2.57.–5	2.98.–5	3.39.–5	3.78.–5	4.48.–5	5.06.–5	5.65.–5	6.19.–5	6.70.–5
	c_p	4.18	4.19	1.99	1.97	1.98	2.02	2.09	2.15	2.22	2.29	2.43	2.58	2.73	3.02	3.79
	k	0.614	0.668	0.0268	0.0311	0.0358	0.0464	0.0581	0.0710	0.0843	0.0981	0.13	0.16	0.21	0.33	0.57
	Pr	5.81	2.32	0.980	0.967	0.955	0.936	0.920	0.906	0.891	0.881	0.83	0.80	0.75	0.57	0.45
5	μ	8.57.–4	3.70.–4	2.17.–4	1.49.–5	1.72.–5	2.15.–5	2.57.–5	2.98.–5	3.39.–5	3.78.–5	4.45.–5	5.06.–5	5.65.–5	6.19.–5	6.70.–5
	c_p	4.18	4.19	4.26	2.21	2.10	2.07	2.11	2.16	2.23	2.29	2.43	2.58	2.73	2.98	3.40
	k	0.614	0.668	0.689	0.0335	0.0369	0.0469	0.0585	0.0713	0.0846	0.0984	0.13	0.16	0.20	0.28	0.43
	Pr	5.82	2.32	1.34	0.983	0.973	0.947	0.925	0.907	0.892	0.881	0.83	0.81	0.77	0.65	0.53
10	μ	8.57.–4	3.70.–4	2.17.–4	1.51.–4	1.71.–5	2.15.–5	2.58.–5	2.99.–5	3.39.–5	3.78.–5	4.45.–5	5.06.–5	5.65.–5	6.19.–5	6.70.–5
	c_p	4.18	4.19	4.25	4.39	2.29	2.13	2.13	2.18	2.24	2.30	2.44	2.58	2.73	2.95	3.29
	k	0.615	0.668	0.689	0.677	0.0380	0.0474	0.0590	0.0717	0.0851	0.0988	0.13	0.16	0.20	0.26	0.39
	Pr	5.82	2.32	1.34	0.981	1.028	0.963	0.931	0.908	0.892	0.881	0.84	0.82	0.78	0.70	0.57
20	μ	8.56.–4	3.71.–4	2.18.–4	1.51.–4	1.68.–5	2.15.–5	2.59.–5	3.00.–5	3.40.–5	3.79.–5	4.46.–5	5.06.–5	5.65.–5	6.19.–5	6.70.–5
	c_p	4.17	4.19	4.25	4.39	2.84	2.26	2.19	2.21	2.26	2.32	2.45	2.59	2.73	2.92	3.21
	k	0.616	0.669	0.689	0.679	0.0402	0.0485	0.0599	0.0726	0.0859	0.0996	0.13	0.16	0.20	0.25	0.36
	Pr	5.80	2.32	1.34	0.979	1.19	0.999	0.946	0.912	0.893	0.881	0.84	0.82	0.79	0.72	0.60
40	μ	8.55.–4	3.71.–4	2.18.–4	1.52.–4	1.19.–4	2.15.–5	2.61.–5	3.02.–5	3.42.–5	3.80.–5	4.47.–5	5.07.–5	5.65.–5	6.19.–5	6.70.–5
	c_p	4.17	4.19	4.25	4.38	4.65	2.60	2.32	2.28	2.30	2.34	2.46	2.59	2.73	2.90	3.14
	k	0.617	0.671	0.690	0.680	0.644	0.516	0.0620	0.0744	0.0877	0.101	0.13	0.16	0.19	0.24	0.33
	Pr	5.78	2.31	1.34	0.977	0.862	1.08	0.975	0.924	0.895	0.881	0.84	0.82	0.80	0.73	0.63
60	μ	8.54.–4	3.72.–4	2.19.–4	1.53.–4	1.20.–4	2.14.–5	2.63.–5	3.04.–5	3.43.–5	3.82.–5	4.48.–5	5.07.–5	5.66.–5	6.19.–5	6.70.–5
	c_p	4.16	4.18	4.24	4.37	4.63	3.11	2.47	2.35	2.34	2.37	2.48	2.60	2.73	2.89	3.11
	k	0.619	0.672	0.692	0.682	0.646	0.0561	0.0645	0.0764	0.0895	0.103	0.13	0.16	0.19	0.24	0.32
	Pr	5.74	2.31	1.34	0.976	0.859	1.19	1.008	0.934	0.899	0.879	0.84	0.82	0.81	0.74	0.65
80	μ	8.53.–4	3.72.–4	2.19.–4	1.53.–4	1.20.–4	2.14.–5	2.66.–5	3.06.–5	3.45.–5	3.83.–5	4.48.–5	5.08.–5	5.66.–5	6.19.–5	6.70.–5
	c_p	4.16	4.18	4.24	4.36	4.62	3.88	2.65	2.43	2.39	2.40	2.49	2.61	2.73	2.88	3.09
	k	0.620	0.674	0.693	0.684	0.648	0.0628	0.0672	0.0785	0.0914	0.105	0.13	0.16	0.10	0.24	0.31
	Pr	5.72	2.31	1.34	0.975	0.856	1.33	1.046	0.946	0.902	0.877	0.84	0.83	0.81	0.74	0.66
100	μ	8.52.–4	3.73.–4	2.20.–4	1.53.–4	1.21.–4	2.14.–5	2.69.–5	3.08.–5	3.47.–5	3.85.–5	4.49.–5	5.08.–5	5.66.–5	6.19.–5	6.70.–5
	c_p	4.15	4.17	4.23	4.35	4.60	5.22	2.85	2.52	2.44	2.44	2.50	2.62	2.73	2.88	3.08
	k	0.622	0.675	0.694	0.685	0.651	0.0730	0.0704	0.0807	0.0934	0.107	0.13	0.16	0.19	0.24	0.31
	Pr	5.69	2.31	1.34	0.975	0.853	1.74	1.088	0.960	0.905	0.876	0.84	0.83	0.81	0.74	0.67
150	μ	8.51.–4	3.74.–4	2.22.–4	1.56.–4	1.22.–4	8.22.–5	2.72.–5	3.12.–5	3.51.–5	3.89.–5	4.52.–5	5.09.–5	5.67.–5	6.19.–5	6.70.–5
	c_p	4.14	4.16	4.22	4.34	4.54		3.55	2.74	2.57	2.53	2.54	2.65	2.75	2.88	3.06
	k	0.624	0.678	0.699	0.693	0.657	0.520	0.079	0.086	0.098	0.110	0.14	0.16	0.19	0.23	
	Pr	5.64	2.30	1.34	0.974	0.842		1.22	0.994	0.916	0.891	0.84	0.83	0.82	0.76	
200	μ	8.50.–4	3.75.–4	2.24.–4	1.57.–4	1.23.–4	8.32.–5	2.80.–5	3.17.–5	3.54.–5	3.93.–5	4.54.–5	5.11.–5	5.67.–5		
	c_p	4.12	4.15	4.21	4.32	4.51		4.67	3.04	2.71	2.62	2.57	2.67	2.76	2.88	3.05
	k	0.626	0.681	0.702	0.697	0.661	0.525	0.095	0.095	0.104	0.113	0.14	0.16	0.19		
	Pr	5.59	2.29	1.34	0.974	0.833		1.38	1.014	0.925	0.903	0.84	0.83	0.82		
250	μ	8.49.–4	3.76.–4	2.26.–4	1.59.–4	1.23.–4	8.41.–5	2.89.–5	3.24.–5	3.59.–5	3.98.–5	4.56.–5	5.12.–5	5.68.–5		
	c_p	4.12	4.14	4.20	4.30	4.49	5.90	6.16	3.40	2.86	2.71	2.61	2.69	2.77	2.89	3.04
	k	0.627	0.683	0.705	0.701	0.672	0.537	0.112	0.103	0.110	0.119	0.136	0.16			
	Pr	5.57	2.28	1.34	0.974	0.826	0.924	1.590	1.070	0.940	0.910	0.85	0.84			
300	μ	8.49.–4	3.77.–4	2.28.–4	1.60.–4	1.24.–4	8.50.–5	3.7.–5	3.4.–5	3.64.–5	4.02.–5	4.59.–5	5.14.–5	5.68.–5		
	c_p	4.10	4.13	4.19	4.29	4.44	5.60	10.20	3.82	3.03	2.81	2.65	2.72	2.78	2.90	3.04
	k	0.629	0.685	0.708	0.704	0.675	0.548	0.173	0.113	0.113	0.123	0.14				
	Pr	5.53	2.27	1.34	0.973	0.820	0.859	2.18	1.149	0.976	0.917	0.87				
400	μ	8.49.–4	3.80.–4	2.30.–4	1.62.–4	1.26.–4	8.64.–5	5.3.–5	3.6.–5	3.8.–5	4.1.–5	4.6.–5	5.17.–5			
	c_p	4.08	4.12	4.16	4.26	4.42	5.31	13.20	4.86	3.39	3.01	2.70	2.77	2.81	2.91	3.04
	k	0.631	0.689	0.714	0.710	0.676	0.567	0.327	0.145	0.129	0.134	0.15				
	Pr	5.49	2.26	1.34	0.971	0.817	0.799	2.14	1.207	0.999	0.926					
500	μ	8.50.–4	3.82.–4	2.31.–4	1.64.–4	1.28.–4	8.83.–5	5.8.–5	4.0.–5	4.0.–5	4.2.–5	4.7.–5				
	c_p	4.06	4.10	4.15	4.23	4.38	5.08	8.44	5.70	3.90	3.21	2.77	2.81	2.84	2.92	3.04
	k	0.634	0.695	0.719	0.717	0.693	0.583	0.378	0.186	0.147	0.145					
	Pr	5.44	2.25	1.33	0.971	0.814	0.773	1.30	1.225	1.061	0.932					

TABLE 2-356 Specific Heat and Other Thermophysical Properties of Water Substance (*Concluded*)

		Temperature, K														
Pressure, bar		300	350	400	450	500	600	700	800	900	1000	1200	1400	1600	1800	2000
600	μ	8.51.–4	3.85.–4	2.32.–4	1.66.–4	1.30.–4	9.17.–5	6.5.–5	4.4.–5	4.2.–5	4.4.–5					
	c_p	4.04	4.08	4.13	4.20	4.33	4.92	6.93	6.83	4.19	3.38	2.87	2.86	2.86	2.92	3.04
	k	0.639	0.699	0.725	0.725	0.700	0.597	0.420	0.239	0.170	0.159					
	Pr	5.38	2.24	1.32	0.970	0.812	0.755	1.073	1.175	1.035	0.935					
700	μ	8.52.–4	3.87.–4	2.33.–4	1.69.–4	1.33.–4	9.50.–5	6.9.–5	4.9.–5	4.5.–5	4.6.–5					
	c_p	4.01	4.07	4.12	4.17	4.29	4.78	6.12	6.26	4.62	3.59	2.94	2.91	2.88	2.93	3.05
	k	0.644	0.706	0.730	0.732	0.707	0.614	0.442	0.279	0.198	0.177					
	Pr	5.33	2.23	1.32	0.970	0.810	0.739	1.047	1.098	1.010	0.935					
800	μ	8.53.–4	3.90.–4	2.34.–4	1.72.–4	1.36.–4	9.82.–5	7.3.–5	5.4.–5	4.8.–5	4.8.–5					
	c_p	3.99	4.05	4.10	4.15	4.26	4.67	5.60	6.09	4.77	3.75	3.01	2.96	2.91	2.95	3.05
	k	0.648	0.709	0.735	0.736	0.714	0.625	0.478	0.320	0.228	0.193					
	Pr	5.28	2.23	1.31	0.970	0.808	0.725	0.855	1.028	1.003	0.933					
900	μ	8.54.–4	3.93.–4	2.35.–4	1.74.–4	1.38.–4	1.00.–4	7.6.–5	5.8.–5	5.1.–5	5.0.–5					
	c_p	3.98	4.03	4.08	4.13	4.23	4.57	5.29	5.86	4.85	3.86	3.08	3.00	2.94	2.97	3.06
	k	0.651	0.713	0.738	0.742	0.724	0.636	0.496	0.351	0.260	0.210					
	Pr	5.23	2.22	1.30	0.969	0.806	0.712	0.810	0.968	0.950	0.919					
1000	μ	8.56.–4	3.96.–4	2.36.–4	1.76.–4	1.40.–4	1.02.–4	7.9.–5	6.2.–5	5.4.–5	5.1.–5					
	c_p	3.97	4.02	4.06	4.11	4.20	4.47	5.08	5.51	4.88	3.96	3.16	3.05	2.97	2.98	3.07
	k	0.653	0.717	0.743	0.747	0.731	0.650	0.516	0.372	0.288	0.228					
	Pr	5.19	2.22	1.30	0.968	0.804	0.701	0.778	0.918	0.900	0.886					

*μ = viscosity, Ns/m^2; c_p = specific heat at constant pressure, kJ/(kg·K); k = thermal conductivity, W/(m·K); Pr = Prandtl number.

TABLE 2-357 Thermodynamic Properties of Water Substance along the Melting Line

P, bar	T, °C	$10^3\, v_f$, m^3/kg	h_f, kJ/kg	s_f, kJ/kg·K	c_{pf}, kJ/kg·K	c_{melt}, kJ/kg·K	$10^6 \alpha_f$, K^{-1}	$10^6 K_{f,T}$ bar^{-1}
6.117.–5[t]	0.0100	1.00021	0	0	4.219	3.969	–67.42	50.90
1.01325	0.0026	1.00016	0.0719	–0.0001	4.218	3.970	–67.17	50.88
50	–0.3618	0.99770	3.5140	–0.0054	4.196	3.997	–54.92	50.30
100	–0.7410	0.99523	6.9794	–0.0110	4.174	4.023	–42.52	49.73
150	–1.1249	0.99278	10.3964	–0.0167	4.152	4.047	–30.24	49.17
200	–1.5166	0.99037	13.7648	–0.0225	4.132	4.070	–18.05	48.63
250	–1.9151	0.98798	17.0843	–0.0285	4.112	4.092	–5.93	48.11
300	–2.3206	0.98562	20.3547	–0.0347	4.092	4.113	6.12	47.59
400	–3.1532	0.98098	26.7472	–0.0474	4.056	4.150	30.09	46.61
500	–4.0156	0.97643	32.9403	–0.0607	4.022	4.184	53.97	45.68
600	–4.909	0.97196	38.932	–0.0747	3.992	4.215	77.87	44.80
800	–6.790	0.96326	50.300	–0.1046	3.937	4.270	126.18	43.19
1000	–8.803	0.95493	60.836	–0.1371	3.893	4.320	175.98	41.74

Condensed from U. Grigull, Private communication, January 18, 1995.

Materials prepared at Technical University München, Germany by U. Grigull and S. Marek. For a table as a function of temperature, see Grigull, U. and S. Marek, *Warme u. Stoff.*, **30** (1994): 1–8.

t = the triple point (at 6.117×10^{-5} bar, 0.01°C); $v_f = 0.0010021$ m^3/kg: $\alpha_f = -67.42 \times 10^{-6}$/K.

Other equations for properties are given by Jones, F. E. and G. L. Harris, *J. Res. N.I.S.T.*, **97,** 3 (1992): 335–340, and by Wagner, W. and A. Pruss, *J. Phys. Chem. Ref. Data,* **22,** 3 (1993): 783–787. Steam tables include Walker, W. A., U.S. Naval Ordn. Lab. rept. NOLTR NOLTR-66-217 = AD 651105 (0–1000 bar, 0–150°C), 1967 (72 pp.); Grigull, U., J. Straub, et al., *Steam Tables in S.I. Units* (0.01–1000 bar, 0–1000°C), Springer-Verlag, Berlin, 1990 (133 pp.); Tseng, C. M., T. A. Hamp, et al., Atomic Energy of Canada rept. (30 props, sat liq & vap., 1–220 bar), AECL-5910 1977 (90 pp.). For dissociation, see e.g., Knonicek, V., *Rozpr. Cesko Acad Ved., Rada techn ved* (0.01–100 bar, 1000–5000 K). **77,** 1 (1967). The proceedings of the 10th international conference on the properties of steam were edited by Sytchev, V. V. and A. A. Aleksandrov, Plenum, NY, 1984; and for the 11th conference by Pichal, M. and O. Sifner, Hemisphere, 1989 (550 pp.).

For electrical conductivity, see e.g., Marshall, W. L., *J. Chem. Eng. Data,* **32** (1987): 221–226.

TABLE 2-358 Saturated Xenon*

T, K	P, bar	v_f, m^3/kg	v_g, m^3/kg	h_f, kJ/kg	h_g, kJ/kg	s_f, kJ/(kg·K)	s_g, kJ/(kg·K)	c_{pf}, kJ/(kg·K)	μ_f, 10^{-4} Pa·s	k_f, W/(m·K)
10		2.642.–4		0.19		0.0236		0.058		
20		2.650.–4		1.21		0.0901		0.133		
30		2.661.–4		2.74		0.1510		0.164		
40		2.675.–4		4.47		0.2003		0.178		
50		2.689.–4		6.31		0.2410		0.186		
60		2.704.–4		8.21		0.2755		0.191		
80		2.737.–4		12.14		0.3319		0.202		
100		2.776.–4		16.30		0.3783		0.214		
120		2.820.–4		20.81		0.4197		0.231		
140		2.874.–4		25.67		0.4581		0.251		
160		2.941.–4		30.94		0.4946		0.270		
161.4[m]		2.946.–4		31.30		0.4969		0.271		
161.4[m]	0.816	3.372.–4	0.1219	48.98	145.5	0.6072	1.206	0.350		
170	1.336	3.439.–4	0.0776	52.01	146.5	0.6253	1.181	0.349	4.50	0.0707
180	2.218	3.523.–4	0.0487	55.52	147.5	0.6452	1.156	0.349	3.99	0.0663
190	3.480	3.615.–4	0.0321	59.04	148.3	0.6641	1.134	0.352	3.51	0.0622
200	5.212	3.715.–4	0.0220	62.61	148.9	0.6820	1.113	0.357	3.09	0.0582
210	7.504	3.828.–4	0.0156	66.25	149.2	0.6994	1.095	0.365	2.71	0.0542
220	10.45	3.955.–4	0.0113	70.00	149.4	0.7163	1.077	0.379	2.39	0.0506
230	14.16	4.100.–4	0.0084	73.91	149.2	0.7330	1.060	0.400	2.09	0.0468
240	18.72	4.271.–4	0.0063	78.05	148.5	0.7498	1.044	0.432	1.83	0.0429
250	24.25	4.476.–4	0.0047	82.54	147.5	0.7671	1.027	0.482	1.60	0.0393
260	30.87	4.730.–4	0.0036	87.52	145.7	0.7855	1.009	0.560	1.38	0.0355
270	38.69	5.079.–4	0.0027	93.30	142.8	0.8058	0.989	0.685	1.18	0.0313
280	47.86	5.689.–4	0.0019	100.6	138.0	0.8308	0.964	0.995	0.95	0.0275
289.7[c]	58.21	9.091.–4	0.0009	120.0	120.0	0.8962	0.896	∞		∞

*Values extracted and in some cases rounded off from those cited in Rabinovich (ed.), *Thermophysical Properties of Neon, Argon, Krypton and Xenon,* Standards Press, Moscow, 1976. This source contains values for the compressed state for pressures up to 1000 bar, etc. m = melting point; c = critical point. The notation 2.642.–4 signifies 2.642×10^{-4}. This book was published in English translation by Hemisphere, New York, 1988 (604 pp.).

TABLE 2-359 Compressed Xenon*

	Pressure, bar										
T, K	1	100	200	300	400	500	600	700	800	900	1000
100 *v*	2.776.–4	2.764.–4	2.752.–4	2.742.–4	2.731.–4	2.721.–4	2.711.–4	2.702.–4	2.693.–4	2.684.–4	2.675.–4
h	16.30	18.84	21.40	23.95	26.50	29.05	31.59	34.13	36.67	39.21	41.74
s	0.3783	0.3762	0.3742	0.3723	0.3704	0.3686	0.3669	0.3652	0.3636	0.3621	0.3802
200 *v*	0.1245	3.623.–4	3.547.–4	3.484.–4	3.430.–4	3.383.–4	3.342.–4	3.304.–4	3.270.–4	3.240.–4	3.211.–4
h	151.8	64.22	66.14	68.19	70.34	72.56	74.83	77.13	79.46	81.81	84.18
s	1.228	0.6727	0.6643	0.6570	0.6505	0.6446	0.6391	0.6340	0.6292	0.6247	0.6204
300 *v*	0.1890	5.729.–4	4.769.–4	4.431.–4	4.220.–4	4.068.–4	3.955.–4	3.862.–4	3.783.–4	3.716.–4	3.657.–4
h	168.0	106.4	101.6	101.3	102.0	103.3	104.9	106.7	108.5	110.6	112.8
s	1.294	0.8401	0.8073	0.7908	0.7789	0.7691	0.7608	0.7540	0.7477	0.7424	0.7370
400 *v*	0.2527	1.998.–3	8.759.–4	6.452.–4	5.604.–4	5.141.–4	4.839.–4	4.622.–4	4.457.–4	4.325.–4	4.217.–4
h	183.9	164.2	145.4	137.4	134.7	134.1	134.5	135.5	136.8	138.3	140.0
s	1.340	1.012	0.9330	0.8945	0.8730	0.8581	0.8467	0.8373	0.8292	0.8220	0.8162
500 *v*	0.3163	2.899.–3	1.389.–3	9.449.–4	7.577.–4	6.593.–4	5.986.–4	5.570.–4	5.268.–4	5.038.–4	4.859.–4
h	199.8	187.8	177.1	169.4	165.1	163.0	162.3	162.4	163.1	164.3	165.7
s	1.375	1.065	1.004	0.9664	0.9409	0.9228	0.9088	0.8975	0.8881	0.8801	0.8731
600 *v*	0.3798	3.673.–3	1.823.–3	1.240.–3	9.699.–4	8.206.–4	7.273.–4	6.636.–4	6.172.–4	5.820.–4	5.545.–4
h	215.7	207.4	200.3	194.8	191.1	188.9	187.9	187.6	188.0	188.8	189.9
s	1.404	1.101	1.047	1.013	0.9885	0.9700	0.9555	0.9435	0.9334	0.9247	0.9172
700 *v*	0.4432	4.397.–3	2.217.–3	1.513.–3	1.175.–3	9.815.–4	8.583.–4	7.734.–4	7.115.–4	6.642.–4	6.268.–4
h	231.5	225.6	220.6	216.7	213.8	212.2	211.3	211.1	211.3	212.0	213.1
s	1.428	1.129	1.078	1.047	1.023	1.006	0.9916	0.9797	0.9695	0.9606	0.9528
800 *v*	0.5066	5.093.–3	2.587.–3	1.769.–3	1.370.–3	1.137.–3	9.870.–4	8.824.–4	8.057.–4	7.469.–4	7.005.–4
h	247.4	243.0	239.5	236.7	234.8	233.6	233.0	232.9	233.3	234.0	235.0
s	1.450	1.152	1.103	1.073	1.052	1.035	1.021	1.009	0.9988	0.9901	0.9823
900 *v*	0.5700	5.773.–3	2.944.–3	2.014.–3	1.557.–3	1.288.–3	1.112.–3	9.893.–4	8.989.–4	8.289.–4	7.737.–4
h	263.2	260.1	257.5	255.7	254.4	253.6	253.4	253.7	254.2	254.9	256.1
s	1.468	1.172	1.125	1.096	1.075	1.058	1.045	1.033	1.023	1.015	1.007
1000 *v*	0.6333	6.441.–3	3.291.–3	2.252.–3	1.738.–3	1.435.–3	1.235.–3	1.094.–3	9.899.–4	9.097.–4	8.461.–4
h	279.1	276.8	275.1	273.9	273.2	272.9	273.0	273.4	274.1	275.1	276.2
s	1.485	1.190	1.143	1.115	1.095	1.079	1.065	1.054	1.044	1.036	1.028

*Values extracted and in some cases rounded off from those cited in Rabinovich (ed.), *Thermophysical Properties of Neon, Argon, Krypton and Xenon.* Standards Press, Moscow, 1976. This source contains an exhaustive tabulation of values. v = specific volume, m^3/kg; h = specific enthalpy, kJ/kg; s = specific entropy, kJ/(kg·K). The notation 2.776.–4 signifies 2.776×10^{-4}. This book was published in English translation by Hemisphere, New York, 1988 (604 pp.).

TABLE 2-360 Surface Tension (N/m) of Saturated Liquid Refrigerants*

	Temperature, °C								
R no.	–50	–25	0	25	50	75	100	125	150
11	0.0279	0.0244	0.0210	0.0178	0.0146	0.0116	0.0087	0.0060	0.0036
12	0.0188	0.0152	0.0118	0.0085	0.0055	0.0029	0.0007	—	—
13	0.0092	0.0056	0.0025	0.0002	—	—	—	—	—
22	0.0197	0.0156	0.0117	0.0081	0.0047	0.0018	—	—	—
23	0.0115	0.0065	0.0025		—	—	—	—	—
32				0.0069	0.0032	0.0002	—	—	—
113	—	0.0231	0.0201	0.0172	0.0144	0.0118	0.0092	0.0067	0.0045
114			0.0138	0.0109	0.0082	0.0056	0.0033	0.0012	—
115			0.0075	0.0047	0.0022		—	—	—
134a	0.0192	0.0154	0.0117	0.0082	0.0050	0.0021	0.0000	—	—
142b	0.0213	0.0178	0.0145	0.0113	0.0083	0.0055	0.0029		—
152a	0.0201	0.0166	0.0132	0.0100	0.0068	0.0038	0.0011	—	—
170	0.0100	0.0051	0.0032	0.0005	—	—	—	—	—
290			0.0101	0.0082	0.0041	0.0016	—	—	—
C318	—	0.0143	0.0113	0.0085	0.0048	0.0033	0.0011	—	—
502	0.0159	0.0121	0.0086	0.0054	0.0026		—	—	—
503	0.0094	0.0053	0.0018	—	—	—	—	—	—
600		0.0180	0.0150	0.0122	0.0094	0.0068	0.0043	0.0020	0.0001
600a			0.0132	0.0101	0.0073	0.0047	0.0024	0.0005	—
718	—	—	0.0755	0.0720	0.0680	0.0636	0.0590	0.0540	0.0488
744		0.0096	0.0044	0.0005	—	—	—	—	—
1150	0.0100	0.0055	0.0013						
1270	0.0171	0.0136	0.0102	0.0070	0.0041	0.0014			

*Dashes indicate inaccessible states; blanks indicate no available data.

Values and equations were given by Srinivasan, K., *Can. J. Chem. Eng.* (27 liquids), **68** (1990): 493; Lielmezs, J. and T. A. Herrick, *Chem. Eng. J.* (34 liquids), **32** (1986): 165–169. Somayajulu, G. R., *Int. J. Thermophys.* (64 liquids); **9,** 4 (1988): 559–566; Ibrahim, N. and S. Murad, *Chem. Eng. Commun.* (29 polar liquids), **79** (1979): 165–174; Yaws, C. L.; Morachevsky, A. G. and I. B. Sladkov, *Physico-Chemical Properties of Molecular Inorganic Compounds* (200 compounds), Khimiya, Leningrad, 1987, Jasper, J., *J. Phys. Chem. Ref. Data* (2200 compounds), **1,** (1972): 841–1009; and Vargaftik, N. B., B. N. Volkov, et al., *J. Phys. Chem. Ref. Data* (water), **12,** 3 (1983): 817–820. See also Escobedo, J. and Mansoori, G. R., *AIChE J.*, **42**(5), May 1996: 1425–1433.

TABLE 2-361 Velocity of Sound (m/s) in Gaseous Refrigerants at Atmospheric Pressure*

	Temperature, °C								
R. no.	–50	–25	0	25	50	75	100	125	150
11	—	—	—	141	147	153	158	163	168
12	—	136	143	150	156	162	168	173	179
13	142	150	157	164	170	176	182	188	193
14	158	166	173	180	187	194	200	206	212
22	—	166	174	182	189	196	202	208	215
23	179	188	197	205	212	220	227	234	240
32									
113	—	—	—	—	121	126	131	135	140
114	—	—	—	120	126	131	136	141	146
134a		146	154	162	169	175	180	186	192
170	272	286	299	311	323	334	344	355	364
290	—	227	238	249	258	268	277	286	294
600	—	—	200	210	220	228	237	245	252
600a	—	—	201	211	221	229	237	246	253
718	—	—	—	—	—	—	473	490	505
744		248	258	269	279	288	297	307	316
1150	290	305	318	330	341	352	363	373	384
1270	—	235	246	257	267	277	286	295	303

*Dashes indicate inaccessible states; blanks indicate no available data.

TABLE 3-362 Velocity of Sound (m/s) in Saturated Liquid Refrigerants*

	Temperature, °C								
R. no.	–50	–25	0	25	50	75	100	125	150
11	933	843	772	705	639	569	493	408	323
12	829	695	564	434				—	—
13	602	444	302		—	—	—	—	—
14	182	—	—	—	—	—	—	—	—
22	899	790	682	571	446	319	—	—	—
23		538	348	191	—	—	—	—	—
32							—	—	—
113	—	871	786	700	633				
114	853	726	623	540	453	371	284	183	—
115			454	346	255		—	—	—
134a	858	743	626	517	387	262	105	—	—
290	1210	982	884	719	551	367	—	—	—
600	1290	1163	1031	896	759	609	477	325	142
600a	1205	1078	947	812	661	528	378	208	—
718	—	—	1402	1495	1542	1554	1543	1514	1468
744		751	525	272	—	—	—	—	—
1150	874	644	372						
1270	1184	1022	859	694	524	335			

*Dashes indicate inaccessible states; blanks indicate no available data.

TRANSPORT PROPERTIES

INTRODUCTION

Extensive tables of the viscosity and thermal conductivity of air and of water or steam for various pressures and temperatures are given with the thermodynamic-property tables. The thermal conductivity and the viscosity for the saturated-liquid state are also tabulated for many fluids along with the thermodynamic-property tables earlier in this section.

UNITS CONVERSIONS

For this subsection the following units conversions are applicable:

Diffusivity: to convert square centimeters per second to square feet per hour, multiply by 3.8750; to convert square meters per second to square feet per hour, multiply by 38,750.

Pressure: to convert bars to pounds-force per square inch, multiply by 14.504.

Temperature: °F = $\frac{9}{5}$ °C + 32; °R = $\frac{9}{5}$ K.

Thermal conductivity: to convert watts per meter-kelvin to British thermal unit–feet per hour–square foot–degree Fahrenheit, multiply by 0.57779; and to convert British thermal unit–feet per hour–square foot–degree Fahrenheit to watts per meter-kelvin, multiply by 1.7307.

Viscosity: to convert pascal-seconds to centipoises, multiply by 1000.

ADDITIONAL REFERENCES

An extensive coverage of the general pressure and temperature variation of thermal conductivity is given in the monograph by Vargaftik, Filippov, Tarzimanov, and Totskiy, *Thermal Conductivity of Liquids and Gases* (in Russian), Standartov, Moscow, 1978, now published in English translation by CRC Press, Miami, FL.

For a similar work on viscosity, see Stephan and Lucas, *Viscosity of Dense Fluids*, Plenum, New York and London, 1979. Tables and polynomial fits for refrigerants in both the gaseous and the liquid state are contained in *ASHRAE Thermophysical Properties of Refrigerants*, American Society of Heating, Refrigerating and Ventilating Engineers, Atlanta, GA, 1993. Other sources for viscosity include Fischer & Porter Co. catalog 10-A-94, "Fluid densities and viscosities," 1953 (200 industrial fluids in 48 pp.) and van Velzen, D., R. L. Cardozo et al., EURATOM Ispra, Italy rept. 4735 e, 1972 (160 pp.). Liquid viscosity, 314 cpds, is summarized in *I&EC Fundtls.*, 11 (1972): 20–26. Five hundred forty-nine binary and ternary systems are discussed in Skubla, P., *Coll. Czech. Chem. Commun.*, **46** (1981): 303–339.

See also Duhne, C. R., *Chem. Eng.* (NY), **86,** 15 (July 16, 1979): 83–91 (equations and 326 liquids); and Rao, K. V. K., *Chem. Eng.* (NY), **90,** 11 (May 30, 1983): 90–91 (nomograph, 87 liquids). For rheology, non-Newtonian behavior, and the like, see, for instance, Barnes, H., *The Chem. Engr.* (UK), (June 24, 1993): 17–23; Hyman, W. A., *I&EC Fundtls.*, **16** (1976): 215–218; and Ferguson, J. and Z. Kemblowski, *Applied Fluid Rheology*, Elsevier, 1991 (325 pp.). Other sources for thermal conductivity include Ho, C. Y., R. W. Powell et al., *J. Phys. Chem. Ref. Data*, **1** (1972) and **3,** suppl. 1 (1974); Childs, Ericks et al., N.B.S. Monogr. 131, 1973; Jamieson, D. T., J. B. Irving et al., *Liquid Thermal Conductivity*, H.M.S.O., Edinburgh, Scotland, 1975 (220 pp.).

TABLE 2-363 Transport Properties of Selected Gases at Atmospheric Pressure*

	Thermal conductivity, W/(m·K) Temperature, K					Viscosity, 10^{-4} Pa·s Temperature, K					Prandtl number, dimensionless Temperature, K			
Substance	250	300	400	500	600	250	300	400	500	600	250	300	400	500
Acetone	0.0080	0.0115	0.0201	0.0310			0.077	0.101	0.128	0.156				
Acetylene	0.0162	0.0213	0.0332	0.0452	0.0561		0.104	0.135	0.164					
Ammonia	0.0197	0.0246	0.0364	0.0506	0.0656	0.085	0.102	0.139	0.175	0.211		0.91	0.87	0.86
Argon	0.0152	0.0177	0.0223	0.0264	0.0301	0.195	0.229	0.289	0.343	0.390	0.669	0.668	0.666	0.663
Benzene	0.0077	0.0104	0.0195	0.0335	0.0524		0.076	0.101	0.127	0.154				
Bromine	0.0038	0.0048	0.0067					0.203	0.260	0.291				
Butane	0.0117	0.0160	0.0264	0.0377			0.076	0.101	0.125	0.151		0.805	0.820	
CO_2	0.0129	0.0166	0.0244	0.0323	0.0403	0.126	0.150	0.196	0.239	0.278	0.793	0.778	0.752	0.734
CCl_4	0.0053	0.0067	0.0099	0.0126			0.101	0.131	0.162	0.191				
Chlorine	0.0071	0.0089	0.0124	0.0156	0.0190		0.136	0.178	0.218	0.259				
Deuterium	0.122	0.141	0.176			0.111	0.126	0.153	0.178	0.201				
Ethane	0.0156	0.0218	0.0360	0.0516	0.0685	0.079	0.094	0.123	0.148	0.171	0.817	0.773	0.746	0.746
Ethylene	0.0152	0.0214	0.0342	0.0491	0.0653	0.087	0.103	0.135	0.162	0.187	0.812	0.796	0.769	0.750
Helium	0.134	0.150	0.180	0.211	0.247	0.176	0.199	0.243	0.284	0.322	0.671	0.668	0.663	0.661
Heptane	0.0082	0.0120	0.0214	0.0325	0.0447			0.080	0.099	1.116				
Hydrogen	0.156	0.182	0.221	0.256	0.291	0.080	0.090	0.109	0.126	0.143	0.71	0.71	0.71	0.71
Methane	0.0277	0.0343	0.0484	0.0671	0.0948	0.095	0.112	0.142	0.170	0.195	0.742	0.739	0.737	0.736
Nitrogen	0.0222	0.0260	0.0325	0.0386	0.0441	0.156	0.180	0.223	0.261	0.295	0.721	0.714	0.708	0.707
Oxygen	0.0225	0.0267	0.0343	0.0412	0.0480	0.179	0.207	0.258	0.306	0.348				
Pentane	0.0107	0.0152	0.0250	0.0362										
Propane	0.0129	0.0183	0.0295	0.0417		0.069	0.082	0.108	0.131		0.810	0.774	0.788	0.826
Propylene	0.0114	0.0168	0.0226	0.0430	0.0580	0.073	0.087	0.115	0.141		0.860	0.797	0.762	
R 11		0.0078	0.0119			0.094	0.110	0.144				0.814	0.761	
R 12	0.0072	0.0097	0.0151	0.0208		0.108	0.126	0.162			0.827	0.781	0.745	0.708
R 13	0.0091	0.0121	0.0185	0.0248		0.123	0.145	0.190			0.796	0.766	0.759	0.757
R 21		0.0088	0.0135	0.0181		0.100	0.115	0.154				0.779	0.773	
R 22	0.0080	0.0109	0.0170	0.0230	0.0290	0.109	0.129	0.168			0.820	0.771	0.760	
SO_2	0.0078	0.0096	0.0143	0.0200	0.0256		0.129	0.175	0.217	0.256				

*An approximate interpolation scheme is to plot the logarithm of the viscosity or the thermal conductivity versus the logarithm of the absolute temperature. At 250 K the viscosity of gaseous argon is to be read as 1.95×10^{-5} Pa·s = 0.0000195 Ns/m^2.

TABLE 2-364 Viscosities of Gases: Coordinates for Use with Fig. 2-32*

Gas	*X*	*Y*	$\mu \times 10^7$ p	Ref.
Acetic acid	7.0	14.6	825 (50°C)	1
Acetone	8.4	13.2	735	1
Acetylene	9.3	15.5	1017	1
Air	10.4	20.4	1812	1
Ammonia	8.4	16.0	1000	1
Amylene (β)	8.6	12.2	676	1
Argon	9.7	22.6	2215	1
Arsine	8.6	20.0	1576	1
Benzene	8.7	13.2	746	1
Bromine	8.8	19.4	1495	1
Butane (*n*)	8.6	13.2	735	1
Butane (iso)	8.6	13.2	744	1
Butyl acetate (iso)	5.7	16.3	778	1
Butylene (α)	8.4	13.5	761	1
Butylene (β)	8.7	13.1	746	1
Butylene (iso)	8.3	13.9	786	1
Butyl formate (iso)	6.6	16.0	840	1
Cadmium	7.8	22.5	5690 (500)	1
Carbon dioxide	8.9	19.1	1463	1
Carbon disulfide	8.5	15.8	990	1
Carbon monoxide	10.5	20.0	1749	1
Carbon oxysulfide	8.2	17.9	1220	1
Carbon tetrachloride	8.0	15.3	966	1
Chlorine	8.8	18.3	1335	1
Chloroform	8.8	15.7	1000	1
Cyanogen	8.2	16.2	1002	1
Cyclohexane	9.0	12.2	701	1
Cyclopropane	8.3	14.7	870	1
Deuterium	11.0	16.2	1240	1
Diethyl ether	8.8	12.7	730	1
Dimethyl ether	9.0	15.0	925	1
Diphenyl ether	8.6	10.4	610 (50)	1
Diphenyl methane	8.0	10.3	605 (50)	1
Ethane	9.0	14.5	915	1
Ethanol	8.2	14.5	835	1
Ethyl acetate	8.4	13.4	743	1
Ethyl chloride	8.5	15.6	978	1
Ethylene	9.5	15.2	1010	1
Ethyl propionate	12.0	12.4	890	1
Fluorine	7.3	23.8	2250	2
Freon-11	8.6	16.2	1298 (93)	3
Freon-12	9.0	17.4	1496 (93)	3
Freon-14	9.5	20.4	1716	5
Freon-21	9.0	16.7	1389 (93)	3
Freon-22	9.0	17.7	1554 (93)	3
Freon-113	11.0	14.0	1166 (93)	3
Freon-114	9.4	16.4	1364 (93)	3
Helium	11.3	20.8	1946	1
Heptane (*n*)	8.6	10.6	618 (50)	1
Hexane (*n*)	8.4	12.0	644	1
Hydrogen	11.3	12.4	880	1
Hydrogen-helium				1
10% H_2, 90% He	11.0	20.5	1780 (0)	
25% H_2, 75% He	11.0	19.4	1603 (0)	
40% H_2, 60% He	10.7	18.4	1431 (0)	
60% H_2, 40% He	10.8	16.7	1227 (0)	
81% H_2, 19% He	10.5	15.0	1016 (0)	
Hydrogen–sulfur dioxide				4
10% H_2, 90% SO_2	8.7	18.1	1259 (17)	
20% H_2, 80% SO_2	8.6	18.2	1277 (17)	
50% H_2, 50% SO_2	8.9	18.3	1332 (17)	
80% H_2, 20% SO_2	9.7	17.7	1306 (17)	
Hydrogen bromide	8.4	21.6	1843	1
Hydrogen chloride	8.5	19.2	1425	1
Hydrogen cyanide	7.1	14.5	737	1
Hydrogen iodide	8.5	21.5	1830	1
Hydrogen sulfide	8.4	18.0	1265	1
Iodine	8.7	18.7	1730 (100)	1
Krypton	9.4	24.0	2480	1
Mercury	7.4	24.9	4500 (200)	1
Mercuric bromide	8.5	19.0	2253	1
Mercuric chloride	7.7	18.7	2200 (200)	1
Mercuric iodide	8.4	18.0	2045 (200)	1
Mesitylene	9.5	10.2	660 (50)	1
Methane	9.5	15.8	1092	1
Methane (deuterated)	9.5	17.6	1290	1
Methanol	8.3	15.6	935	1
Methyl acetate	8.4	14.0	870 (50)	
Methyl acetylene	8.9	14.3	867	1
3-Methyl-1-butene	8.0	13.3	716	1
Methyl butyrate (iso)	6.6	15.8	824	1
Methyl bromide	8.1	18.7	1327	1
Methyl chloride	8.5	16.5	1062	1
3-Methylene-1-butene	8.0	13.3	716	1
Methylene chloride	8.5	15.8	989	1
Methyl formate	5.1	18.0	923	6
Neon	11.1	25.8	3113	1
Nitric oxide	10.4	20.8	1899	1
Nitrogen	10.6	20.0	1766	1
Nitrous oxide	9.0	19.0	1460	1
Nonane (*n*)	9.2	8.9	554 (50)	1
Octane (*n*)	8.8	9.8	586 (50)	1
Oxygen	10.2	21.6	2026	1
Pentane (*n*)	8.5	12.3	668	1
Pentane (iso)	8.9	12.1	685	1
Phosphene	8.8	17.0	1150	1
Propane	8.9	13.5	800	1
Propanol (*n*)	8.4	13.5	770	1
Propanol (iso)	8.4	13.6	774	1
Propyl acetate	8.0	14.3	797	1
Propylene	8.5	14.4	840	1
Pyridine	8.6	13.3	830 (50)	1
Silane	9.0	16.8	1148	1
Stannic chloride	9.1	16.0	1330 (100)	1
Stannic bromide	9.0	16.7	142 (100)	1
Sulfur dioxide	8.4	18.2	1250	1
Thiazole	10.0	14.4	958	1
Thiophene	8.3	14.2	901 (50)	1
Toluene	8.6	12.5	686	1
2,2,3-Trimethylbutane	10.0	10.4	691 (50)	1
Trimethylethane	8.0	13.0	686	1
Water	8.0	16.0	1250 (100)	1
Xenon	9.3	23.0	2255	
Zinc	8.0	22.0	5250 (500)	1

*Viscosity at 20°C unless otherwise indicated. From Beerman, *Meas. Control* (June 1982): 154–157.

References:

1. I. F. Golubev, *Viscosity of Gases and Gas Mixtures,* Moscow 1959; transl. U.S. Department of Commerce, Clearinghouse for Federal Scientific and Technical Information, Springfield, Va., TT 70-50022, ISPT Cat. No. 5680, Table 4, Jerusalem 1970.
2. R. H. Perry and C. H. Chilton, *Chemical Engineers' Handbook,* 5th ed., McGraw-Hill, New York, 1973, pp. 3-210, 3-211.
3. Ibid., Table 3-282, p. 3-210.
4. By interpolation of data in Ref. 1.
5. *Thermophysical Properties of Refrigerants,* American Society of Heating, Refrigerating and Air-Conditioning Engineers, New York.
6. N. A. Lange, *Handbook of Chemistry,* 4th ed., Handbook Publishers, Sandusky, Ohio, 1941.

For another alignment chart for 165 hydrocarbons from −100 to 500°C, see Sastry, R. C. and A. Satyanarayan, *Chem. Industry Devs.* (July 1978): 11–14.

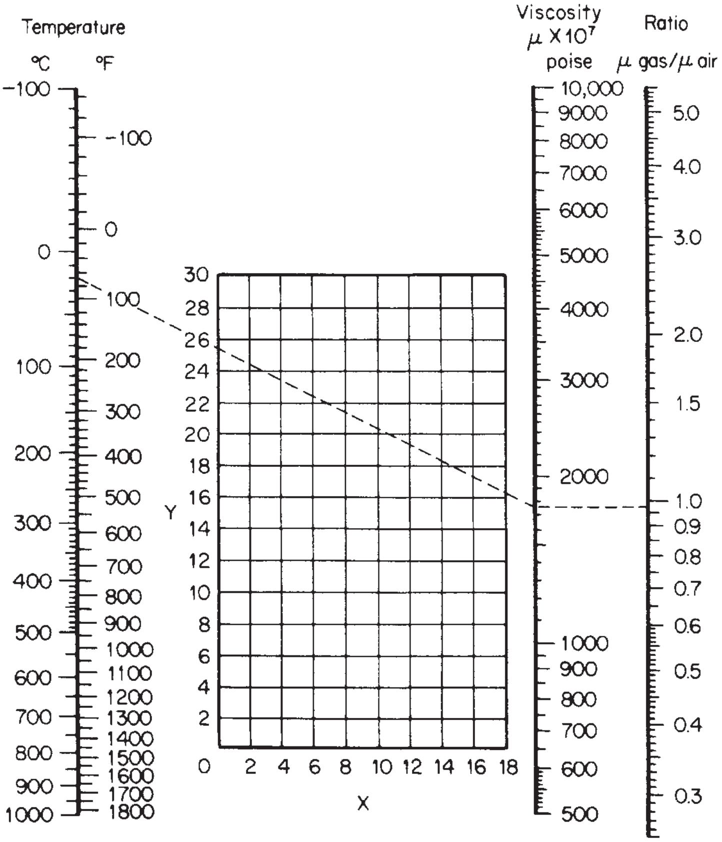


FIG. 2-32 Nomograph for determining (*a*) absolute viscosity of a gas as a function of temperature near ambient pressure and (*b*) relative viscosity of a gas compared with air. For coordinates see Table 2-364. To convert poises to pascal-seconds, multiply by 0.1. [*From Beerman,* Meas. Control, *154–157 (June 1982).*]

TABLE 2-365 Viscosities of Liquids: Coordinates for Use with Fig. 2-33

Liquid	*X*	*Y*
Acetaldehyde	15.2	4.8
Acetic acid, 100%	12.1	14.2
Acetic acid, 70%	9.5	17.0
Acetic anhydride	12.7	12.8
Acetone, 100%	14.5	7.2
Acetone, 35%	7.9	15.0
Acetonitrile	14.4	7.4
Acrylic acid	12.3	13.9
Allyl alcohol	10.2	14.3
Allyl bromide	14.4	9.6
Allyl iodide	14.0	11.7
Ammonia, 100%	12.6	2.0
Ammonia, 26%	10.1	13.9
Amyl acetate	11.8	12.5
Amyl alcohol	7.5	18.4
Aniline	8.1	18.7
Anisole	12.3	13.5
Arsenic trichloride	13.9	14.5
Benzene	12.5	10.9
Brine, $CaCl_2$, 25%	6.6	15.9
Brine, NaCl, 25%	10.2	16.6
Bromine	14.2	13.2
Bromotoluene	20.0	15.9
Butyl acetate	12.3	11.0
Butyl acrylate	11.5	12.6
Butyl alcohol	8.6	17.2
Butyric acid	12.1	15.3
Carbon dioxide	11.6	0.3
Carbon disulfide	16.1	7.5
Carbon tetrachloride	12.7	13.1
Chlorobenzene	12.3	12.4
Chloroform	14.4	10.2
Chlorosulfonic acid	11.2	18.1
Chlorotoluene, ortho	13.0	13.3
Chlorotoluene, meta	13.3	12.5
Chlorotoluene, para	13.3	12.5
Cresol, meta	2.5	20.8
Cyclohexanol	2.9	24.3
Cyclohexane	9.8	12.9
Dibromomethane	12.7	15.8
Dichloroethane	13.2	12.2
Dichloromethane	14.6	8.9
Diethyl ketone	13.5	9.2
Diethyl oxalate	11.0	16.4
Diethylene glycol	5.0	24.7
Diphenyl	12.0	18.3
Dipropyl ether	13.2	8.6
Dipropyl oxalate	10.3	17.7
Ethyl acetate	13.7	9.1
Ethyl acrylate	12.7	10.4
Ethyl alcohol, 100%	10.5	13.8
Ethyl alcohol, 95%	9.8	14.3
Ethyl alcohol, 40%	6.5	16.6
Ethyl benzene	13.2	11.5
Ethyl bromide	14.5	8.1
2-Ethyl butyl acrylate	11.2	14.0
Ethyl chloride	14.8	6.0
Ethyl ether	14.5	5.3
Ethyl formate	14.2	8.4
2-Ethyl hexyl acrylate	9.0	15.0
Ethyl iodide	14.7	10.3
Ethyl propionate	13.2	9.9
Ethyl propyl ether	14.0	7.0
Ethyl sulfide	13.8	8.9
Ethylene bromide	11.9	15.7
Ethylene chloride	12.7	12.2
Ethylene glycol	6.0	23.6
Ethylidene chloride	14.1	8.7
Fluorobenzene	13.7	10.4
Formic acid	10.7	15.8
Freon-11	14.4	9.0
Freon-12	16.8	5.6
Freon-21	15.7	7.5
Freon-22	17.2	4.7
Freon-113	12.5	11.4
Glycerol, 100%	2.0	30.0
Glycerol, 50%	6.9	19.6
Heptane	14.1	8.4
Hexane	14.7	7.0
Hydrochloric acid, 31.5%	13.0	16.6
Iodobenzene	12.8	15.9
Isobutyl alcohol	7.1	18.0
Isobutyric acid	12.2	14.4
Isopropyl alcohol	8.2	16.0
Isopropyl bromide	14.1	9.2
Isopropyl chloride	13.9	7.1
Isopropyl iodide	13.7	11.2
Kerosene	10.2	16.9
Linseed oil, raw	7.5	27.2
Mercury	18.4	16.4
Methanol, 100%	12.4	10.5
Methanol, 90%	12.3	11.8
Methanol, 40%	7.8	15.5
Methyl acetate	14.2	8.2
Methyl acrylate	13.0	9.5
Methyl *i*-butyrate	12.3	9.7
Methyl *n*-butyrate	13.2	10.3
Methyl chloride	15.0	3.8
Methyl ethyl ketone	13.9	8.6
Methyl formate	14.2	7.5
Methyl iodide	14.3	9.3
Methyl propionate	13.5	9.0
Methyl propyl ketone	14.3	9.5
Methyl sulfide	15.3	6.4
Napthalene	7.9	18.1
Nitric acid, 95%	12.8	13.8
Nitric acid, 60%	10.8	17.0
Nitrobenzene	10.6	16.2
Nitrogen dioxide	12.9	8.6
Nitrotoluene	11.0	17.0
Octane	13.7	10.0
Octyl alcohol	6.6	21.1
Pentachloroethane	10.9	17.3
Pentane	14.9	5.2
Phenol	6.9	20.8
Phosphorus tribromide	13.8	16.7
Phosphorus trichloride	16.2	10.9
Propionic acid	12.8	13.8
Propyl acetate	13.1	10.3
Propyl alcohol	9.1	16.5
Propyl bromide	14.5	9.6
Propyl chloride	14.4	7.5
Propyl formate	13.1	9.7
Propyl iodide	14.1	11.6
Sodium	16.4	13.9
Sodium hydroxide, 50%	3.2	25.8
Stannic chloride	13.5	12.8
Succinonitrile	10.1	20.8
Sulfur dioxide	15.2	7.1
Sulfuric acid, 110%	7.2	27.4
Sulfuric acid, 100%	8.0	25.1
Sulfuric acid, 98%	7.0	24.8
Sulfuric acid, 60%	10.2	21.3
Sulfuryl chloride	15.2	12.4
Tetrachloroethane	11.9	15.7
Thiophene	13.2	11.0
Titanium tetrachloride	14.4	12.3
Toluene	13.7	10.4
Trichloroethylene	14.8	10.5
Triethylene glycol	4.7	24.8
Turpentine	11.5	14.9
Vinyl acetate	14.0	8.8
Vinyl toluene	13.4	12.0
Water	10.2	13.0
Xylene, ortho	13.5	12.1
Xylene, meta	13.9	10.6
Xylene, para	13.9	10.9

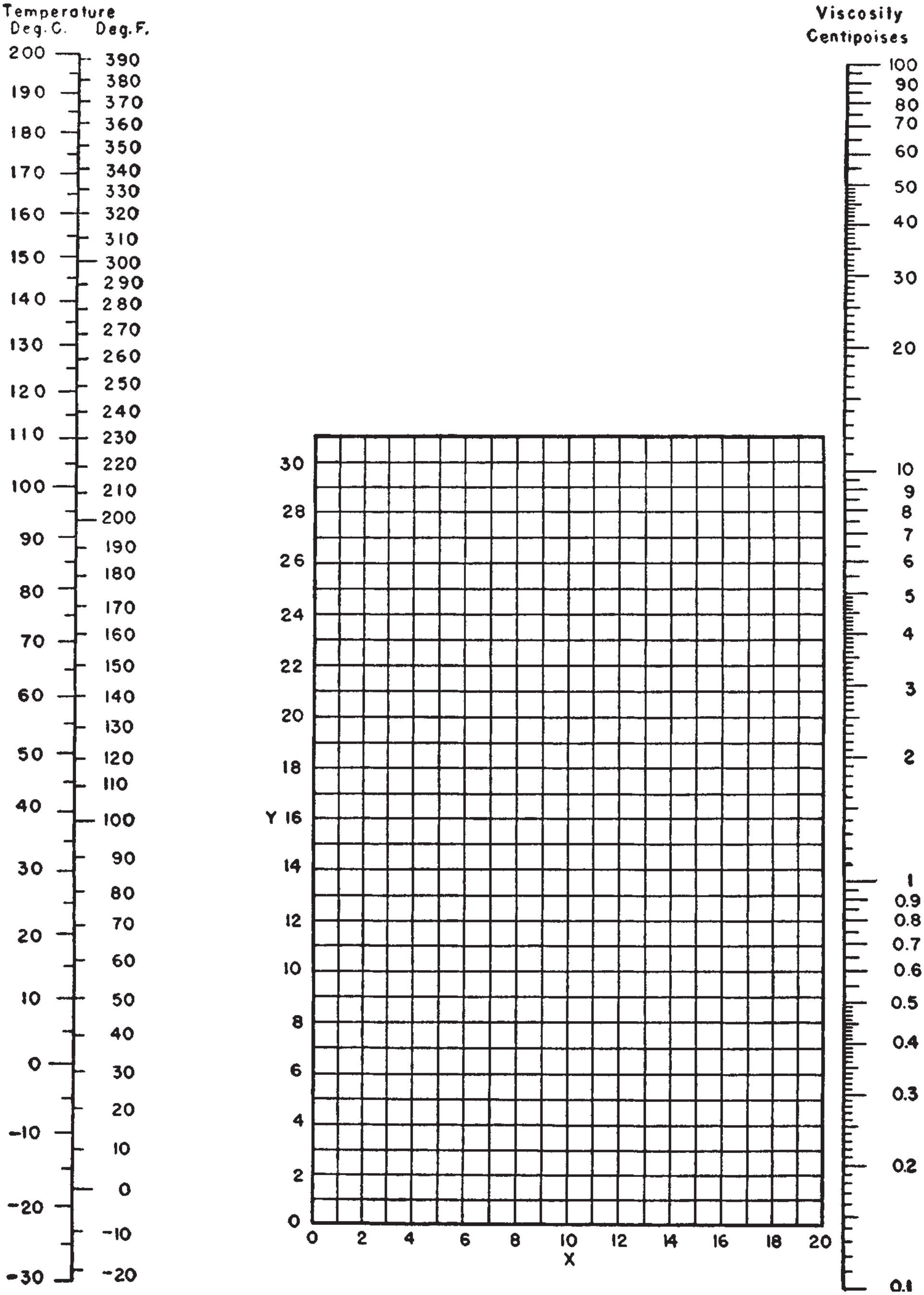


FIG. 2-33 Nomograph for viscosities of liquids at 1 atm. For coordinates see Table 2-365. To convert centipoises to pascal-seconds, multiply by 0.001.

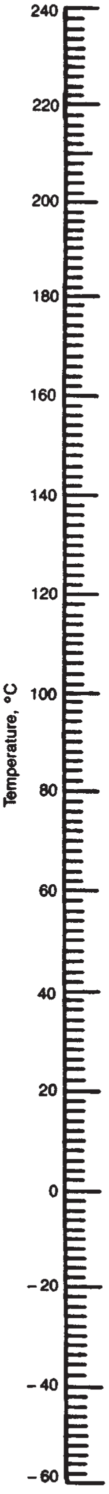
TABLE 2-366 Viscosity of Sucrose Solutions*

Viscosity in centipoises

Temp., °C	Percentage sucrose by weight			Temp., °C	Percentage sucrose by weight		
	20	40	60		20	40	60
0	3.818	14.82		50	0.974	2.506	14.06
5	3.166	11.60		55	0.887	2.227	11.71
10	2.662	9.830	113.9	60	0.811	1.989	9.87
15	2.275	7.496	74.9	65	0.745	1.785	8.37
20	1.967	6.223	56.7	70	0.688	1.614	7.18
25	1.710	5.206	44.02	75	0.637	1.467	6.22
30	1.510	4.398	34.01	80	0.592	1.339	5.42
35	1.336	3.776	26.62	85	0.552	1.226	4.75
40	1.197	3.261	21.30	90		1.127	4.17
45	1.074	2.858	17.24	95		1.041	3.73

*International Critical Tables, vol. 5, p. 23. Bingham and Jackson, *Bur. Standards Bull.* **14** (1919): 59.

TABLE 2-367



No.	Compound	Range, °C	Exp pt	% Avg abs devi
31	Acetaldehyde	0 – 30	2	0.4
40	Acetic acid	18 – 79	5	0.1
29	Acetone	0 – 40	3	0.4
20	Aniline	0 – 93	6	1.3
2	Benzaldehyde	16 – 68	4	0.7
13	Benzene	20 – 116	5	0.6
47	n-Butane	−21 – 0	2	0.2
16	n-Butanol	0 – 102	7	0.4
48	i-Butanol	0 – 20	2	0.6
49	s-Butanol	0 – 65	3	0.2
18	t-Butanol	20 – 77	3	2.5
28	Butyl acetate	0 – 38	4	1.1
23	Carbon tetrachloride	−20 – 25	4	1.1
25	Chlorobenzene	−40 – 80	6	0.5
42	Chloroform	0 – 40	3	1.3
19	m-Cresol	20 – 80	2	0.2
11	Cyclohexane	20 – 38	2	0.4
7	n-Decane	20 – 76	5	1.0
30	Diethyl ether	0 – 25	3	0.7
9	2,3-Dimethylbutane	32 – 49	2	0.3
38	n-Dodecane	0 – 63	6	1.1
15	Ethanol	17 – 77	7	0.5
27	Ethyl acetate	6 – 160	9	1.6
14	Ethylbenzene	0 – 80	3	0.7
24	Ethyl bromide	0 – 30	3	0.3
4	n-Heptane	0 – 60	3	0.3
3	n-Hexane	17 – 40	5	1.4
26	Iodobenzene	−20 – 80	4	0.7
41	Methanol	20 – 62	6	0.2
39	Methyl acetate	4 – 21	2	0.4
12	Methylcyclopentane	20 – 38	2	0.1
22	Methylene chloride	−20 – 20	3	0.9
8	2-Methylpentane	32 – 49	2	0.5
6	n-Nonane	16 – 77	5	2.0
5	n-Octane	0 – 77	3	0.3
10	i-Octane	20 – 77	4	1.6
17	n-Octanol	20 – 212	3	1.3
43	n-Pentanol	0 – 38	3	0.4
1	Propane	−60 – 50	4	1.6
32	n-Propanol	16 – 66	6	0.6
21	Propionic acid	12 – 30	3	1.7
44	n-Propyl acetate	0 – 38	2	0.1
33	i-Propylbenzene	0 – 38	4	0.2
45	Refrigerant-11, $CFCl_3$	0 – 20	4	0.5
46	Refrigerant-12, CF_2Cl_2	−42 – 70	4	1.8
50	Refrigerant-13, CF_3Cl	−20 – 20	4	1.7
51	Refrigerant-22, CHF_2Cl	−65 – 60	7	2.5
52	Refrigerant-113, $C_2F_3Cl_3$	0 – 20	4	0.7
53	Refrigerant-114, $C_2F_4Cl_2$	−25 – 20	4	0.8
54	Refrigerant-142, $C_2H_3F_2Cl$	0 – 90	2	0.9
34	Toluene	−70 – 200	5	1.8
55	n-Tridecane	20 – 228	5	2.4
36	m-Xylene	0 – 208	5	1.0
35	o-Xylene	0 – 208	5	0.7
37	p-Xylene	0 – 251	5	1.4

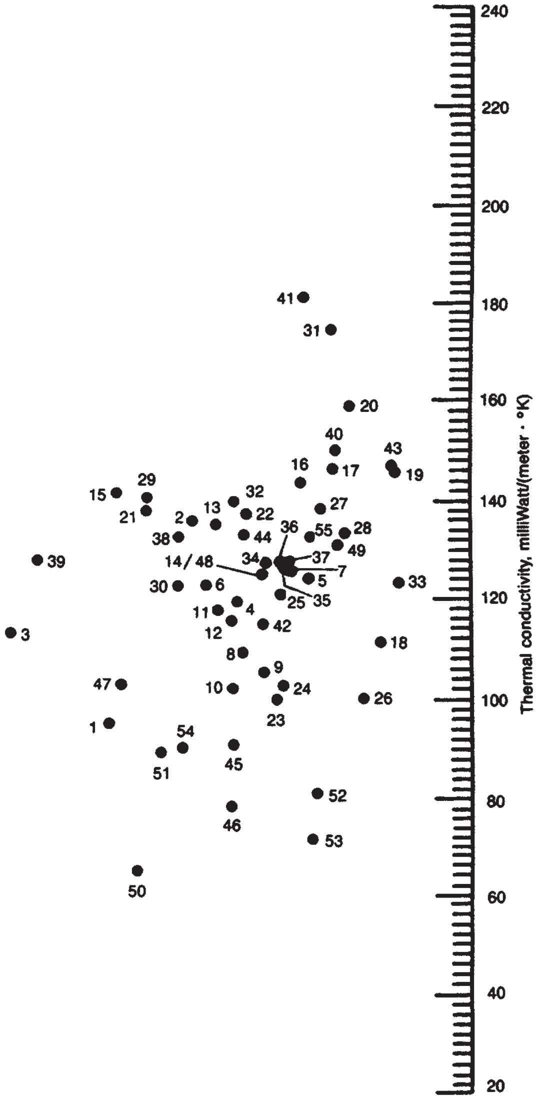


FIG. 2-34 and TABLE 2-367 Nomograph (*right*) for thermal conductivity of organic liquids.

TABLE 2-368 Prandtl Number of Air*

	Pressure, bar											
Temperature, K	1	5	10	20	30	40	50	60	70	80	90	100
80	mix	2.31	2.32	2.35	2.37	2.40	2.42	2.45	2.48	2.51	2.54	2.57
90	0.796	1.76	1.77	1.78	1.79	1.81	1.82	1.83	1.85	1.87	1.89	1.91
100	0.786	0.872	1.54	1.53	1.53	1.53	1.53	1.53	1.53	1.54	1.54	1.55
120	0.773	0.813	0.89	1.44	1.65	1.54	1.48	1.43	1.40	1.38	1.36	1.34
140	0.763	0.782	0.82	0.94	1.20	1.59	2.14	2.43	2.07	1.78	1.62	1.52
160	0.754	0.765	0.78	0.84	0.92	1.03	1.13	1.25	1.37	1.65	1.83	1.72
180	0.745	0.754	0.763	0.792	0.830	0.876	0.932	1.00	1.07	1.14	1.20	1.25
200	0.738	0.743	0.749	0.766	0.788	0.812	0.841	0.87	0.90	0.95	0.97	1.00
240	0.724	0.727	0.729	0.737	0.746	0.756	0.767	0.78	0.80	0.81	0.81	0.82
280	0.710	0.711	0.713	0.717	0.721	0.726	0.731	0.737	0.742	0.75	0.75	0.76
300	0.705	0.707	0.708	0.712	0.715	0.717	0.721	0.725	0.728	0.732	0.737	0.742
350	0.699	0.699	0.699	0.701	0.703	0.705	0.707	0.709	0.711	0.712	0.714	0.716
400	0.694	0.694	0.694	0.695	0.696	0.697	0.698	0.699	0.700	0.701	0.703	0.704
450	0.691	0.691	0.691	0.691	0.692	0.692	0.693	0.693	0.694	0.695	0.695	0.696
500	0.689	0.689	0.689	0.689	0.689	0.690	0.690	0.690	0.690	0.691	0.691	0.691
600	0.690	0.690	0.690	0.689	0.689	0.689	0.689	0.689	0.689	0.690	0.690	0.690
700	0.696	0.696	0.695	0.695	0.695	0.695	0.695	0.695	0.695	0.695	0.695	0.695
800	0.705	0.704	0.704	0.704	0.704	0.703	0.703	0.703	0.703	0.702	0.702	0.702
900	0.709	0.709	0.708	0.708	0.708	0.708	0.708	0.708	0.708	0.708	0.708	0.708
1000	0.711	0.711	0.711	0.711	0.711	0.710	0.710	0.710	0.710	0.709	0.709	0.709

*Compiled by P. E. Liley from tables of specific heat at constant pressure, thermal conductivity, and viscosity given in SI units for integral kelvin temperatures and pressures in bars by Vasserman. *Thermophysical Properties of Air and Its Components* and *Thermophysical Properties of Liquid Air and Its Components.* Nauka, Moscow, and in translated form by the National Bureau of Standards, Washington. The number of significant figures given above reflects the similar numbers appearing for the constituent properties in the source references. While reasonable agreement occurs for atmospheric pressure with some other works, the fragmentary data available for the saturated, etc., states show large deviations.

TABLE 2-369 Prandtl Number of Liquid Refrigerants*

		Temperature, K										
Refrigerant	No.	180	200	220	240	260	280	300	320	340	360	380
Trichlorofluoromethane	11		11.9	8.64	6.73	5.33	4.74	4.18				
Dichlorodifluoromethane	12	7.00	5.25	4.27	3.65	3.27	3.08	3.04	3.19	3.44	4.00	
Chlorotrifluoromethane	13		2.96	2.67	2.69	3.05	3.57		—	—	—	—
Bromotrifluoromethane	13B1	4.80	3.75	3.27	2.94	2.83	3.03	3.61	4.52		—	—
Dichlorofluoromethane	21			5.72	4.50	3.87	3.48	3.25	3.16	3.17		
Chlorodifluoromethane	22	4.68	3.76	3.23	2.93	2.79	2.77	2.87	3.18	3.54		—
Methyl chloride	40			2.53	2.42	2.40	2.45	2.60	2.85			
Trichlorotrifluoroethane	113	—	—	—					7.04	6.23	5.61	5.18
Dichlorotetrafluoroethane	114	25.7	15.13	11.18	8.59	6.94	5.77	5.06	4.78	4.82		
Chloropentafluoroethane	115	—	7.85	6.16	5.21	4.67	4.40	4.46	4.90		—	—
Ethane	170	2.55	2.29	2.22	2.40	2.70			—	—	—	—
Propane	290	5.28	4.46	3.88	3.44	3.16	3.02	3.16				
Octafluorocyclobutane	C318	—	—	—	11.2	8.74	7.35	6.37	5.87	5.96		—
Dichlorodifluoromethane/difluoroethane	500		5.78	4.23	3.40	3.13	3.01	3.13	3.35	3.72		—
Chlorodifluoromethane/chloropentafluoroethane	502		5.73	4.71	4.13	3.81					—	—
Trifluoromethane/chlorotrifluoromethane	503	2.10	2.09	2.24	2.43	2.89		—	—	—	—	—
Methylene fluoride/chloropentafluoroethane	504		4.90	3.60	3.04	2.79	2.69	2.85	3.30	—	—	—
Butane	600	8.35	6.19	5.20	4.44	3.83	3.44	3.22	3.07	3.02		
Isobutane (2-methyl propane)	600a		8.26	6.36	5.18	4.49	3.93	3.66	3.53	3.53	3.77	4.68
Ammonia	717	—			1.97	1.76	1.54	1.40	1.29	1.24	1.25	1.34
Water	718	—	—	—	—	—	10.3	5.69	3.65	2.60	1.99	1.59
Ethylene	1150	1.85	1.74	1.78	2.07	2.70	4.4	—	—	—	—	—
Propylene	1270	3.80	2.24	1.88	1.71	1.71	1.88	2.24	3.91	4.73		—

*Dashes indicate inaccessible states. Average uncertainty is about 20 percent. Values derived from formulations for thermal conductivity, specific heat at constant pressure, and viscosity contained in *Thermophysical Properties of Refrigerants.* American Society of Heating, Refrigerating and Air-Conditioning Engineers, New York, 1976. For further details see M. W. Johnson, M.S.M.E. thesis, Purdue University, West Lafayette, Ind., 1976.

TABLE 2-370 Thermophysical Properties of Miscellaneous Saturated Liquids

Substance	Property	Temperature, °C															
		−50	−40	−30	−20	−10	0	10	20	30	40	50	60	70	80	90	100
Acetaldehyde	ρ (kg/m^3)	863	852	840	828	816	804	794	783								
	c_p(kJ/kg·K)	2.05	2.08	2.11	2.14	2.17	2.20	2.24	2.28								
	μ (10^{-6}Pa·s)	460	404	358	321	290	263	241	222								
	k (W/m·K)	0.211	0.206	0.200	0.195	0.189	0.184	0.182	0.180								
	Pr	4.47	4.08	3.78	3.52	3.33	3.14	2.97	2.81								
Acetic acid	ρ (kg/m^3)								1049	1039	1028	1018	1006	995	984	972	960
	c_p (kJ/kg·K)								2.031								
	μ (10^{-6}Pa·s)								1210	1102	1010	795	600				
	k (W/m·K)								0.173	0.170	0.168	0.167	0.165	0.163	0.161		
	Pr								14.2								
Aniline	ρ (kg/m^3)	—	—	—	—	—	1039	1030	1022	1013	1005	996	987	978	969	960	951
	c_p(kJ/kg·K)	—	—	—	—	—	2.024	2.047	2.071	2.093	2.113	2.132	2.17	2.20	2.23	2.27	2.32
	μ (10^{-6}Pa·s)	—	—	—	—	—	10200	6500	4400	3160	2370	1850	1510	1270	1090	935	825
	k (W/m·K)	—	—	—	—	—	0.186	0.184	0.182	0.180	0.177	0.174	0.171	0.169	0.168	0.167	0.167
	Pr	—	—	—	—	—	111	72	50	36.7	28.3	22.7	19.2	16.5	14.5	12.7	11.5
Butanol	ρ (kg/m^3)	845	841	837	833	829	825	817	810	803	797	791	784	776	768	760	753
	c_p(kJ/kg·K)	1.947	1.996	2.046	2.100	2.153	2.202	2.262	2.345	2.437	2.524	2.621					
	μ (10^{-6}Pa·s)	34700	22400	14700	10300	7400	5190	3870	2950	2300	1780	1410	1140	930	760	630	535
	k (W/m·K)	0.175	0.174	0.173	0.172	0.171	0.170	0.168	0.167	0.166	0.165	0.164	0.163	0.162	0.161	0.160	0.159
	Pr	3860	2570	1740	1260	930	670	120	41	33.8	27.2	22.5					
Carbon disulfide	ρ (kg/m^3)	1362	1348	1334	1320	1306	1292	1278	1263								
	c_p(kJ/kg·K)	0.988	0.989	0.990	0.991	0.993	0.996	1.004	1.017								
	μ (10^{-6}Pa·s)	630	580	535	496	463	435	405	375	350	330						
	k (W/m·K)	0.194	0.190	0.186	0.182	0.178	0.174	0.170	0.166	0.161	0.158	0.156	0.154	0.152	0.150		
	Pr	3.21	3.02	2.85	2.70	2.58	2.49	2.39	2.30								
Cyclohexane	ρ (kg/m^3)	—	—	—	—	—	—	789	779	769	759	750	740	731	721		
	c_p(kJ/kg·K)	—	—	—	—	—	—	2.068	2.081	2.094	2.106	2.119					
	μ (10^{-6}Pa·s)	—	—	—	—	—	—	1175	980	820	710	605	540				
	k (W/m·K)	—	—	—	—	—	—	0.122	0.120	0.119	0.118	0.117	0.116	0.114	0.112		
	Pr	—	—	—	—	—	—	19.9	17.0	14.4	12.7	11.0					
Ethanol	ρ (kg/m^3)						806	798	789	781	776	763	754	745	735	725	716
	c_p(kJ/kg·K)	2.01	2.04	2.08	2.13	2.19	2.27	2.35	2.43	2.52	2.62	2.73	2.83	2.93	3.03	3.19	3.30
	μ (10^{-6}Pa·s)	6400	4790	3650	2825	2220	1770	1470	1200	1000	835	700	590	500	435	370	314
	k (W/m·K)	0.188	0.186	0.184	0.181	0.179	0.177	0.175	0.173	0.171	0.168	0.165	0.162	0.159	0.156	0.153	0.151
	Pr	68.4	52.5	41.3	33.2	27.2	22.7	19.7	16.9	14.7	13.0	11.6	10.3	9.2	8.4	7.7	6.9
Ethyl acetate	ρ (kg/m^3)				947	935	924	912	901	888	876	863	851	838	825	811	797
	c_p(kJ/kg·K)								2.01								
	μ (10^{-6}Pa·s)	1090					580	510	455	400	370	345	310	280	250	230	220
	k (W/m·K)								0.145	0.142	0.139	0.136	0.133	0.130	0.127	0.123	0.119
	Pr								6.3								
Ethylamine	ρ (kg/m^3)	761	750	739	729	718	707	695	683	671	658	646	633	620	607		
	c_p(kJ/kg·K)	2.95	2.97	2.98	3.00	3.01	3.03										
	μ (10^{-6}Pa·s)	580	500	435	390	350	320										
	k (W/m·K)	0.204	0.201	0.199	0.196	0.194	0.191										
	Pr	8.39	7.39	6.51	5.97	5.43	5.08										
Ethyl ether	ρ (kg/m^3)	790	780	769	758	747	736	725	714	702	689	676	666	653	640	625	611
	c_p(kJ/kg·K)	2.135	2.156	2.179	2.205	2.233	2.265	2.299	2.332	2.36	2.39	2.43	2.47	2.51			
	μ (10^{-6}Pa·s)	550	470	410	365	330	290	265	233	214	197	181	166	153	140	129	118
	k (W/m·K)	0.159	0.155	0.151	0.147	0.144	0.140	0.139	0.134	0.129	0.125	0.120	0.116	0.112			
	Pr	7.39	6.54	5.92	5.48	5.12	4.69	4.38	4.05	3.92	3.77	3.67	3.54	3.43			
Ethyl iodide	ρ (kg/m^3)																
	c_p(kJ/kg·K)			0.656	0.663	0.670	0.677	0.684	0.691	0.698	0.705	0.712	0.718	0.724			
	μ (10^{-6}Pa·s)						730	655	590	539	495	455	420	390			
	k (W/m·K)						0.092	0.090	0.088	0.086	0.085	0.083	0.081	0.080			
	Pr						5.37	4.98	4.63	4.30	4.11	3.90	3.72	3.53			
Ethylene glycol	ρ (kg/m^3)						1127	1120	1113	1106	1099	1092	1085	1077	1070	1063	1056
	c_p(kJ/kg·K)						2.272	2.327	2.381	2.431	2.484	2.536	2.586	2.636	2.685	2.734	2.779
	μ (10^{-6}Pa·s)						57000	33300	20200	13400	9100	7070	4000	3450	3000	2440	2000
	k (W/m·K)						0.254	0.255	0.256	0.258	0.259	0.260					
	Pr						510	305	190	126	87.3	69.0					
Formic acid	ρ (kg/m^3)						1241	1231	1220	1209	1196	1184	1170	1156	1140	1124	1108
	c_p(kJ/kg·K)																
	μ (10^{-6}Pa·s)							2260	1800	1470	1220	1030	890	780	680	615	550
	k (W/m·K)						0.265	0.261	0.257	0.257	0.253	0.250	0.246	0.243	0.240	0.236	0.232
	Pr																

TABLE 2-370 Thermophysical Properties of Miscellaneous Saturated Liquids (*Concluded*)

Substance	Property	Temperature, °C															
		–50	–40	–30	–20	–10	0	10	20	30	40	50	60	70	80	90	100
Gasoline	ρ (kg/m^3)				784	775	767	759	751	743	735	721	717	708	699	690	681
	c_p(kJ/kg·K)				1.88	1.92	1.97	2.02	2.06	2.11	2.15	2.20	2.25	2.30	2.35	2.41	2.46
	μ (10^{-6}Pa·s)	1710	1400	1170	990	850	735	645	530	464	410	367	330	298	270	246	225
	k (W/m·K)	0.131	0.128	0.125	0.123	0.121	0.120	0.118	0.116	0.114	0.112	0.110	0.108	0.106	0.104	0.102	0.100
	Pr				15.1	13.5	12.1	11.0	9.41	8.59	7.87	7.34	6.88	6.47	6.10	5.81	5.54
Glycerol	ρ (kg/m^3)	—	—	—	—	—	1276	1270	1260	1254	1248	1242					
	c_p(kJ/kg·K)								2.393	2.406	2.457	2.504	2.548	2.588	2.625	2.657	2.686
	μ (10^{-6}Pa·s)						1.2.+7	4.0.+6	1.5.+6								
	k (W/m·K)								0.284	0.285	0.287	0.288	0.289	0.291	0.293	0.294	0.295
	Pr								12650								
Kerosine	ρ (kg/m^3)						781	774	767	760	754	748	742				
	c_p(kJ/kg·K)						1.91	1.96	2.02	2.07	2.13	2.18	2.23	2.28	2.32	2.35	2.38
	μ (10^{-6}Pa·s)	1150	725	500	360	275	215	173	149	126	108	95	83	73	66	60	55
	k (W/m·K)						0.140	0.139	0.139	0.138	0.138	0.137	0.137				
	Pr						2.93	2.44	2.17	1.89	1.67	1.51	1.35				
Methanol	ρ (kg/m^3)									783	774	766	756	746	736	725	711
	c_p(kJ/kg·K)	2.30	2.32	2.35	2.37	2.40	2.42	2.45	2.47	2.49	2.52	2.55	2.65	2.78	2.94	3.13	3.30
	μ (10^{-6}Pa·s)	2305	1800	1410	1170	975	820	692	590	510	455	400	355	315	271	240	218
	k(W/m·K)	0.225	0.222	0.219	0.216	0.212	0.209	0.206	0.203	0.199	0.195	0.192	0.189	0.187	0.184	0.182	0.180
	Pr	23.6	18.8	15.1	12.9	11.0	9.53	8.23	7.18	6.38	5.88	5.31	4.98	4.68	4.34	4.13	3.99
Methyl formate	ρ (kg/m^3)	1069	1056	1043	1030	1017	1003	989	975	960	944	929	913	897	880	863	845
	c_p(kJ/kg·K)	1.84	1.86	1.88	1.90	1.92	1.95	1.99	2.03	2.08							
	μ (10^{-6}Pa·s)	830	711	618	544	481	430	380	345	315							
	k (W/m·K)	0.217	0.213	0.209	0.205	0.200	0.195	0.191	0.186	0.180							
	Pr	7.04	6.21	5.56	5.04	4.62	4.30	3.96	3.77	3.64							
Oil, castor	ρ (kg/m^3)																
	c_p(kJ/kg·K)																
	μ (10^{-6}Pa·s)							2,420,000	986,000	451,000	231,000	125,000	74,000	43,000			
	k (W/m·K)							0.182	0.181	0.180	0.179	0.178	0.177	0.176	0.175	0.174	0.17
	Pr																
Oil, olive	ρ (kg/m^3)								914								
	c_p(kJ/kg·K)								1.633								
	μ (10^{-6}Pa·s)							138,000	84,000	52,000	36,300	24,500	17,000	12,400			
	k (W/m·K)							0.170	0.169	0.168	0.167	0.166	0.166	0.165	0.165	0.164	0.164
	Pr								810								
Pentane	ρ (kg/m^3)	693	684	674	665	656	646	636	626	616	606	596	585	574	562	550	538
	c_p(kJ/kg·K)	2.060	2.084	2.110	2.137	2.167	2.206	2.239	2.273								
	μ (10^{-6}Pa·s)	489	428	379	339	307	279	254	234	209	190	175	161	148	137	124	113
	k (W/m·K)	0.142	0.139	0.136	0.132	0.128	0.125	0.122	0.119	0.115	0.112	0.108	0.105	0.101	0.098	0.095	0.091
	Pr	7.14	6.42	5.88	5.49	5.20	4.92	4.66	4.47								
Propanol	ρ (kg/m^3)	849					819	811	814	796	788	779	770	761	752	747	743
	c_p(kJ/kg·K)	1.955					2.219										
	μ (10^{-6}Pa·s)	20,200	13,500	9500	6900	5110	3900	2900	2245	1720	1400	1130	921	760	630	508	447
	k (W/m·K)	0.167	0.166	0.165						0.171	0.169	0.168	0.167	0.165	0.164	0.163	0.162
	Pr	236															
Sulfuric acid	ρ (kg/m^3)								1834								
	c_p(kJ/kg·K)								1.382								
	μ (10^{-6}Pa·s)						48,400	35,200	25,400	15,700	11,500	8820	7220	6090	5190		
	k (W/m·K)						0.314										
	Pr																
Toluene	ρ (kg/m^3)	932	923	913	904	895	886	876	867	858	848	839	829	820	810	800	790
	c_p(kJ/kg·K)	1.514	1.535	1.556	1.579	1.602	1.633	1.652	1.675	1.701	1.73	1.76	1.80	1.83	1.87	1.92	1.97
	μ (10^{-6}Pa·s)	2120	1670	1345	1100	915	770	670	590	520	470	420	380	355	325	295	270
	k (W/m·K)	0.152	0.149	0.147	0.144	0.142	0.139	0.137	0.134	0.132	0.129	0.126	0.124	0.122	0.119	0.117	0.114
	Pr	21.1	17.8	14.2	12.1	10.3	9.0	8.1	7.4	6.7	6.3	5.9	5.5	5.3	5.1	4.8	4.7
Turpentine	ρ (kg/m^3)																
	c_p(kJ/kg·K)						1.72	1.76	1.80			1.93					
	μ (10^{-6}Pa·s)						2250	1780	1490	1270	1070	925	820	730	675		
	k (W/m·K)						0.130	0.129	0.128	0.127	0.126	0.125					
	Pr						29.8	24.3	20.9	18.4	16.1	14.3					

TABLE 2-371 Diffusivities of Pairs of Gases and Vapors (1 atm)

D_v in cm^2/s

Substance	Temp., °C	Air	A	H_2	O_2	N_2	CO_2	N_2O	CH_4	C_2H_6	C_2H_4	*n*-C_4H_{10}	*i*-C_4H_{10}	Ref.
Acetic acid	0	0.1064		0.416			0.0716							8
Acetone	0	.109		.361										6, 16
n-Amyl alcohol	0	.0589		.235			.0422							8
sec-Amyl alcohol	30	.072												5
Amyl butyrate	0	.040												8
Amyl formate	0	.0543												8
i-Amyl formate	0	.058												8
Amyl isobutyrate	0	.0419		.171										8
Amyl propionate	0	.046		.1914			.0347							8
Aniline	0	.0610												8
	30	.075												5
Anthracene	0	.0421												8
Argon	20					0.194								18
Benzene	0	.077		.306	0.0797		.0528							8, 15
Benzidine	0	.0298												8
Benzyl chloride	0	.066												8
n-Butyl acetate	0	.058												8
i-Butyl acetate	0	.0612		.2364			.0425							8
n-Butyl alcohol	0	.0703		.2716			.0476							8
	30	.088												5
i-Butyl alcohol	0	.0727		.2771			.0483							8
Butyl amine	0	.0821												8
i-Butyl amine	0	.0853												8
i-Butyl butyrate	0	.0468		.185			.0327							8
i-Butyl formate	0	.0705												8
i-Butyl isobutyrate	0	.0457		.191			.0364							8
i-Butyl proprionate	0	.0529		.203			.0366							8
i-Butyl valerate	0	.0424		.173			.0308							8
Butyric acid	0	.067		.264			.0476							8
i-Butyric acid	0	.0679		.271			.0471							8
Cadmium	0					.17								13
Caproic acid	0	.050												8
i-Caproic acid	0	.0513												8
Carbon dioxide	0	.138		.550	.139			0.096	0.153					8
	20					.163								19
	25							.0996*	.00215†					1, 9
	500‡				.9									18
Carbon disulfide	0	.0892		.369			.063							8
Carbon monoxide	0			.651	.185		.137				0.116			8
	450‡				1.0									18
Carbon tetrachloride	0			.293	0.0636									16, 17
Chlorobenzene	30	.075												5
Chloroform	0	.091												6
Chloropicrin	25	.088												10
m-Chlorotoluene	0	.054												8
o-Chlorotoluene	0	.059												8
p-Chlorotoluene	0	.051												8
Cyanogen chloride	0	.111												10
Cyclohexane	15		0.0719	.319	.0744	.0760								3
	45	.086												6
n-Decane	90			.306		.0841								3
Diethylamine	0	.0884												8
2,3-Dimethyl butane	15		.0657	.301	.0753	.0751								3
Diphenyl	0	.0610												8
n-Dodecane	126			.308		.0813								3
Ethane	0			.459										8
Ethanol	0			.377			.0686							20
Ether (diethyl)	0	.0778		.298			.0546							7, 8
Ethyl acetate	0	.0715		.273			.0487							8
	30	.089												5
Ethyl alcohol	0	.102		.375			.0685							8
Ethyl benzene	0	.0658												8
Ethyl *n*-butyrate	0	.0579		.224			.0407							8
Ethyl *i*-butyrate	0	.0591		.229			.0413							8
Ethylene	0			.486										8
Ethyl formate	0	.0840		.337			.0573							8
Ethyl propionate	0	.068		.236			.0450							4, 8
Ethyl valerate	0	.0512		.205			.0367							8
Eugenol	0	.0377												8
Formic acid	0	.1308		.510			.0874							8
Helium	0		.641											8
	20					.705								19
n-Heptane	38								.066§					
n-Hexane	15		.0663	.290	.0753	.0757								3
Hexyl alcohol	0	.0499		.200			.0351							8
Hydrogen	0	.611			.697	.674	.550	.535	.625	0.459	0.486	0.272	0.277	8
	25						.646			.537	.726			2
	500				4.2									18

TABLE 2-371 Diffusivities of Pairs of Gases and Vapors (1 atm) (*Concluded*)

D_v in cm²/s

Substance	Temp., °C	Air	A	H_2	O_2	N_2	CO_2	N_2O	CH_4	C_2H_6	C_2H_4	*n*-C_4H_{10}	*i*-C_4H_{10}	Ref.
Hydrogen cyanide	0	.173												10
Hydrogen peroxide	60	.188												11
Iodine	0	.07				.070								8, 12, 14
Mercury	0	.112		.53		.13								8, 12, 13
Mesitylene	0	.056												8
Methane	500				1.1									18
Methyl acetate	0	.084		.333			.0567							8
Methyl alcohol	0	.132		.506			.0879							8
Methyl butyrate	0	.0633		.242			.0446							8
Methyl *i*-butyrate	0	.0639		.257			.0451							8
Methyl cyclopentane	15		.0731	.318	0.0742	.0758								3
Methyl formate	0	.0872												8
Methyl propionate	0	.0735		.295			.0528							8
Methyl valerate	0	0.0569												8
Naphthalene	0	.0513												8
Nitrogen	0				0.181									8
	25						0.165			0.148	0.163	0.0960	0.0908	2
Nitrous oxide	0			0.535			.096							8
n-Octane	0	.0505												8
	30		0.0642	.271	.0705	0.0710								3
Oxygen	0	.178		.697		.181	.139							8
Phosgene	0	.095												10
Propionic acid	0	.0829		.330			.0588							8
Propyl acetate	0	.067												8
n-Propyl alcohol	0	.085		.315			.0577							8
i-Propyl alcohol	0	.0818												8
	30	.101												5
n-Propyl benzene	0	.0481												8
i-Propyl benzene	0	.0489												8
n-Propyl bromide	0	.085												8
i-Propyl bromide	0	.0902												8
Propyl butyrate	0	.0530		.206			.0364							8
Propyl formate	0	.0712		.281			.0490							8
n-Propyl iodide	0	.079												8
i-Propyl iodide	0	.0802												8
n-Propyl isobutyrate	0	.0549		.212			.0388							8
i-Propyl isobutyrate	0	.059												8
Propyl propionate	0	.057		.212			.0395							8
Propyl valerate	0	.0466		.189			.0341							8
Safrol	0	.0434												8
i-Safrol	0	.0455												8
Sulfur hexafluoride	25			.418										2
Toluene	0	.076	.071											4, 8
	30	.088												5
Trimethyl carbinol	0	.087												8
2,2,4-Trimethyl pentane	30		.0618	.288	.0688	.0705								3
2,2,3-Trimethyl heptane	90			.270		.0684								3
n-Valeric acid	0	.050												8
i-Valeric acid	0	.0544		.212			.0376							8
Water	0	.220		.75			.138							8, 20
	450				1.3									18

* 320 mm Hg.

† 40 atm.

‡ Also at other temperatures.

§ Strong function of concentration.

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In this table are a representative selection of diffusion coefficients. The subsection "Prediction and Correlation of Physical Properties" should be consulted for estimation techniques. As general references, the works by Hirschfelder, Curtiss, and Bird, *Molecular Theory of Gases and Liquids,* Wiley, New York, 1964; Chapman and Cowling, *The Mathematical Theory of Non-Uniform Gases,* Cambridge, New York, 1970; Reid and Sherwood, *The Properties of Gases and Liquids,* McGraw-Hill, New York, 1964; and Bretsznajder, *Prediction of Transport and Other Physical Properties of Fluids,* Pergamon, New York, 1971, may be found useful. The most exhaustive recent compilation for gases is by Mason and Marrero, *J. Phys. Chem. Ref. Data,* **1** (1972). Unfortunately, the Mason and Marrero work cites only equations and equation constants and not direct tabulations. For these, the Landolt-Börnstein series is suggested.

TABLE 2-372 Diffusivities in Liquids (25°C)

Dilute solutions and 1 atm unless otherwise noted; use $D_L\mu/T$ = constant to estimate effect of temperature; * indicates that reference gives effect of concentration.

Solute	Solvent	$D_L \times 10^5$, sq cm/sec	Estimated possible, error, ± %1	Ref.
Acetal*	Ethanol	1.25	5	11
Acetamide*	Ethanol	0.68	5	11
Acetamide*	Water	1.19	3	11
Acetic acid	Acetone	3.31		4
Acetic acid	Benzene	2.11		1, 4
Acetic acid	Carbon tetrachloride	1.49		4
Acetic acid	Ethylene glycol	0.13		4
Acetic acid	Toluene	2.26		4
Acetic acid*	Water	1.24	3	11
Acetonitrile	Water	1.66	5	11
Acetylene	Water	1.78, 2.11		1, 24
Allyl alcohol*	Ethanol	1.06	5	11
Allyl alcohol	Water	1.19	6	11
Ammonia*	Water	1.7, 2.0, 2.3		1, 11
i-Amyl alcohol*	Ethanol	0.87	5	11
i-Amyl alcohol	Water	1.0	8	11, 25
Benzene	Carbon tetrachloride	1.53		7
Benzene (50 mole %)	*n*-Decane	1.72		26
Benzene (50 mole %)	2,4-Dimethyl pentane	2.49		26
Benzene (50 mole %)	*n*-Dodecane	1.40		26
Benzene (50 mole %)	*n*-Heptane	2.47		26
Benzene (50 mole %)	*n*-Hexadecane	0.96		26
Benzene (50 mole %)	*n*-Octadecane	0.86		26
Benzoic acid	Acetone	2.62		4
Benzoic acid	Benzene	1.38		4
Benzoic acid	Carbon tetrachloride	0.91		4
Benzoic acid	Ethylene glycol	0.043		4
Benzoic acid	Toluene	1.49		4
Bromine	Benzene	2.7		11
Bromine	Carbon disulfide	4.1		11
Bromine	Water	1.3		11
Bromobenzene	Benzene	2.30		25
Bromoform*	Acetone	2.90		11
Bromoform	*i*-Amyl alcohol	0.53		11
Bromoform	Ethanol	1.08	5	11
Bromoform*	Ethyl ether	3.62		11
Bromoform	Methanol	2.20		23
Bromoform	*n*-Propanol	0.94		11
n-Butanol	Water	0.96	5	1, 11, 18, 25
Caffeine	Water	0.63	6	11
Carbon dioxide	Ethanol	4.0	6	11
Carbon dioxide	Water	1.96	1	1, 3, 5, 20, 24, 28
Carbon disulfide (50 mole %, 200 atm.)	*n*-Butanol	3.57		14
Carbon disulfide (50 mole %, 200 atm.)	*i*-Butanol	2.42		14
Carbon disulfide (50 mole %, 218 atm.)	Chlorobenzene	3.00		14
Carbon disulfide (50 mole %, 200 atm.)	2,4-Dimethyl pentane	3.63		14
Carbon disulfide (50 mole %, 100 atm.)	*n*-Heptane	3.0		14
Carbon disulfide (50 mole %, 50 atm.)	Methyl cyclohexane	3.5		14
Carbon disulfide (50 mole %, 200 atm.)	*n*-Octane	3.10		14
Carbon disulfide (50 mole %)	Toluene	2.06		14
Carbon tetrachloride	Benzene	2.04	3	7, 9
Carbon tetrachloride*	Cyclohexane	1.49	2	9, 10*
Carbon tetrachloride	Decalin	0.776	2	9
Carbon tetrachloride	Dioxane	1.02	2	9
Carbon tetrachloride*	Ethanol	1.50	2	9, 10*
Carbon tetrachloride	*n*-Heptane	3.17	2	9
Carbon tetrachloride	Kerosene	0.961	2	9
Carbon tetrachloride	Methanol	2.30	2	9
Carbon tetrachloride	*i*-Octane	2.57	2	9
Carbon tetrachloride	Tetralin	0.735	2	9
Chloral*	Ethanol	0.68	5	11
Chloral hydrate	Water	0.77	7	11

TABLE 2-372 Diffusivities in Liquids (25°C) (*Continued*)

Dilute solutions and 1 atm unless otherwise noted; use $D_L\mu/T$ = constant to estimate effect of temperature; * indicates that reference gives effect of concentration.

Solute	Solvent	$D_L \times 10^5$, sq cm/sec	Estimated possible, error, ± %1	Ref.
Chlorine	Water	1.44	4	1, 28
Chlorobenzene	Benzene	2.66		25
Chloroform	Benzene	2.50	6	1, 25
Chloroform	Ethanol	1.38	3	11
Cinnamic acid	Acetone	2.41		4
Cinnamic acid	Benzene	1.12		4
Cinnamic acid	Carbon tetrachloride	0.76		4
Cinnamic acid	Toluene	2.41		4
1,1′-Dichloropropanol	Water	1.0	6	11
Dicyanodiamide*	Water	1.18	4	11
Diethyl ether	Benzene	2.73		25
Diethyl ether	Water	0.85		2
2,4-Dimethyl pentane (50 mole %)	*n*-Dodecane	1.44		26
2,4-Dimethyl pentane (50 mole %)	*n*-Hexadecane	0.88		26
Ethanol*	Water	1.28	4	1, 7, 9,* 11,* 22
Ethyl acetate	Ethyl benzoate	0.94		6
Ethylene dichloride	Benzene	2.8		1, 25
Formic acid	Acetone	3.77		4
Formic acid	Benzene	2.28		4
Formic acid	Carbon tetrachloride	1.89		4
Formic acid	Ethylene glycol	0.094		4
Formic acid	Toluene	2.65		
Formic acid	Water	1.37	10	11
Glucose	Water	0.69	6	11
Glycerol	*i*-Amyl alcohol	0.12		11
Glycerol	Ethanol	0.56		11
Glycerol*	Water	0.94	6	1, 11*
n-Heptane (50 mole %)	*n*-Dodecane	1.58		26
n-Heptane (50 mole %)	*n*-Hexadecane	1.00		26
n-Heptane (50 mole %)	*n*-Octadecane	0.92		26
n-Heptane (50 mole %)	*n*-Tetradecane	1.29		26
Hexamethylene tetramine	Water	0.67		11
Hydrogen chloride*	Water	3.10	3	4, 11,* 12*
Hydrogen	Water	5.85 (4.4)		1, 11, 24(?)
Hydrogen sulfide	Water	1.61		1
Hydroquinone*	Ethanol	0.53	5	11
Hydroquinone*	Water	0.88, 1.12		2, 11*
Iodine	Acetic acid	1.13		11
Iodine	Anisole	1.25		11
Iodine	Benzene	1.98		9, 19, 23
Iodine	Bromobenzene	1.25	10	4, 11, 19
Iodine	Carbon disulfide	3.2		11, 19, 23
Iodine	Carbon tetrachloride	1.45	8	9, 11, 19
Iodine	Chloroform	2.30	3	11, 23
Iodine	Cyclohexane	1.80		4
Iodine	Dioxane	1.07		9
Iodine*	Ethanol	1.30		4, 11*
Iodine	Ethyl acetate	2.2		11, 19
Iodine	Ethyl ether	3.61		11
Iodine	Ethylene bromide	0.93		11
Iodine	*n*-Heptane	3.4, 2.5		9, 11, 19
Iodine	*n*-Hexane	4.15		4, 9
Iodine	Mesitylene	1.49		9
Iodine	Methanol	1.74		19
Iodine	Methyl cyclohexane	2.1		4
Iodine	*n*-Octane	2.76		4
Iodine	Tetrabromoethane	2.0		11
Iodine	*n*-Tetradecane	0.96		4
Iodine	Toluene	2.1		11
Iodine	*m*-Xylene	1.82		9, 11
Iodobenzene	Ethanol	1.09	3	11
Lactose*	Water	0.49	5	11
Maltose*	Water	0.48	5	11
Mannitol*	Water	0.65	5	11
Methanol	Water	1.6		1, 7, 11
Nicotine*	Water	0.60	8	11
Nitric acid*	Water	2.98	2	11
Nitrobenzene	Carbon tetrachloride	1.00		7
Nitrogen	Water	1.9		1, 24
Nitrous oxide	Water	1.8		1, 11
Oxalic acid*	Water	1.61	2	11

TABLE 2-372 Diffusivities in Liquids (25°C) (*Concluded*)

Dilute solutions and 1 atm unless otherwise noted; use $D_L\mu/T$ = constant to estimate effect of temperature; * indicates that reference gives effect of concentration.

Solute	Solvent	$D_L \times 10^5$, sq cm/sec	Estimated possible, error, ± %1	Ref.
Oxygen	Glycerol*-water (106 poise)	0.24		13
Oxygen	Sucrose*-water (125 poise)	0.25		13
Oxygen	Water	2.5	20	1, 3, 15, 21, 24
Pentaerythritol*	Water	0.77	4	11
Phenol	*i*-Amyl alcohol	0.2		11
Phenol	Benzene	1.68		1
Phenol	Carbon disulfide	3.7		11
Phenol	Chloroform	2.0		11
Phenol	Ethanol	0.89		11
Phenol	Ethyl ether	3.9		11
n-Propanol	Water	1.1		1, 7, 11
Pyridine*	Ethanol	1.24	3	11
Pyridine	Water	0.76	7	11
Pyrogallol	Water	0.74	7	11
Raffinose*	Water	0.41	4	11
Resorcinol*	Ethanol	0.46	5	11
Resorcinol*	Water	0.87	4	11
Saccharose*	Water	0.49	4	11
Stearic acid*	Ethanol	0.65	5	11
Succinic acid*	Water	0.94		11
Sucrose	Water	0.56	6	2, 27
Sulfur dioxide	Water	1.7		15, 17
Sulfuric acid*	Water	1.97	3	11
Tartaric acid*	Water	0.80	10	11
1,1,2,2-Tetrabromoethane	1,1,2,2-Tetrachloroethane	0.61	4	11
Toluene	*n*-Decane	2.09		4
Toluene	*n*-Dodecane	1.38		4
Toluene	*n*-Heptane	3.72		4
Toluene	*n*-Hexane	4.21		4
Toluene	*n*-Tetradecane	1.02		4
Urea	Ethanol	0.73		11
Urea	Water	1.37	2	8, 11
Urethane	Water	1.06		11, 25
Water	Glycerol	0.021		16

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TABLE 2-373 Thermal Conductivities of Some Building and Insulating Materials*

$k = \text{Btu}/(\text{h}\cdot\text{ft}^2)(°\text{F}/\text{ft})$

Material	Apparent density ρ, lb/ft^3 at room temperature	t, °C	k
Aerogel, silica, opacified	8.5	120	0.013
		290	.026
Asbestos-cement boards	120	20	.43
Asbestos sheets	55.5	51	.096
Asbestos slate	112	0	.087
	112	60	.114
Asbestos	29.3	−200	.043
	29.3	0	.090
	36	0	.087
	36	100	.111
	36	200	.120
	36	400	.129
	43.5	−200	.090
	43.5	0	.135
Aluminum foil (7 air spaces per 2.5 in.)	0.2	38	.025
		177	.038
Ashes, wood		0–100	.041
Asphalt	132	20	.43
Boiler scale (Note 1)			
Bricks:			
Alumina (92–99% Al_2O_3 by wt.) fused		427	1.8
Alumina (64–65% Al_2O_3 by wt.)		1315	2.7
(See also Bricks, fire clay)	115	800	0.62
	115	1100	.63
Building brick work		20	.4
Carbon	96.7		3.0
Chrome brick (32% Cr_2O_3 by wt.)	200	200	.67
	200	650	.85
	200	1315	1.0
Diatomaceous earth, natural, across strata (Note 2)	27.7	204	0.051
	27.7	871	.077
Diatomaceous, natural, parallel to strata (Note 2)	27.7	204	.081
	27.7	871	.106
Diatomaceous earth, molded and fired (Note 2)	38	204	.14
	38	871	.18
Diatomaceous earth and clay, molded and fired (Note 2)	42.3	204	.14
	42.3	871	.19
Diatomaceous earth, high burn, large pores (Note 3)	37	200	.13
	37	1000	.34
Fire clay (Missouri)		200	.58
		600	.85
		1000	.95
		1400	1.02
Kaolin insulating brick (Note 3)	27	500	0.15
	27	1150	.26
Kaolin insulating firebrick (Note 4)	19	200	.050
	19	760	.113
Magnesite (86.8% MgO, 6.3% Fe_2O_3, 3% CaO, 2.6% SiO_2 by wt.)	158	204	2.2
	158	650	1.6
	158	1200	1.1
Silicon carbide brick, recrystallized (Note 3)	129	600	10.7
	129	800	9.2
	129	1000	8.0
	129	1200	7.0
	129	1400	6.3
Calcium carbonate, natural	162	30	1.3
White marble			1.7
Chalk	96		0.4
Calcium sulfate ($4H_2O$), artificial	84.6	40	.22
plaster (artificial)	132	75	.43
(building)	77.9	25	.25
Cambric (varnished)		38	.091
Carbon, gas		0–100	2.0
Carbon stock	94	−184	0.55
		0	3.6
Cardboard, corrugated			0.037
Cotton wool	5	30	0.024
Cork board	10	30	.025
Cork (regranulated)	8.1	30	.026
(ground)	9.4	30	.025
Diatomaceous earth powder, coarse (Note 2)	20.0	38	.036
	20.0	871	.082
fine (Note 2)	17.2	204	.040
	17.2	871	.074
molded pipe covering (Note 2)	26.0	204	.051
	26.0	871	.088
4 vol. calcined earth and 1 vol. cement, poured and fired (Note 2)	61.8	204	.16
	61.8	871	.23
Dolomite	167	50	1.0
Ebonite			0.10
Enamel, silicate	38		0.5–0.75
Felt, wool	20.6	30	0.03
Fiber insulating board	14.8	21	.028
Fiber, red	80.5	20	.27
(with binder, baked)		20–97	.097
Gas carbon		0–100	2.0
Glass			0.2–0.73
Borosilicate type	139	30–75	0.63
Window glass			0.3–0.61
Soda glass			0.3–0.44
Granite			1.0–2.3
Graphite, longitudinal		20	95
powdered, through 100 mesh	30	40	0.104
Gypsum (molded and dry)	78	20	.25
Hair felt (perpendicular to fibers)	17	30	.021
Ice	57.5	0	1.3
Infusorial earth, see diatomaceous earth			
Kapok	0.88	20	0.020
Lampblack	10	40	.038
Lava			.49
Leather, sole	62.4		.092
Limestone (15.3 vol. % H_2O)	103	24	.54
Linen		30	.05
Magnesia (powdered)	49.7	47	.35
Magnesia (light carbonate)	13	21	0.034
Magnesium oxide (compressed)	49.9	20	.32
Marble			1.2–1.7
Mica (perpendicular to planes)		50	0.25
Mill shavings			0.033–0.05
Mineral wool	9.4	30	0.0225
	19.7	30	.024
Paper			.075
Paraffin wax		0	.14
Petroleum coke		100	3.4
		500	2.9
Porcelain		200	0.88
Portland cement, see concrete		90	.17
Pumice stone		21–66	.14
Pyroxylin plastics			.075
Rubber (hard)	74.8	0	.087
(para)		21	.109
(soft)		21	0.075–0.092
Sand (dry)	94.6	20	0.19
Sandstone	140	40	1.06
Sawdust	12	21	0.03
Scale (Note 1)			
Silk	6.3		.026
varnished		38	.096
Slag, blast furnace		24–127	.064
Slag wool	12	30	.022
Slate		94	.86
Snow	34.7	0	.27
Sulfur (monoclinic)		100	0.09–0.097
(rhombic)		21	0.16
Wall board, insulating type	14.8	21	.028
Wall board, stiff paste board	43	30	.04
Wood shavings	8.8	30	.034

TABLE 2-373 Thermal Conductivities of Some Building and Insulating Materials[*] (*Concluded*)

k = Btu/(h·ft^2)(°F/ft)

Material	Apparent density ρ, lb/ft^3 at room temperature	t, °C	k	Material	Apparent density ρ, lb/ft^3 at room temperature	t, °C	k
Celluloid	87.3	30	.12	Wood (across grain):			
Charcoal flakes	11.9	80	.043	Balsa	7–8	30	0.025–0.03
	15	80	.051	Oak	51.5	15	0.12
Clinker (granular)		0–700	.27	Maple	44.7	50	.11
Coke, petroleum		100	3.4	Pine, white	34.0	15	.087
		500	2.9	Teak	40.0	15	.10
Coke, petroleum (20–100 mesh)	62	400	0.55	White fir	28.1	60	.062
Coke (powdered)		0–100	.11	Wood (parallel to grain):			
Concrete (cinder)			.20	Pine	34.4	21	.20
(stone)			.54	Wool, animal	6.9	30	.021
(1:4 dry)			.44				

[*] Marks, *Mechanical Engineers' Handbook,* 4th ed., McGraw-Hill, New York, 1941. *International Critical Tables,* McGraw-Hill, 1929, and other sources.

Note 1: B. Kamp [*Z. tech. Physik,* **12,** 30 (1931)] shows the effect of increased porosity in decreasing thermal conductivity of boiler scale. Partridge [University of Michigan, *Eng. Research Bull.,* **15,** 1930] has published a 170-page treatise on Formation and Properties of Boiler Scale.

Note 2: Townshend and Williams, *Chem. & Met.,* **39,** 219 (1932).

Note 3: Norton, *Refractories,* 2d ed., McGraw-Hill, New York, 1942.

Note 4: Norton, private communication.

TABLE 2-374 Thermal-Conductivity-Temperature Table for Metals[*]

Thermal conductivities tabulated in watts per meter-kelvin

Substance	Temperature, K														
	10	20	40	60	80	100	200	300	400	500	600	800	1000	1200	1400
Alumina	7	32	121	174	160	125	55	36	26	20	16	10	8	7	6
Aluminum	38,000	13,500	2,300	850	380	300	237	273	240	237	232	220	93	99	105
Antimony	470	230	110	80	60	48	32	26	22	20					
Beryllium oxide	47	196	810	1,400	1,650	1,490	480	272	196	146	111	70	47	33	25
Bismuth	240	100	45	31	24	22	18	16	14	12					
Boron	165	305	400	327	230	170	45	25	15	12					
Cadmium	900	250	150	120	110	110	105	104	101	99					
Chromium	400	570	450	250	180	158	111	90	87	85	81	71	65	62	61
Cobalt	250	450	380	250	190	160	120	100	85	70					
Constantan	4	9	16	18	19	20	23	25	27	30					
Copper	19,000	10,700	2,100	850	570	483	413	398	392	388	383	371	357	342	
Gallium	2,200	640	250	200	170	140	100	85							
Gold	2,800	1,500	520	380	350	345	327	315	312	309	304	292	278	262	
Graphite[†]	27	108	135	81	54	39	15	10	7	5	4	3	3	2	2
Graphite[‡]	81	420	1,630	2,980	4,290	4,980	3,250	2,000	1,460	1,140	930	680	530	440	370
Hastelloy	1	3	4	5	6	7	9	10	11	13					
Inconel	2	4	8	10	11	11	14	15							
Iridium	1,300	1,900	750	360	230	172	147	145	143	140					
Iron	710	1,000	560	270	170	132	94	80	69	61	55	43	33	28	31
Lead	175	57	43	42	41	40	37	35	34	33	31	19	22	24	26
Magnesium	1,200	1,300	620	290	190	169	159	156	153	151	149	146	84	98	112
Magnesium oxide	1,100	3,100	2,200	950	460	260	75	48	36	27	21	13	10	8	7
Manganese	2	2	4	5	5	6	7	8	9	9					
Manganin	2	4	9	11	13	13	17	22	28	34	40				
Mercury	54	40	35	33	33	32	32	8	10	11	12	13	14		
Molybdenum	150	280	350	250	210	179	143	138	134	130	126	118	112	105	100
Nickel	2,600	1,700	570	290	200	158	106	91	80	72	66	67	72	76	80
Nylon	0.04	0.10	0.17	0.20	0.23	0.25	0.28	0.30							
Palladium	1,200	610	160	100	88	80	78	78	78	80					
Platinum	1,200	490	130	92	82	79	75	73	72	72	72	73	78	78	81
PTFE[§]	0.94	1.43	1.94	2.1	2.15	2.16	2.20	2.25	2.3	2.5					
Pyrex	0.12	0.20	0.33	0.42	0.51	0.57	0.88	1.1	1.6	2.1					
Quartz	1,200	480	82	40	30										
Rhodium	2,900	3,900	1,000	370	250	190	160	150	145	140					
Rubber			0.13	0.15	0.16	0.17	0.20	0.22	0.24	0.25					
Selenium (axis)	140	57	25	15	10	8	6	4	3	2					
Silica								1.34	1.52	1.70	1.87	2.22	2.60		
Silver	16,500	5,200	1,100	630	500	430	425	424	420	413	405	389	374	358	
Tantalum	108	146	88	68	62	59	58	57	58	58	59	59	60	61	62
Tellurium	300	93	29	17	13	11	6	4	3	3					
Tin		320	130	101	90	84	72	67	62	60					
Titanium	14	28	39	37	33	31	26	21	20	20	19				
Tungsten			880	330	310	280	190	180	170	150	140				
Uranium				20	22	23	26	28	30	32					
Zinc				150	135	130	123	120	116	110	110				
Zirconium	100	110	59	42	38	34	25	23	22	21	21				

[*] Especially at low temperatures, the thermal conductivity can often be markedly reduced by even small traces of impurities. This table, for the highest-purity specimens available, should thus be used with caution in applications with commercial materials. From Perry, *Engineering Manual,* 3d ed., McGraw-Hill, New York, 1976. A more detailed table appears as Section 5.5.6 in the *Heat Exchanger Design Handbook,* Hemisphere Pub. Corp., Washington, DC, 1983.

[†] Parallel to basal plane.

[‡] Perpendicular to basal plane.

[§] Also known as Teflon, etc.

TABLE 2-375 Thermal Conductivity of Chromium Alloys*

k = Btu/(h·ft^2)(°F/ft)

American Iron and Steel Institute Type No.	k at 212°F	k at 932°F
301, 302, 302B, 303, 304, 316†	9.4	12.4
308	8.8	12.5
309, 310	8.0	10.8
321, 347	9.3	12.8
403, 406, 410, 414, 416†	14.4	16.6
430, 430F†	15.1	15.2
442	12.5	14.2
501, 502†	21.2	19.5

*Table 3-322 is based on information from manufacturers.

†Shelton and Swanger (National Bureau of Standards), *Trans. Am. Soc. Steel Treat.*, **21,** 1061–1078 (1933).

TABLE 2-376 Thermal Conductivity of Some Alloys at High Temperature*

	Thermal conductivity, Btu/(ft)(hr)(°R)					
°R	Kovar	Advance	Monel	Hastelloy A	Inconel	Nichrome V
500	7.8		9.0	5.6	6.0	5.5
600	8.3	11.4	10.2	6.2	6.5	6.1
700	8.6	12.6	11.2	6.8	7.0	6.7
800	8.7	13.9	12.3	7.3	7.6	7.3
900	8.7	15.1	13.4	7.8	8.1	7.8
1000	8.9	16.4	14.4	8.4	8.6	8.4
1100	9.2	17.6	15.4	9.0	9.1	9.0
1200	9.5	18.8	16.5	9.5	9.7	9.5
1300	9.8	20.0	17.6	10.1	10.2	10.1
1400	10.2	21.2	18.7	10.7	10.8	10.7
1500	10.5	22.5	19.8	11.3	11.3	11.3
1600	10.8	23.8	20.8	11.8	11.8	11.9
1700	11.1	25.0	21.9	12.3	12.4	12.4
1800	11.3	26.2	23.0	12.9	13.0	13.0
1900	11.5	27.4	24.0	13.4	13.6	13.5
2000	11.8	28.7	25.1	14.0	14.0	14.1
2100	12.1	30.0	26.1	14.6	14.5	14.7
2200	12.3		27.2	15.1	15.0	15.3

*Silverman, *J. Metals*, **5,** 631 (1953). Copyright American Institute of Mining, Metallurgical and Petroleum Engineers, Inc.

TABLE 2-377 Thermal Conductivities of Some Materials for Refrigeration and Building Insulation*

k = Btu/(h·ft^2)(°F/ft) at approximately room temperature

Material	Apparent density, lb/cu ft room temp.	k
Soft flexible materials in sheet form:		
Chemically treated wood fiber	2.2	0.023
Eel grass between paper	3.4–4.6	0.021–0.022
Felted cattle hair	11–13	0.022
Flax fibers between paper	4.9	.023
Hair and asbestos fibers, felted	7.8	.023
Insulating hair, and jute	6.1–6.3	0.022–0.023
Jute and asbestos fibers, felted	10.0	0.031
Loose materials:		
Cork, regranulated, fine particles	8–9	.025
Charcoal, 6 mesh	15.2	.031
Diatomaceous earth, powdered	10.6	.026
Glass wool, curled	4–10	.024
Gypsum in powdered form	26–34	0.043–0.05
Mineral wool, fibrous	6	0.0217
	10	.0225
	14	.0233
	18	.0242
Sawdust	12	.034
Wood shavings, from planer	8.8	.034
Semiflexible materials in sheet form:		
Flax fiber	13.0	.026
Semirigid materials in board form:		
Corkboard	7.0	.0225
	10.6	.025
Mineral wool, block, with binder	16.7	.031
Stiff fibrous materials in sheet form:		
Wood pulp	16.2–16.9	.028
Sugar-cane fiber	13.2–14.8	.028
Cellular gypsum	8	.029
	12	.037
	18	.049
	24	.064
	30	.083

*Abstracted from *U.S. Bur. Standards Letter Circ.* **227,** Apr. 19, 1927.

TABLE 2-378 Thermal Conductivities of Insulating Materials at High Temperatures*

k = Btu/(h·ft^2)(°F/ft)

Material	For temperatures, °F up to	Mean temperatures, °F									
		100	200	300	400	500	600	800	1000	1500	2000
Laminated asbestos felt (approx. 40 laminations per in)	700	0.033	0.037	0.040	0.044	0.048					
Laminated asbestos felt (approx. 20 laminations per in)	500	.045	.050	.055	.060	.065					
Corrugated asbestos (4 plies per in)	300	.050	.058	.069							
85% magnesia (density, 13 lb/ft^3)	600	.034	.036	.038	.040						
Diatomaceous earth, asbestos and bonding material	1600	.045	.047	.049	.050	.053	0.055	0.060	0.065		
Diatomaceous earth brick	1600	.054	.056	.058	.060	.063	.065	.069	.073		
Diatomaceous earth brick	2000	.127	.130	.133	.137	.140	.143	.150	.158	0.176	
Diatomaceous earth brick	2500	.128	.131	.135	.139	.143	.148	.155	.163	.183	0.203
Diatomaceous earth powder (density, 18 lb/ft^3)		.039	.042	.044	.048	.051	.054	.061	.068		
Rock wool		.030	.034	.039	.044	.050	.057				

Asbestos cement, 1.2; 85% magnesia cement, 0.05; asbestos and rock wool cement, 0.075 approx.

*Marks, "Mechanical Engineers' Handbook," 4th ed., McGraw-Hill, New York, 1941.

TABLE 2-379 Thermal Conductivities of Insulating Materials at Moderate Temperatures (Nusselt)*

k = Btu/(h·ft^2)(°F/ft)

Material	Weight, lb/cu ft	Temperatures, °F						
		32	100	200	300	400	600	800
Asbestos	36.0	0.087	0.097	0.110	0.117	0.121	0.125	0.130
Burned infusorial earth for pipe coverings	12.5	.043	.046	.052	.057	.062	.073	.085
Insulating composition (loose)	25.0	.040	.046	.050	.053	.055		
Cotton	5.0	.032	.035	.039				
Silk hair	9.1	.026	.030	.034				
Silk	6.3	.025	.028	.034				
Wool	8.5	.022	.027	.033				
Pulverized cork	10.0	.021	.026	.032				
Infusorial earth (loose)	22.0	.035	.039	.045	.047	.050	.053	

*Marks, *Mechanical Engineers' Handbook,* 4th ed., McGraw-Hill, New York, 1941.

TABLE 2-380 Thermal Conductivities of Insulating Materials at Low Temperatures (Gröber)*

k = Btu/(h·ft^2)(°F/ft)

Material	Weight, lb/cu ft	Temperatures, °F				
		32	−50	−100	−200	−300
Asbestos	44.0	0.135	0.132	0.130	0.125	0.100
Asbestos	29.0	.0894	.0860	.0820	.0720	.0545
Cotton	5.0	.0325	.0302	.0276	.0235	.0198
Silk	6.3	.0290	.0256	.0235	.0196	.0155

*Marks, *Mechanical Engineers' Handbook,* 4th ed., McGraw-Hill, New York, 1941.

TABLE 2-381 Thermal Diffusivity (m^2/s) of Selected Elements*

Element	Temperature, K									
	20	40	60	80	100	200	400	600	800	1000
Aluminum	0.50	0.012	0.0014	4.4. – 4	2.3. – 4	1.1. – 4	9.4. – 5	8.4. – 5	7.4. – 5	6.6. – 5
Beryllium					0.0036	1.5. – 4	4.0. – 5	2.6. – 5	2.1. – 5	1.7. – 5
Chromium	0.038	0.0037	5.9. – 4	2.0. – 4	1.2. – 4	4.1. – 5	2.6. – 5	2.0. – 5	1.7. – 5	1.4. – 5
Copper	0.16	0.0040	6.9. – 4	3.1. – 4	2.2. – 4	1.3. – 4	1.1. – 4	1.0. – 4	9.0. – 5	9.0. – 5
Gold	0.005	4.5. – 4	2.3. – 4	1.8. – 4	1.5. – 4	1.3. – 4	1.2. – 4	1.2. – 4	1.1. – 4	9.8. – 5
Iridium	0.046				8.4. – 5	5.6. – 5	4.8. – 5	4.4. – 5	4.1. – 5	3.5. – 5
Iron	0.043	3.2. – 3	4.9. – 4	1.6. – 4	8.2. – 5	3.1. – 5	1.8. – 5	1.3. – 5	1.1. – 5	1.0. – 5
Lead	9.3. – 5	3.9. – 5	3.3. – 5	3.1. – 5	2.9. – 5	2.6. – 5	2.3. – 5	2.0. – 5	1.3. – 5	1.5. – 5
Molybdenum	0.0095	0.0014	4.0. – 4	2.0. – 4	1.3. – 4	6.3. – 5	5.1. – 5	4.5. – 5	4.2. – 5	3.8. – 5
Nickel	0.033	0.0017	3.1. – 4	1.3. – 4	8.0. – 5	3.1. – 5	1.9. – 5	1.3. – 5	1.4. – 5	1.5. – 5
Platinum	0.0029	1.6. – 4	6.3. – 5	4.3. – 5	3.6. – 5	2.7. – 5	2.5. – 5	2.5. – 5	2.5. – 5	2.5. – 5
Silver	0.031	0.0013	4.5. – 4	2.8. – 4	2.3. – 4	1.8. – 4	1.7. – 4	1.6. – 4	1.5. – 4	1.4. – 4
Zinc	0.0046	3.1. – 4	1.0. – 4	7.0. – 5	5.5. – 5	4.7. – 5	3.9. – 5	3.4. – 5	1.8. – 5	2.2. – 5

*Tables for up to 24 temperatures for 47 elements appear in the *Handbook of Heat Transfer,* 2d ed., McGraw-Hill, New York, 1984. The notation 3.2. – 4 signifies 2.3×10^{-4}.

TABLE 2-382 Thermophysical Properties of Selected Nonmetallic Solid Substances

Material	Density, kg/m^3	Emissivity	Specific heat, kJ/(kg·K)	Thermal conductivity, W/(m·K)	Thermal diffusivity, m^2/s × 10^6
Alumina	3975		0.765	36	11.9
Asphalt	2110		0.920	0.06	0.03
Bakelite	1300		1.465	1.4	0.74
Beryllia	3000	0.82	1.030	270	88
Brick	1925	0.93	0.835	0.72	0.45
Brick, fireclay	2640	0.93	0.960	1.0	0.39
Carbon, amorphous	1950	0.86	0.724	1.6	1.13
Clay	1460	0.91	0.880	1.3	1.01
Coal	1350	0.80	1.26	0.26	0.15
Cotton	80		1.30	0.06	0.58
Diamond	3500		0.509	2300	1290
Granite	2630		0.775	2.79	1.37
Hardboard	1000		1.38	0.15	0.11
Magnesite	3025	0.38	1.13	4.0	1.2
Magnesia	3635	0.72	0.943	48	14
Oak	770	0.90	2.38	0.18	0.10
Paper	930	0.83	1.34	0.011	0.01
Pine	525	0.84	2.75	0.12	0.54
Plaster board	800	0.91		0.17	
Plywood	540		1.22	0.12	0.18
Pyrex	2250	0.92	0.835	1.4	0.74
Rubber	1150	0.92	2.00	0.2	0.09
Rubber, foam	70	0.90		0.03	
Salt		0.34	0.854	7.1	
Sandstone	2150	0.59	0.745	2.9	1.8
Silica		0.79	0.743	1.3	
Sapphire	3975	0.48	0.765	46	15
Silicon carbide	3160	0.86	0.675	490	230
Soil	2050	0.38	1.84	0.52	0.14
Teflon	2200	0.92	0.35	0.26	0.34
Thoria	4160	0.28	0.71	14	4.7
Urethane foam	70		1.05	0.03	0.36
Vermiculite	120		0.84	0.06	0.60

NOTE: Difficulties of accurately characterizing many of the specimens mean that many of the values presented here must be regarded as being of order of magnitude only. For some materials, actual measurement may be the only way to obtain data of the required accuracy. To convert kilograms per cubic meter to pounds per cubic foot, multiply by 0.062428; to convert kilojoules per kilogram-kelvin to British thermal units per pound-degree Fahrenheit, multiply by 0.23885.

PREDICTION AND CORRELATION OF PHYSICAL PROPERTIES

INTRODUCTION

In the absence of reliable experimental data, the methods presented here provide physical property estimates that are sufficiently accurate for many engineering applications. These techniques have been selected on the basis of accuracy, generality, and, in most cases, simplicity; they are divided into 11 categories: (1) pure component constants: critical properties, normal freezing and boiling temperatures, acentric factor, radius of gyration, dipole moment, and van der Waals area and volume; (2) vapor pressure; (3) ideal gas thermal properties: heat capacity and enthalpy, Gibbs energy, and entropy of formation; (4) enthalpy of vaporization and fusion; (5) solid and liquid heat capacity; (6) vapor, liquid, and solid density; (7) vapor and liquid viscosity; (8) vapor and liquid thermal conductivity; (9) vapor and liquid diffusivity; (10) surface tension; and (11) flammability properties: flash point, flammability limits, and autoignition temperature. The definition of the property and limitations and accuracy of each method of correlation or prediction are given for each property. Numerical examples are included for many of the methods. Equation symbols are listed under "Nomenclature," and literature citations, indicated by superscript numbers, follow the nomenclature under "References." Essentially all of the methods are derived from work on the *American Petroleum Institute Technical Data Book*[23] (hydrocarbon compounds and their mixtures), the AIChE Design Institute for Physical Property Data (DIPPR) *Data Prediction Manual*[22] (nonhydrocarbon compounds and their mixtures), and the DIPPR Data Compilation Project[24].

UNITS

Applicable dimensional units are shown individually with each equation. The International Metric System (SI) is used when feasible; otherwise commonly used U.S. engineering units are employed. The reader is referred to Sec. 1 for unit conversion factors.

Nomenclature

Symbol	Definition	SI units	U.S. customary units
B	Second virial coefficient	m^3/kmol	ft^3/lbmol
C_p	Heat capacity at constant pressure	J/(kmol·K)	Btu/(lbm °F)
C_v	Heat capacity at constant volume	kg/m^3	lbm/ft^3
d	Mass density	m^2/s	ft^2/s
D	Diffusivity		
F	Conductivity factor in Eq. (2-136)		
k	Thermal conductivity	W/(m·K)	Btu/(h·ft °F)
K	Watson/UOP characterization factor = $(1.8T_b)^{1/3}$/rel den		
ln	Denotes natural logarithm		
M	Molecular weight		
MeABP	Mean average boiling point		
N	Carbon number		
N_A	Avogadro's number		
P	Pressure	Pa	lbf/in^2
P^{sat}	Vapor pressure	Pa	lbf/in^2
$[P]$	Parachor		
rel den	Relative density at 15°C and 0.1 MPa		
R	Universal gas constant; e.g., 8314 Pa·m^3/kmol K		
$\overline{R}$	Radius of gyration		
S	Absolute entropy	J/kg	Btu/lbm
T	Absolute temperature	K	R
V	Molar volume	m^3/kmol	ft^3/lbmole
x	Mole fraction of component in liquid phase		
y	Mole fraction of component in vapor phase		
Z	Compressibility factor = PV/RT		
	Greek symbols		
ΔG_f	Gibbs energy of formation	J/kg	Btu/lbm
ΔH_f	Enthalpy (heat) of formation	J/kg	Btu/lbm
ΔH_{fus}	Enthalpy (heat) of fusion	J/kg	Btu/lbm
ΔH_V	Enthalpy (heat) of vaporization	J/kg	Btu/lbm
ΔS_f	Entropy of formation	J/(kg·K)	Btu/lbm
ΔS_{fus}	Entropy of fusion	J/(kg·K)	Btu/lbm
ΔZ_V	Difference of vapor and liquid compressibility factors defined in Eq. (2-55)		
Θ	T_b/T_c		
λ	Dipole moment		
μ	Absolute viscosity	Pa·s	lbm/(ft·s)
ν	Kinematic viscosity	m^2/s	ft^2/s
ρ	Molar density	kmol/m^3	lb·mole/ft^3
σ	Surface tension	N/m	dyne/cm
ϕ	Volume fraction		
ω	Acentric factor		
	Superscripts		
r	At reference condition		
(0)	Simple spherical molecule, corresponding states		
(1)	Correction factor, corresponding states		
°	Of the ideal gas		
′	At atmospheric pressure		
	Subscripts		
b	At normal boiling temperature		
bp	At bubble point		
c	At critical point		
G	Of the gas/vapor		
HI	Upper limit		
i	Component index, of the ith component		
j	Component index, of the jth component		
L	Of the liquid		
m	Of the mixture		
mc	Mixture correspondence		
mlt	At melting temperature		
o	Of organic component		
pc	Pseudocritical quantity		
r	Reduced quantity		
RA	Rackett parameter		
sat	Saturated		
S	Of the solid		
V	Of the vapor		
w	Of water		

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PURE COMPONENT CONSTANTS

Basic pure component constants required to characterize components or mixtures for calculation of other properties include the melting point, normal boiling point, critical temperature, critical pressure, critical volume, critical compressibility factor, acentric factor, and several other characterization properties. This section details for each property the method of calculation for an accurate technique of prediction for each category of compound, and it references other accurate techniques for which space is not available for inclusion.

Critical Temperature The critical temperature of a compound is the temperature above which a liquid phase cannot be formed, no matter what the pressure on the system. The critical temperature is important in determining the phase boundaries of any compound and is a required input parameter for most phase equilibrium thermal property or volumetric property calculations using analytic equations of state or the theorem of corresponding states. Critical temperatures are predicted by various empirical methods according to the type of compound or mixture being considered.

For **pure hydrocarbons,** the method of Ambrose[2] is the most accurate and will also be useful for predicting critical pressure and volume. Equation (2-1) requires only the normal boiling point, T_b, and the molecular structure of the compound.

$$T_c = T_b\left[1 + \frac{1}{1.242 + \sum \Delta_T - 0.023\Delta(\text{Platt no.})}\right] \tag{2-1}$$

T_c and T_b are the critical and normal boiling temperatures, respectively, expressed in kelvins. Values of Δ_T from Table 2-383 are summed for each part of the molecule to yield $\sum \Delta_T$ (e.g., for isobutane, $3 \times$ —$CH_3 + 1 \times$ >CH—). Δ(Platt no.) is equal to the Platt number of any alkyl chains in the molecule minus the Platt number of the *n*-alkane with the same number of carbon atoms. The Platt number is defined as the number of pairs of carbon atoms that are separated by three carbon-carbon bonds and is an indicator of branching (e.g., for 2,2,3-trimethylpentane, the Platt number is 5). The Platt number of an *n*-alkane is the number of carbon atoms minus three (e.g., for *n*-octane, the Platt number is five). Errors in T_c average about 4 K for paraffins to C_{20} and other hydrocarbons to C_{14}.

Equation (2-2), another somewhat simpler method for estimating the critical temperature of pure hydrocarbons only, is the method of Nokay[76] and requires the normal boiling point, the relative density, and the compound family.

$$\log T_c = A + B \log_{10} (\text{rel den}) + C \log T_b \tag{2-2}$$

T_c and T_b are the critical and normal boiling temperatures, respectively, expressed in kelvins. The relative density (rel den) of the liquid at 15°C is 0.1 MPa. The regression constants *A, B,* and *C* are tabulated by family in Table 2-384. Errors average about 3 K.

For **pure nonhydrocarbon organics,** the most accurate method for prediction of critical temperature for all compound groups is also the Ambrose[2] method. Equation (2-1) applies to all nonhydrocarbon compounds except perfluorocarbons, where the constant 1.242 is replaced by 1.570. For compounds containing any of C, H, O, N, S, or halogens up to C_{13} and ranging in critical temperature from 228–790 K, the average error is about 6 K.

Alternate methods for nonhydrocarbon organics are the first order method of Lydersen[63] with an average error of 9 K although the method of Ambrose is considerably better for alcohols and ketones.

Equation (2-3) is the Lydersen equation for critical temperature and requires only the normal boiling point and the molecular structure for solution.

$$T_c = \frac{T_b}{[0.567 + \sum \Delta_T - (\sum \Delta_T)^2]} \tag{2-3}$$

Contributions to $\sum \Delta_T$ are given in Table 2-385.

For **pure inorganic compounds,** the method of Gambill[31] was modified to yield Eq. (2-4) and only requires the normal boiling point as input.

$$T_c = 1.64 T_b \tag{2-4}$$

Although this equation was tested with available experimental data (38 compounds), it can only be considered a rough approximation. **Inorganic-organic** and **inorganic-halide** compounds are predicted better by replacing the constant 1.64 in Eq. (2-4) by 1.55.

For both **hydrocarbons** and **nonhydrocarbon organic defined mixtures,** the method of Li[60] is used with a relatively simple volumetric average mixing rule as shown in Eq. (2-5) to calculate the true critical temperature.

$$T_{cm} = \sum_j \left(\frac{y_j V_{c_j}}{\sum_i y_i V_{c_i}}\right) T_{c_j} \tag{2-5}$$

T_{cm} is the mixture critical temperature in K. V_c is the critical volume of a component, m^3/kmole. The mole fraction of a component is *y*. The mixture contains *i* components.

For hydrocarbon systems, the average error is about 3 K, while for systems containing nonhydrocarbons, the average error is 15 K with the highest errors occurring where simple gases are present. The method of Chueh and Prausnitz[18] yields average errors slightly lower than the method of Li, but it is computationally more complex.

Critical Pressure The critical pressure of a compound is the vapor pressure of the compound at the critical temperature. Below the critical temperature, any compound above its vapor pressure will be a liquid. The critical pressure is required for calculations discussed in the part of the section on critical temperature.

For **pure hydrocarbons,** the method of Ambrose[2] is the most accurate. Equation (2-6) requires only the molecular weight (*M*) and the molecular structure of the compound.

$$P_c = \frac{0.101325M}{[0.339 + \sum \Delta_P - 0.026\Delta(\text{Platt no.})]^2} \tag{2-6}$$

P_c is the critical pressure, MPa. Values of Δ_P from Table 2-383 are summed for each part of the molecule to yield $\sum \Delta_P$. Calculation of the Platt number is discussed under "Critical Temperature." Errors in P_c average 0.07 MPa and are less reliable for compounds with 12 or more carbon atoms.

TABLE 2-383 Group Increments for the Ambrose Method

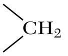
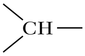
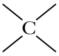
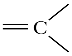
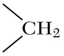
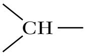
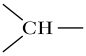
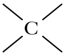
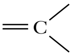
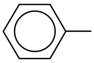
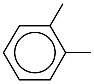
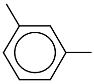
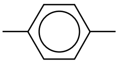
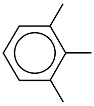
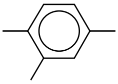
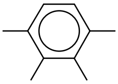
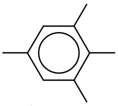
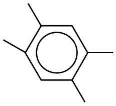
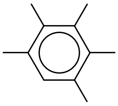
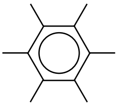
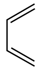
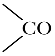
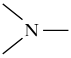
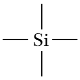
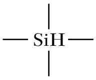
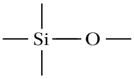
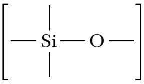
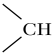
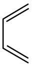
Group description	Δ_T	Δ_P	Δ_V
—CH_3	0.138	0.2260	55.1
	0.138	0.2260	55.1
	0.095	0.2200	47.1
	0.018	0.1960	38.1
=CH_2	0.113	0.1935	45.1
=CH—	0.113	0.1935	45.1
	0.070	0.1875	37.1
=C=	0.088	0.1610	35.1
≡CH	0.038	0.1410	35.1
≡C—	0.038	0.1410	35.1
Ring Increments			
	0.090	0.1820	44.5
	0.090	0.1820	44.5
 in fused ring*	0.030	0.1820	44.5
	0.090	0.1820	44.5
=CH—	0.075	0.1495	37.0
	0.075	0.1495	37.0
=C=	0.060	0.1170	29.5
Aromatic Compounds			
	0.458	0.9240	222
	0.448	0.8940	222
	0.488	0.9440	222
	0.488	0.9440	222
	0.438	0.8640	222
	0.478	0.9140	222
	0.428	0.8340	222
Aromatic Compounds (*Cont.*)			
	0.468	0.8840	222
	0.468	0.8840	222
	0.418	0.8040	222
	0.368	0.7240	222
 in fused ring*	0.220	0.5150	148
Nonring Increments			
—OH	Use Eq. (*a*), below	Use Eq. (*b*), below	
—O—	0.138	0.160	
	0.220	0.282	
—CHO	0.220	0.220	
—COOH	0.578	0.450	
—CO—O—OC—	1.156	0.900	
—CO—O—	0.330	0.470	
—NO_2	0.370	0.420	
—NH_2	0.208	0.095	
—NH—	0.208	0.135	
	0.088	0.170	
—CN	0.423	0.360	
—S—	0.105	0.270	
—SH	0.090	0.270	
	0.138	0.461	
	0.371	0.507	
—SiH_3	0.195	—	
	0.159	0.725	
 *cyclic*	0.131	0.663	

TABLE 2-383 Group Increments for the Ambrose Method *(Concluded)*

Group description	Δ_T	Δ_P	Δ_V	Group description	Δ_T	Δ_P	Δ_V
Double Bond	−0.050	−0.065		—Cl	0.080	0.318	
Triple Bond	−0.200	−0.170		—Br	0.080	0.600	
—F	0.180 (1st) 0.055	0.223		—I		0.850	
—Cl	0.110 (1st) 0.055	0.318		The single or first substituent on an aromatic ring	0.010	0	
—Br	0.110 (1st) 0.055	0.500		The second or subsequent ring substituents	0.030	0.020	
Aromatic Compounds				Each pair of ring substituents in ortho positions with respect to each other	−0.040	−0.050	
Corrections				If one of the ortho pair is —OH	−0.080	0	
benzene	0.448	0.924					
pyridine	0.448	0.850					
—OH	0.198	−0.025					
C_4H_4 (fused ring)	0.220	0.515					
—F	0.080	0.183					

*Group contributions for  and  in fused rings have been calculated from minimal data and may be less reliable than the other values.

Substituent increments do not apply to halogens.
Eq. (*a*): Δ_T (—OH) $= 0.87 - 0.11n + 0.003n^2$
Eq. (*b*): Δ_p (—OH) $= 0.100 - 0.013n$
n = carbon number of compound. For branched alcohols, an effective carbon number can be determined by interpolation between the normal alcohol of the same carbon number and the immediately lower normal alcohol using normal boiling points. (See Example 1.)

TABLE 2-384 Nokay Equation

Type compound	*A*	*B*	*C*
Paraffin	1.35940	0.43684	0.56224
Naphthene	0.65812	−0.07165	0.81196
Olefin	1.09534	0.27749	0.65563
Acetylene	0.74673	0.30381	0.79987
Diolefin	0.1384	−0.39618	0.99481
Aromatic	1.0615	0.22732	0.66929

Example 1 Estimate the critical temperature and critical pressure of 2-butanol using the Ambrose method, Eqs. (2-1) and (2-6). The experimental normal boiling point is 372.7 K.

$$T_c = T_b\left[1 + \frac{1}{1.242 + \sum \Delta_T - 0.023\Delta\ (\text{Platt no.})}\right]$$

$$P_c = \frac{0.101325M}{[0.339 + \sum \Delta_P - 0.026\Delta\ (\text{Platt no.})]^2}$$

Determine group contributions from Table 2-383 for a structure $CH_3CHOHCH_2CH_3$:

Group	Number of groups	Δ_T	Δ_P
$-CH_3$	2	0.138	0.2260
$>CH_2$	1	0.138	0.2260
$>CH^-$	1	0.095	0.2200
$-OH$	1	(a)	(b)

$\Delta_T°(\text{—OH}) = 0.87 - 0.11(n) + 0.003\,n^2 = 0.558$
$\Delta_p°(\text{—OH}) = 0.100 - 0.013(n) = 0.0597$

To determine n, the normal boiling points of 1-propanol (370.3 K) and 1-butanol (390.9 K) are required:

$$n = 3 + \left(\frac{372.7 - 370.3}{390.9 - 370.3}\right)(4 - 3) = 3.1$$

The Platt number of the compound is determined by substituting a CH_3 group for the OH.

$$CH_3\text{—}CH(CH_3) - CH_2CH_3,\ \text{Platt no.} = 2$$

The Platt number of the n-alkane of the same carbon number is 5 − 3 = 2. Thus, Δ(Platt no.) = 2 − 2 = 0. Therefore:

$$\sum \Delta_T = 2(.138) + .138 + .095 + .558 = 1.067$$

$$T_c = 372.7\left[1 + \frac{1}{1.242 + 1.067 - 0}\right]$$

$$T_c = 534.1\ \text{K}$$

An accurate experimental value is 536.05 K.

$$\sum \Delta_P = 2(.226) + .226 + .220 + .0597 = 0.9577$$

$$P_c = \frac{.101325(74.12)}{(.339 + .9577 - 0)^2}$$

$$P_c = 4.467\ \text{MPa}$$

An accurate experimental value is 4.179 MPa.

For **pure nonhydrocarbon organics,** the simplest accurate method for prediction of critical pressure is the method of Lydersen.[63] Equation (2-7) requires the molecular weight (M) and the molecular structure of the compound.

$$P_c = \frac{0.101325M}{(0.34 + \sum \Delta_P)^2} \tag{2-7}$$

P_c is the critical pressure, MPa. Values of Δ_P from Table 2-385 are summed to yield $\sum \Delta_P$. The average error in P_c is about 0.2 MPa when tested on compounds ranging in carbon number from C_1 to C_{10}.

Example 2 Estimate the critical temperature and critical pressure of 2-butanol, which has an experimental normal boiling point of 372.7 K. Use the Lydersen method, Eqs. (2-3) and (2-7).

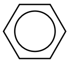
The structure of 2-butanol is $CH_3CHOHCH_2CH_3$. Determine group contributions from Table 2-385.

Group	Number of groups	Δ_T	Δ_P
$-CH_3$	2	0.020	0.227
$-CH_2-$	1	0.020	0.227
$-\underset{\vert}{CH}-$	1	0.012	0.210
$-OH$	1	0.082	0.06
		$\sum$ 0.154	0.951

$$T_c = \frac{T_b}{0.567 + \sum \Delta_T - (\sum \Delta_T)^2} = \frac{372.7}{.567 + .154 - (.154)^2}$$

$$T_c = 534.5\ \text{K}$$

TABLE 2-385 Group Increments for the Lydersen Method

Group description	Incremental contributions		
	Δ_T	Δ_P	Δ_V
Nonring Elements			
$-CH_3$, $-CH_2-$	0.020	0.227	0.055
$-\underset{\vert}{CH}-$	0.012	0.210	0.051
$-\overset{\vert}{\underset{\vert}{C}}-$	0.00	0.210	0.041
$=CH_2$, $=\overset{\vert}{CH}$	0.018	0.198	0.045
$=\overset{\vert}{C}-$, $=C=$	0.00	0.198	0.036
$\equiv CH$, $\equiv C-$	0.005	0.153	(0.036)
Ring Increments			
$-CH_2-$	0.013	0.184	0.0445
$-\overset{\vert}{\underset{\vert}{CH}}$	0.012	0.192	0.046
$-\overset{\vert}{\underset{\vert}{C}}-$	(–0.007)	0.154	(0.031)
$=\overset{\vert}{C}-$, $=C=$	0.011	0.154	0.036
$=\underset{\vert}{CH}$	0.011	0.154	0.037
	0.066	0.924	
Oxygen Increments			
$-OH$ (alcohols)	0.082	0.06	(0.018)
$-OH$ (phenols)	0.031	(–0.02)	(0.003)
$-O-$ (nonring)	0.021	0.16	0.020
$-O-$ (ring)	(0.014)	(0.12)	(0.008)
$-\overset{\vert}{C}=O$ (nonring)	0.040	0.29	0.060
$-\overset{\vert}{C}=O$ (ring)	(0.033)	(0.2)	(0.050)
$\underset{\vert}{H}C=O$ (aldehyde)	0.048	0.33	0.073
Oxygen Increments (*Cont.*)			
$-COOH$ (acid)	0.085	(0.4)	0.080
$-COO-$ (ester)	0.047	0.47	0.080
$=O$ (except for combinations above)	(0.02)	(0.12)	(0.011)
Halogen Increments			
$-F$	0.018	0.224	0.018
$-Cl$	0.017	0.320	0.049
$-Br$	0.010	(0.50)	(0.070)
$-I$	0.012	(0.83)	(0.095)
Nitrogen Increments			
$-NH_2$	0.031	0.095	0.028
$-\overset{\vert}{N}H$ (nonring)	0.031	0.135	(0.037)
$-\overset{\vert}{N}H$ (ring)	(0.024)	(0.09)	(0.027)
$-\overset{\vert}{N}-$ (nonring)	0.014	0.17	(0.042)
$-\overset{\vert}{N}-$ (ring)	(0.007)	(0.13)	(0.032)
$-CN$	(0.060)	(0.36)	(0.080)
$-NO_2$	(0.055)	(0.42)	(0.078)
Sulfur Increments			
$-SH$	0.015	0.27	0.055
$-S-$ (nonring)	0.015	0.27	0.055
$-S-$ (ring)	(0.008)	(0.24)	(0.045)
$=S$	(0.003)	(0.24)	(0.047)
Organometallic Increments			
$-\overset{\vert}{\underset{\vert}{Si}}-$	0.026	0.468	—
$-\overset{\vert}{\underset{\vert}{Si}}H$	0.040	0.513	—
$-SiH_3$	0.027	—	—
$-\overset{\vert}{\underset{\vert}{Si}}-O-$	0.025	0.730	—
$\left[-\overset{\vert}{\underset{\vert}{Si}}-O-\right]$ *cyclic*	0.027	0.668	—

Values in parentheses are based on too few experimental points to be reliable.

The accurate experimental critical temperature is 536.05 K.

$$P_c = \frac{0.101325M}{(0.34 + \sum \Delta_P)^2} = \frac{(0.101325)(74.12)}{(0.34 + 0.951)^2}$$

$$P_c = 4.506 \text{ MPa}$$

The accurate experimental critical pressure is 4.179 MPa. No known method is available to predict the critical pressure of inorganic compounds.

For both **hydrocarbon** and **nonhydrocarbon organic defined mixtures,** the method of Kreglewski and Kay[52] is recommended. The critical temperature, critical pressure, and acentric factor of each compound and the critical temperature of the mixture must be known or predicted from the methods of this section.

$$P_{cm} = P_{pc} + P_{pc}\left[5.808 + 4.93\left(\sum_{i=1}^{n} x_i\omega_i\right)\right]\left[\frac{T_{cm} - T_{pc}}{T_{pc}}\right] \tag{2-8}$$

Use of Eq. (2-8) requires the pseudocritical properties defined by Eqs. (2-9) and (2-10)

$$T_{pc} = \sum_{i=1}^{n} x_i T_{c_i} \tag{2-9}$$

$$P_{pc} = \sum_{i=1}^{n} x_i P_{c_i} \tag{2-10}$$

Each component *i* of the mixture must have available its T_c, P_c, and ω. T_{cm} can be predicted from Eq. (2-5). For hydrocarbon systems, average errors in predicted critical pressures are about 0.2 MPa, except when organic gases are present and errors are unacceptably large. Errors for nonhydrocarbon organics not including inorganic gases average 0.5 MPa.

Critical Volume The critical volume of a compound is the volume occupied by a set mass of a compound at its critical temperature and pressure. While useful in itself, the critical volume is extensively used in equations for estimating volumetric fractions.

For **pure hydrocarbons,** two methods are quite accurate. The Ambrose[2] method used for T_c and P_c is also used for critical volume. Eq. (2-11) only requires the molecular structure of the compound.

$$V_c = 10^{-3}(40 + \sum \Delta_V) \tag{2-11}$$

V_c is the critical volume, m^3/kmole. Values of Δ_V are given in Table 2-383.

The average error for hydrocarbons of twelve or less carbon atoms is about 0.01 m^3/kmole.

The Riedel method[90] requires the critical temperature (T_c), critical pressure (P_c), and acentric factor (ω) of the compound as given by Eqs. (2-12) and (2-13). If the gas constant is in Pa·m^3/kmole·K, the critical volume will be in m^3/kmole.

$$V_c = \frac{RT_c}{P_c[3.72 + 0.26(\alpha - 7.00)]} \tag{2-12}$$

$$\alpha = 5.811 + 4.919\omega \tag{2-13}$$

The average error for paraffins up to C_{18} and other hydrocarbon families up to C_{11} is about 0.015 m^3/kmole. If estimated values of T_c and P_c are used, errors may be higher.

For **pure nonhydrocarbon organics,** the method of Fedors,[29] which requires only molecular structure, is the most accurate. Equation (2-14) shows the method to depend only on the molecular structure. The resulting V_c will be in m^3/kmole.

$$V_c = 0.0266 + \sum \Delta_V \tag{2-14}$$

Values for Δ_V are given in Table 2-386. The average error for compounds up to C_7 is about 0.007 m^3/kmole, although a maximum error of 0.03 m^3/kmole has been noted. No experimental data above C_7 are available for comparison.

Example 3 Estimate the critical volume of 2-butanol. Use the method of Fedors, Eq. (2-14).

$$V_c = 0.0266 + \sum \Delta_V$$

The molecular formula is $C_4H_{10}O$. Using the atomic contribution values from Table 2-386.

$$\sum \Delta_V = 4(.034426) + 10(.009172) + 1(.018000)$$

$$\sum \Delta_V = 0.2474$$

$$V_c = 0.0266 + 0.2474 = 0.2740 \text{ m}^3/\text{kmole}$$

The accurate experimental critical volume is 0.2690 m^3/kmole.

TABLE 2-386 Atomic and Structural Contributions for the Fedors Method

Atomic increments		Structural increments	
Atom	Δ_V	Feature	Δ_V
C	0.034426	Cl	0.052801
H	0.009172	Br	0.071774
O	0.020291	I	0.096402
O (alcohols)	0.018000	S	0.050866
N	0.048855	3-membered ring	–0.105824
N (amines)	0.047422	4-membered ring	–0.017247
F	0.022242	5-membered ring	–0.039126
		6-membered ring	–0.039508
Si	0.086174	double bond	+0.005028
$Si_{siloxane}$	0.126483	triple bond	+0.000797
$Si_{cyclic\ siloxane}$	0.126483	ring attached directly to another ring	+0.035524

The method of Lydersen[63] may also be used for prediction of critical volume, but it is not so accurate as the method of Fedors. Equation (2-15) depends only on molecular structure and gives a critical volume in m^3/kmole.

$$V_c = 0.040 + \sum \Delta_V \tag{2-15}$$

Group contributions for Δ_V are given in Table 2-385. Errors average about 0.01 m^3/kmole.

There is no known method for predicting the critical volume of inorganic compounds.

For both **hydrocarbon** and **nonhydrocarbon organic defined mixtures,** the method of Chueh and Prausnitz[19] is useful. For hydrocarbon systems, the mixing rule is shown by Eq. (2-16) for binaries and by Eq. (2-17) for multicomponents. Equations (2-18) through (2-20) give the input parameters. The mixture critical volume V_{cm} is a function of the pure component critical volumes. The constant *C* is zero for hydrocarbon systems and 0.1559 for systems containing a nonhydrocarbon gas.

$$V_{cm} = \phi_1 V_{c1} + \phi_2 V_{c2} + 2\phi_1\phi_2\nu_{12} \tag{2-16}$$

$$V_{cm} = \sum_{i}^{n}\sum_{j}^{n} \phi_i\phi_j\nu_{ij} \qquad (i \neq j) \tag{2-17}$$

$$\phi_j = \frac{x_j V_{cj}^{2/3}}{\sum_{i=1}^{n} x_i V_{ci}^{2/3}} \tag{2-18}$$

$$\nu_{ij} = \frac{V_{ij}(V_{ci} + V_{cj})}{2.0} \tag{2-19}$$

$$V_{ij} = -1.4684\left(\left|\frac{V_{ci} - V_{cj}}{V_{ci} + V_{cj}}\right|\right) + C \tag{2-20}$$

Errors average about 10 percent for systems containing hydrocarbons.

Systems containing only organics or organics and gases may give very high errors. A specialized modification of the method (Chueh and Prausnitz[18]) is available for binary mixtures containing organics but may give errors over 20 percent.

Critical Compressibility Factor The critical compressibility factor of a compound is calculated from the experimental or predicted values of the critical properties by the definition, Eq. (2-21).

$$Z_c = \frac{P_c V_c}{RT_c} \tag{2-21}$$

Critical compressibility factors are used as characterization parameters in corresponding states methods (especially those of Lydersen) to predict volumetric and thermal properties. The factor varies from about 0.23 for water to 0.26–0.28 for most hydrocarbons to slightly above 0.30 for light gases.

Normal Freezing Temperature (Melting Point) The melting point is the temperature at which melting occurs at atmospheric pressure. In most cases, measurements are made in air, making values slightly lower than if the measurements were made in vacuum. Impurities can cause a substantial decrease in the measured melting point. The melting point is very slightly higher than the triple point temperature—the temperature at which equilibrium exists between solid, liquid, and vapor—for a pure compound. For practical purposes, the two temperatures are equal. Reliable methods for predicting melting points have not until recently been advanced. Constantinou and

Gani[20] derived a group contribution method that shows promise. Initial evaluations show average errors of 5 to 10 percent (10–30 K) on a wide variety of compounds, but larger errors can occur. It is recommended that several compounds of known melting point in the same or a similar family be predicted in order to estimate the probable error.

Normal Boiling Temperature The normal boiling temperature (point) is the temperature at which the vapor pressure equals exactly 101,325 Pa (1 atmosphere). Caution should be taken in using values from older references, where the temperature may be reported for the prevailing pressure (0.95–0.97 atm) rather than at 1 atmosphere. If at least two values of vapor pressure very close to 1 atmosphere are available, the normal boiling point can be interpolated or extrapolated on a plot of log P^{sat} vs. $1/T$. The section on vapor pressure discusses this in more detail.

Various methods are available for estimation of the normal boiling point of organic compounds. Lyman et al.[64] review and give calculational procedures for the methods of Meissner, Miller, and Lydersen/Forman-Thodos. A more recent method that has been determined to be more accurate is the method of Pailhes,[80] which requires one experimental vapor pressure point and Lydersen group contributions for critical temperature and critical pressure (Table 2-385).

$$T_b = T\,\frac{\log P_c + (1-\Theta)\log(1/p)}{\log P_c} \tag{2-22}$$

where T and p = the one low pressure vapor pressure point, in K and atm, respectively
$\Theta = T_c/T_b$ calculated from Eq. (2-3) using Lydersen contributions
P_c = critical pressure calculated from Eq. (2-7) using Lydersen contributions

A recent study of the method on a wide variety of complex organics shows an overall average error of less than 2 percent (~10 K). If no vapor pressure point is available, the new group contribution method of Constantinou and Gani[20] discussed under the section on melting point gives an overall average error of about 4 percent (~20 K) and may be useful. The method of Miller (Lyman et al.[64]), which requires only the molecular structure, has also been found to be relatively accurate for organics.

Example 4 Estimate the normal boiling point of 2-butanol. One vapor pressure point of 0.802 psia at 100°F is available.

Use the Pailhes method, Eq. (2-22).

$$T_B = T\,\frac{\log P_c + (1-\theta)\log(1/p)}{\log P_c}$$

From Example 2, $P_c = 4.506$ MPa; $\theta = T_c/T_b = 1.434$; $T = 100°\text{F} = 310.9$ K; and $p = 0.802$ psia $= 5528$ Pa.

$$T_b = (310.9)\,\frac{\log(4.506\times10^6) + (1-1.434)\log(1/5528)}{\log(4.506\times10^6)}$$

$$T_b = (310.9)(1.244) = 386.8\text{ K}$$

An accepted experimental normal boiling point is 372.7 K.

Note the error here is 3.8 percent, a value above the average. If the vapor pressure point available would have been closer to one atmosphere, the error would have been much lower.

Acentric Factor The acentric factor of a compound (ω) is primarily a measure of the shape of a molecule, though it also measures a molecule's polarity. It is calculated from the reduced vapor pressure (P_r^{sat}) at a reduced temperature of 0.7 by the definition, Eq. (2-23).

$$\omega = -\log\,(P_r^{\text{sat}})_{T_r=0.7} - 1.000 \tag{2-23}$$

Critical temperature and pressure are required and can be estimated from the methods of this section. Vapor pressure is predicted by the methods of the next section. Experimental values should be used if available. The acentric factor is used as a third parameter with T_c and P_c in Pitzer-type corresponding states methods to predict volumetric properties and in cubic equations of state such as the Redlich-Kwong-Soave and Peng-Robinson equations. For simple spherical molecules, the acentric factor is essentially zero, rising as branching and molecular weight increases. For compounds of similar size and shape the acentric factor increases slightly with increasing polarity.

For mixtures, the acentric factor is usually taken as a simple molar average value of the n components of the mixture.

$$\omega = \sum_{i=1}^{n} x_i\omega_i \tag{2-24}$$

Miscellaneous Characterizing Constants The radius of gyration ($\overline{R}$) is a simultaneous size-shape factor varying with the manner in which mass is distributed about the center of gravity of the molecule. For planar molecules, the radius of gyration is

$$\overline{R} = \sqrt{\frac{(AB)^{1/2}N_A}{M}} \tag{2-25}$$

For three-dimensional molecules, it is

$$\overline{R} = \sqrt{\frac{(ABC)^{1/3}2\pi N_A}{M}} \tag{2-26}$$

AB and ABC are the products of the principal moments of inertia. Moments of inertia are calculated from bond angles and bond lengths. Many values are given by Landolt-Bornstein.[53] N_A is Avogadro's number, and M is the molecular weight of the molecule. Stuper et al.[105] give a computerized method for prediction of the radius of gyration.

The dipole moment (λ) of a molecule is the first moment of the electric charge density of a molecule. Paraffins have dipole moments of zero, while dipole moments of almost all hydrocarbons are small. McClellan[68] lists many dipole moments. The computer method of Dixon and Jurs[27] is the most useful method for predicting dipole moments. Lyman et al.[64] give other methods of calculation.

The van der Waals volume and area are characterizing parameters relating molecular configurations. Bondi[8] describes group contribution methods for their calculation.

VAPOR PRESSURE

Vapor pressure is the most important of the basic thermodynamic properties affecting liquids and vapors. The vapor pressure is the pressure exerted by a pure component at equilibrium at any temperature when both liquid and vapor phases exist and thus extends from a minimum at the triple point temperature to a maximum at the critical temperature, the critical pressure. This section briefly reviews methods for both correlating vapor pressure data and for predicting vapor pressure of pure compounds. Except at very high total pressures (above about 10 MPa), there is no effect of total pressure on vapor pressure. If such an effect is present, a correction, the Poynting correction, can be applied. The pressure exerted above a solid-vapor mixture may also be called vapor pressure but is normally only available as experimental data for common compounds that sublime.

Correlation Methods Vapor pressure is correlated as a function of temperature by numerous methods mainly derived from the Clapeyron equation discussed in the section on enthalpy of vaporization. The classic simple equation used for correlation of low to moderate vapor pressures is the Antoine[4] equation (2-27).

$$\ln P^{\text{sat}} = A + \frac{B}{T+C} \tag{2-27}$$

A, B, and C are regression constants for the specific compound.

The Antoine equation does not fit data accurately much above the normal boiling point. Thus, as regression by computer is now standard, more accurate expressions applicable to the critical point have become usable. The entire DIPPR Compilation[24] is regressed with the modified Riedel[89] equation (2-28) with constants available for over 1500 compounds.

$$\ln P^{\text{sat}} = A + \frac{B}{T} + C\ln T + DT^E \tag{2-28}$$

A, B, C, and D are regression constants and E is an exponent equal to 1, 2, or 6 depending on which regression gives the most accurate fit of the data.

For purposes of the *API Technical Data Book* (Daubert and Danner[23]), another modified Riedel equation (2-29) was chosen and found to fit hydrocarbon data well over the entire pressure range. Coefficients are given for several hundred hydrocarbons.

$$\ln P^{sat} = A + \frac{B}{T} + C \ln T + DT^2 + \frac{E}{T^2} \tag{2-29}$$

Both equations (2-28) and (2-29) are also extrapolatable above the critical temperature where necessary for thermodynamic calculations.

The other modern equation used for correlation is the modified and linearized Wagner[124] equation (2-30), which has the advantage that it will match critical data exactly, although it cannot be extrapolated above the critical point. The equation is also included with coefficients to several hundred compounds in the *Technical Data Book—Petroleum Refining.*

$$\ln P_r = aX_1 + bX_2 + cX_3 + dX_4 \tag{2-30}$$

where $$X_1 = \frac{1 - T_r}{T_r},\ X_2 = \frac{(1 - T_r)^{1.5}}{T_r},\ X_3 = \frac{(1 - T_r)^{2.6}}{T_r},\ X_4 = \frac{(1 - T_r)^5}{T_r}$$

$$P_r = P^{sat}/P_c \qquad T_r = T^{sat}/T_c$$

Both Riedel and Wagner regressions usually fit data within a few tenths of a percent over the entire range between the triple point and the critical point.

Prediction Methods Two methods have gained almost universal acceptance for prediction of the vapor pressure of **pure hydrocarbons.**

The method of Lee and Kesler[55] is the preferred method if the critical temperature and the critical pressure of the hydrocarbon is known or can be reasonably predicted by the methods of the first section. The corresponding states method is shown in equation (2-31) with the simple fluid and correction terms to be calculated from equations (2-32) and (2-33), respectively, for any T_r.

$$\ln P_r^{sat} = (\ln P_r^{sat})^{(0)} + \omega(\ln P_r^{sat})^{(1)} \tag{2-31}$$

$$(\ln P_r^{sat})^{(0)} = 5.92714 - 6.09648/T_r - 1.28862 \ln T_r + 0.169347T_r^6 \tag{2-32}$$

$$(\ln P_r^{sat})^{(1)} = 15.2518 - 15.6875/T_r - 13.4721 \ln T_r + 0.43577T_r^6 \tag{2-33}$$

The method is applicable at reduced temperatures above 0.30 or the freezing point, whichever is higher, and below the critical point. The method is most reliable when $0.5 < T_r < 0.95$, where errors in prediction average 3.5 percent when experimental critical properties are known. Errors are higher for predicted criticals. The method is useful when solved iteratively with Eq. (2-23) to predict the acentric factor.

Example 5 Estimate the vapor pressure of 1-butene at 98°C. Use Eq. (2-31):

$$\ln P_r^{sat} = (\ln P_r^{sat})^{(0)} + \omega(\ln P_r^{sat})^{(1)}$$

Pure component properties of 1-butene are $T_c = 146.4°C$, $P_c = 4.02$ MPa, and $\omega = 0.1867$.

$$T_r = \frac{371.1}{419.5} = 0.885$$

From Eq. (2-32): $(\ln P_r^{sat})^{(0)} = -0.7227$

From Eq. (2-33): $(\ln P_r^{sat})^{(1)} = -0.6190$

$$\ln P_r^{sat} = -.7227 + (.1867)(-0.6190)$$

$$\ln P_r^{sat} = -0.8383$$

$$P_r^{sat} = 0.4325$$

$$P^{sat} = P_r^{sat}P_c = (.4325)(4.02) = 1.74 \text{ MPa}$$

An experimental value is 1.72 MPa.

When criticals cannot be estimated with reasonable accuracy, the method of Maxwell and Bonnell[67] is recommended. The normal boiling point and the specific gravity at 60°F (15.5°C) are required inputs. According to what vapor pressure range is expected, the vapor pressure is calculated from Eqs. (2-34), (2-35), or (2-36). If the wrong range is selected, the procedure will need to be repeated.

For $X > 0.0022$ ($P^{sat} < 2$ mm Hg):

$$\log P^{sat} = \frac{3000.538X - 6.761560}{43X - 0.987672} \tag{2-34}$$

For $0.0013 \le X \le 0.0022$ (2 mm Hg $\le P^{sat} \le$ 760 mm Hg):

$$\log P^{sat} = \frac{2663.129X - 5.994296}{95.76X - 0.972546} \tag{2-35}$$

For $X < 0.0013$ ($P^{sat} > 760$ mm Hg):

$$\log P^{sat} = \frac{2770.085X - 6.412631}{36X - 0.989679} \tag{2-36}$$

X is calculated from Eq. (2-37) and T'_b is calculated from Eq. (2-38). Iterative calculation may be required.

$$X = \frac{\dfrac{T'_b}{T} - 0.0002867(T'_b)}{748.1 - 0.2145(T'_b)} \tag{2-37}$$

$$T_b - T'_b = 2.5f(K - 12) \log \frac{P^{sat}}{760} \tag{2-38}$$

where T_b = normal boiling point, °R

T'_b = normal boiling point corrected to $K = 12$, °R

T = absolute temperature, °R

f = correction factor. For all subatmospheric vapor pressures and for all substances having normal boiling points greater than 400°F, $f = 1$. For substances having normal boiling points less than 200°F, $f = 0$. For superatmospheric vapor pressures of substances having normal boiling points between 200°F and 400°F, f is given by $(T_b - 659.7)/200$

K = Watson characterization factor, $T_b^{1/3}$/sp gr

Evaluation of the method for pure hydrocarbons shows errors averaging 8 percent for vapor pressures above 1 mm Hg and 30 percent below 1 mm Hg. The method is also usable for narrow boiling (range up to 50°F) **undefined hydrocarbon mixtures** with the only change being that the mean average boiling point replaces the normal boiling point in all calculations.

Example 6 Estimate the vapor pressure of tetralin at 150°C (302°F). Its normal boiling point is 207.6°C (405.7°F) and its Watson characterization factor is 9.78.

Use the Maxwell-Bonnell method, Eq. (2-35).

$$\log P^{sat} = \frac{2663.129X - 5.994296}{95.76X - 0.972546}$$

At 150°C with a normal boiling point of 207.6°C, a vapor pressure between 2 and 760 mm Hg would be expected.

Assume $T'_b = T_b = 405.7°F$ as a first trial. From Eq. (2-37):

$$X = \frac{(865.7/762) - 0.0002867(865.7)}{748.1 - 0.2145(865.7)}$$

$$X = 0.001579$$

$$\log P^{sat} = \frac{2663.129(0.001579) - 5.994296}{95.76(0.001579) - 0.972546} = 2.179$$

$$P^{sat} = 151.0 \text{ mm Hg}$$

Use Eq. (2-38) to calculate the correction.

$$T_b - T'_b = 2.5f(K - 12) \log \frac{P^{sat}}{760} = 2.5(1)(9.48 - 12) \log \frac{151}{760}$$

$$T_b - T'_b = 4.4°$$

Thus, for the second trial, $T'_b = 405.7 - 4.4 = 401.3°F$.

Using Eq. (2-37), recalculate X.

$$X = \frac{(861.3/762) - 0.0002867(861.3)}{748.1 - 0.2145(861.3)} = 0.001568$$

From Eq. (2-35), $\log P^{sat} = 2.214$; $P^{sat} = 163.7$ mm Hg. Use Eq. (2-38) to recalculate the correction.

$$T_b - T'_b = 2.5(1)(9.48 - 12) \log \frac{163.7}{760} = 4.2°$$

Thus, $T'_b = 401.5°F$. If greater accuracy is desired, carry out a third trial. (An experimental vapor pressure is 161.8 mm Hg.)

For **nonhydrocarbon organics,** vapor pressures above 15 kPa for compounds of known or estimable normal boiling point are predicted using the method of Riedel[89] given by Eq. (2-39).

$$\log P_r^\circ = \phi(T_r) - (\alpha - 7)\psi(T_r) \tag{2-39}$$

Correlation functions $\phi(T_r)$, $\psi(T_r)$, and $\zeta(T_r)$ are given by Eqs. (2-40), (2-41), and (2-42), respectively.

$$\phi(T_r) = 0.118\zeta(T_r) - 7\log_{10} T_r \tag{2-40}$$

$$\psi(T_r) = 0.0364\zeta(T_r) - \log_{10} T_r \tag{2-41}$$

$$\zeta(T_r) = 36/T_r + 96.7\log_{10} T_r - 35 - T_r^6 \tag{2-42}$$

The Riedel α is calculated from Eq. (2-43).

$$\alpha = \frac{0.136\zeta(T_{r_b}) + \log_{10} P_c - 5.01}{0.0364\zeta(T_{r_b}) - \log_{10} T_{r_b}} \tag{2-43}$$

Critical properties, if not available, can be estimated from the methods of the previous section. T_r is the reduced temperature at the temperature of interest, while T_{r_b} is the reduced temperature at the normal boiling point.

The method is accurate within 2 to 3 percent above 15 kPa, while errors increase to 10–30 percent at lower pressures. Care should be taken not to use the method below the freezing point temperature.

Example 7 Estimate the vapor pressure of thiophene at 500 K. Pure component properties are $T_c = 579.4$ K, $P_c = 5.694$ MPa, and $T_b = 357.5$ K. Use the Riedel method, Eq. (2-39).

$$\log P_r^{\text{sat}} = -\phi(T_r) - (\alpha - 7)\,\psi\,(T_r)$$

$$T_{r_b} = \frac{357.5}{579.4} = 0.6170 \qquad T_r = \frac{500}{579.4} = 0.8629$$

From Eq. (2-42):

$$\zeta(T_{r_b}) = \frac{(36)}{(0.6170)} + 96.7\log(0.6170) - 35 - (0.6170)^6 = 3.01$$

From Eq. (2-43):

$$\alpha = \frac{0.136(3.01) + \log(5.694 \times 10^6) - 5.01}{(0.0364)(3.01) - \log(0.6170)}$$

$$\alpha = 6.749$$

From Eq. (2-42), calculate $\zeta(T_r)$ and then calculate $\phi(T_r)$ and $\psi(T_r)$ from Eqs. (2-40) and (2-41).

$$\log P_r^{\text{sat}} = -0.461 - (6.749 - 7)(0.068)$$

$$\log P_r^{\text{sat}} = -0.444$$

$$P_r^{\text{sat}} = 0.3598$$

$$P^{\text{sat}} = P_r^{\text{sat}} P_c = (.3598)(5.694) = 2.049 \text{ MPa}$$

An experimental value is 2.037 MPa.

For **nonhydrocarbon organics** for which normal boiling points are unknown or expected vapor pressures are below 15 kPa, the reference substance method of Othmer and Yu[78] as given by Eq. (2-44) is recommended.

$$\log P^{\text{sat}} = m \log P_w^{\text{sat}} + C \tag{2-44}$$

The vapor pressure of water P_w^{sat} may be calculated by Eq. (2-45).

$$\log P_w^{\text{sat}} = 31.51 - \frac{3.1298 \times 10^3}{T} - 7.1385 \log T + 1.757 \times 10^{-6} T^2 \tag{2-45}$$

with temperatures in K and vapor pressures in Pa.

Values of the compound specific constants m and c were originally derived by Othmer et al. and greatly expanded to over 600 common organics by Danner and Daubert.[22] If constants are not available but any two vapor pressure data points are available, the constants m and C can be calculated using Eqs. (2-46) and (2-47).

$$m = \frac{\log P_1^{\text{sat}} - \log P_2^{\text{sat}}}{\log P_{w_1}^{\text{sat}} - \log P_{w_2}^{\text{sat}}} \tag{2-46}$$

$$C = \log P_1^{\text{sat}} - m \log P_{w_1}^{\text{sat}} \tag{2-47}$$

where the subscripts 1 and 2 refer to the two reference temperatures T_1 and T_2.

Average errors at low pressures for compounds with tabulated m and C are within a few percent. When values of m and C are calculated from only two vapor pressure points, the method should be used only for interpolation and limited extrapolation. The method is usable from about 220 K (so long as it is above the freezing point of the compound) to the critical point of water (about 647 K).

Example 8 Estimate the vapor pressure of acetaldehyde at 0°C. Two vapor pressure points are 20.0 kPa at 256.55 K and 107.6 kPa at 294.85 K.

Use Eq. (2-44), determining parameters from Eqs. (2-45), (2-46), and (2-47).

$$\log P^{\text{sat}} = m \log Pw^{\text{sat}} + C$$

$$\text{at } T_1 = 256.55 \text{ K}, P_1^{\text{sat}} = 2.00 \times 10^4 \text{ Pa}, \log P_1^{\text{sat}} = 4.3010$$

$$\text{at } T_2 = 294.95 \text{ K}, P_2^{\text{sat}} = 1.067 \times 10^5 \text{ Pa}, \log P_2^{\text{sat}} = 5.0282$$

Use Eq. (2-45) to calculate the vapor pressure of water at T_1 and T_2.

$$\log P_{\omega_1}^{\text{sat}} = 2.2282, \quad P_{\omega_1}^{\text{sat}} = 169.12 \text{ Pa}$$

$$\log P_{\omega_2}^{\text{sat}} = 3.4213, \quad P_{\omega_2}^{\text{sat}} = 2637.9 \text{ Pa}$$

From Eq. (2-46):

$$m = \frac{\log P_1^{\text{sat}} - \log \mathrm{P}_2^{\text{sat}}}{\log P_{w_1}^{\text{sat}} - \log \mathrm{P}_{w_2}^{\text{sat}}} = \frac{4.3010 - 5.0282}{2.2282 - 3.4213} = 0.6093$$

From Eq. (2-47):

$$C = \log P_1^{\text{sat}} - m \log P_{w_1}^{\text{sat}} = 4.3010 - 0.6093(2.2282)$$

$$C = 2.9434$$

at $T = 273.15$ K (0°C)

$$\log P_w^{\text{sat}} = 31.51 - \frac{3129.8}{273.15} - 7.1385 \log 273.15 + 1.757 \times 10^{-6}(273.15)^2$$

$$\log P_w^{\text{sat}} = 2.7907$$

$$\log P^{\text{sat}} = (0.6093)(2.7907) + 2.9434$$

$$\log P^{\text{sat}} = 4.6438$$

$$P^{\text{sat}} = 44{,}030 \text{ Pa} = 44.0 \text{ kPa}$$

IDEAL GAS THERMAL PROPERTIES

A substance is in the ideal gas state when the volume of its molecules is a zero fraction of the total volume taken up by the substance and when the individual molecules are far enough apart from each other so that there is no interaction between them. Although this only occurs at infinite volume and zero pressure, in practice, ideal gas properties can be used for gases up to a pressure of two atmospheres with little loss of accuracy. Thermal properties of ideal gas mixtures may be obtained by mole-fraction averaging the pure component values.

Heat Capacity, C_p^o Heat capacity is defined as the amount of energy required to change the temperature of a unit mass or mole one degree; typical units are J/kg·K or J/kmol·K. There are many sources of ideal gas heat capacities in the literature; e.g., Daubert et al.,[24] Daubert and Danner,[23] JANAF thermochemical tables,[15] TRC thermodynamic tables,[115,116] and Stull et al.[104] If C_p^o values are not in the preceding sources, there are several estimation techniques that require only the molecular structure. The methods of Thinh et al.[113] and Benson et al.[6,7] are the most accurate but are also somewhat complicated to use. The equation of Harrison and Seaton[36] for C_p^o between 300 and 1500 K is almost as accurate and easy to use:

$$C_p^o = a_1 + a_2\mathrm{C} + a_3\mathrm{H} + a_4\mathrm{O} + a_5\mathrm{N} + a_6\mathrm{S} + a_7\mathrm{F} + a_8\mathrm{Cl} + a_9\mathrm{I} + a_{10}\mathrm{Br} + a_{11}\mathrm{Si} + a_{12}\mathrm{Al} + a_{13}\mathrm{B} + a_{14}\mathrm{P} + a_{15}\mathrm{E} \tag{2-48}$$

where C_p^o = ideal gas heat capacity, J/mol K
a_1–a_{15} = constant parameters obtained from Table 2-387 as a function of temperature
C = number of carbon atoms in the molecule
H = number of hydrogen atoms in the molecule
O = number of oxygen atoms in the molecule
N = number of nitrogen atoms in the molecule
S = number of sulfur atoms in the molecule
F = number of fluorine atoms in the molecule
Cl = number of chlorine atoms in the molecule
I = number of iodine atoms in the molecule
Br = number of bromine atoms in the molecule
Si = number of silicon atoms in the molecule
Al = number of aluminum atoms in the molecule
B = number of boron atoms in the molecule
P = number of phosphorus atoms in the molecule
E = number of atoms in the molecule excluding the 13 atom-types listed above

TABLE 2-387 Values of the Constant Parameters a_1–a_{15} in Eq. (2-48) at Different Temperatures

	Parameter a														
Temp., K	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
300	4.86	9.04	5.69	11.4	11.9	15.3	12.7	16.8	18.7	17.8	14.6	15.8	11.5	18.0	19.5
400	0.864	12.6	7.37	13.9	14.0	17.0	16.2	18.9	20.5	19.9	17.5	18.3	14.7	20.9	20.8
500	−1.85	15.5	8.89	15.7	16.0	19.4	17.9	20.2	22.1	21.2	19.6	20.0	17.0	21.6	21.7
600	−4.61	17.5	10.5	17.5	17.3	20.3	20.1	21.4	23.3	22.4	20.9	21.1	18.3	22.8	22.1
800	−7.49	20.1	13.1	19.4	19.4	22.3	21.5	22.4	25.0	23.4	23.2	22.3	20.8	23.0	23.0
1000	−8.53	21.6	15.2	20.4	20.4	22.9	22.4	22.8	25.4	23.8	23.9	22.8	22.2	23.4	23.3
1500	−7.37	23.9	17.9	20.6	21.1	22.5	22.1	22.6	24.6	23.0	24.1	23.2	24.2	24.2	23.3

Results and parameters may be interpolated between temperatures. Average errors are between 2 and 6 percent, with the higher errors at the lower temperatures.

Example 9 Using Eq. 2-48 to estimate the ideal gas heat capacity of acetone (C_3H_6O) at 600 K:

$$C_p^\circ = -4.61 + (17.5)(3) + (10.5)(6) + (17.5)(1) = 128.39 \text{ J/mol K}$$

Daubert et al.[24] report a value of 121.8 J/mol K.

Enthalpy of Formation The ideal gas standard enthalpy (heat) of formation (ΔH°_{f298}) of a chemical compound is the increment of enthalpy associated with the reaction of forming that compound in the ideal gas state from the constituent elements in their standard states, defined as the existing phase at a temperature of 298.15 K and one atmosphere (101.3 kPa). Sources for data are Refs. 15, 23, 24, 104, 115, and 116. The most accurate, but again complicated, estimation method is that of Benson et al.[6,7] A compromise between complexity and accuracy is based on the additive atomic group-contribution scheme of Joback[44]; his original units of kcal/mol have been converted to kJ/mol by the conversion 1 kcal/mol = 4.1868 kJ/mol:

$$\Delta H^\circ_{f298} = 68.29 + \sum_{i=1}^{n} N_i \, \Delta_{Hi} \tag{2-49}$$

where ΔH°_{f298} = enthalpy of formation at 298.15 K, kJ/mol
n = number of different atomic groups contained in the molecule
N_i = number of atomic groups i contained in the molecule
Δ_{Hi} = numeric value of atomic group i obtained from Table 2-388.

Average expected errors are about 9 kJ/mol.

For **other temperatures:**

$$\Delta H^\circ_{fT} = \Delta H^\circ_{f298} + \int_{298}^{T} C_p^\circ \, dT \tag{2-50}$$

See above for discussion of the ideal gas heat capacity (C_p°).

Example 10 The ΔH°_{f298} of 2-butanol is estimated using Table 2-388. The molecular groups are $2CH_3$, $1CH_2$, 1CH (all nonring), and 1OH (alcohol). Therefore:

$$\Delta H^\circ_{f298} = 68.29 + 2(-76.45) + (-20.64) + (29.89) + (-208.04) = -283.40 \text{ kJ/mol}$$

The value from Daubert et al.[24] is −292.9 kJ/mol.

Gibbs Energy of Formation The ideal gas standard Gibbs energy of formation (ΔG°_{f298}) of a chemical compound is the increment of Gibbs energy associated with the reaction of forming that compound in the ideal gas state from the constituent elements in their standard state defined as the existing phase at a temperature of 298.15 K and one atmosphere (101.325 kPa). Refs. 15, 23, 24, 104, 115, and 116 are good sources of data. The additive atomic group-contribution scheme of Joback[44] may be used to estimate ΔG°_{f298}; his original units of kcal/mol have been converted to kJ/mol by the conversion 1 kcal/mol = 4.1868 kJ/mol:

$$\Delta G^\circ_{f298} = 53.88 + \sum_{i=1}^{n} N_i \, \Delta_{Gi} \tag{2-51}$$

where ΔG°_{f298} = Gibbs energy of formation at 298.15 K, kJ/mol
n = number of different atomic groups contained in the molecule
N_i = number of atomic groups i contained in the molecule
Δ_{Gi} = numeric value of atomic group i obtained from Table 2-388

Average errors of 8 to 9 kJ/mol may be expected.

Example 11 The ΔG°_{f298} of phenol is estimated using Table 2-388. The molecular groups are

$5 \quad =\overset{|}{\mathrm{C}}\mathrm{H}$
$1 \quad =\overset{|}{\mathrm{C}}—$ (both ring)
$1 \quad \mathrm{OH}$ (phenol)

Therefore,

$$\Delta G^\circ_{f298} = 53.88 + 5(11.30) + (54.05) + (-197.37) = -32.94 \text{ kJ/mol}$$

The value from Daubert et al.[24] is −32.64 kJ/mol.

For **other temperatures,** the exact Eq. (2-52) may be used at temperature T (K):

$$\Delta G^\circ_{fT} = \Delta H^\circ_{fT} - T\,\Delta S^\circ_{fT} \tag{2-52}$$

where ΔG°_{fT} = Gibbs energy of formation at T, kJ/mol
ΔH°_{fT} = enthalpy of formation at T, kJ/mol (see above)
ΔS°_{fT} = entropy of formation at T, kJ/mol K (see below)

Entropy of Formation The ideal gas standard entropy of formation (ΔS°_{f298}) of a chemical compound is the increment of entropy associated with the reaction of forming that compound in the ideal gas state from the constituent elements in their standard state defined as the existing phase at a temperature of 298.15 K and one atmosphere (101.325 kPa). Thus:

$$\Delta S^\circ_{f298} = S^\circ_{\text{compound}} - \sum_{i=1}^{n} N_i S^r_{\text{element } i} \tag{2-53}$$

where ΔS°_{f298} = entropy of formation at 298.15 K and 1 atm, J/mol K
$S^\circ_{\text{compound}}$ = ideal gas absolute entropy of the compound at 298.15 K and 1 atm, J/mol K
n = number of different elements contained in the compound
N_i = moles of element i contained in one mole of compound
$S^r_{\text{element } i}$ = absolute entropy of element i in its standard state at 298.15 K and 1 atm, J/mol K.

Ideal gas absolute entropies of many compounds may be found in Daubert et al.,[24] Daubert and Danner,[23] JANAF Thermochemical Tables,[15] TRC Thermodynamic Tables,[115,116] and Stull et al.[104] Otherwise, the estimation method of Benson et al.[6,7] is reasonably accurate, with average errors of 1–2 J/mol K. Elemental standard-state absolute entropies may be found in Cox et al.[21] Values from this source for some common elements are listed in Table 2-389. ΔS°_{f298} may also be calculated from Eq. (2-52) if values for ΔH°_{f298} and ΔG°_{f298} are known.

TABLE 2-388 Atomic Group Contributions to Estimate ΔH°_{f298} and ΔG°_{f298}

	Δ_H	Δ_G
Nonring Increments		
$-\mathrm{CH_3}$	–76.45	–43.96
$-\mathrm{CH_2}-$	–20.64	8.42
$-\underset{\vert}{\overset{\vert}{\mathrm{CH}}}$	29.89	58.36
$-\underset{\vert}{\overset{\vert}{\mathrm{C}}}-$	82.23	116.02
$=\mathrm{CH_2}$	–9.63	3.77
$=\overset{\vert}{\mathrm{CH}}$	37.97	48.53
$=\underset{\vert}{\mathrm{C}}-$	83.99	92.36
$=\mathrm{C}=$	142.14	136.70
$\equiv\mathrm{CH}$	79.30	77.71
$\equiv\mathrm{C}-$	115.51	109.82
Ring Increments		
$-\mathrm{CH_2}-$	–26.80	–3.68
$-\underset{\vert}{\overset{\vert}{\mathrm{CH}}}$	8.67	40.99
$-\underset{\vert}{\overset{\vert}{\mathrm{C}}}-$	79.72	87.88
$=\overset{\vert}{\mathrm{CH}}$ (aromatic or cyclic olefin)	2.09	11.30
$=\overset{\vert}{\mathrm{C}}-$ (aromatic or cyclic olefin)	46.43	54.05
Oxygen Increments		
$-\mathrm{OH}$ (alcohol)	–208.04	–189.20
$-\mathrm{OH}$ (phenol)	–221.65	–197.37
$-\mathrm{O}-$ (nonring)	–132.22	–105.00
$-\mathrm{O}-$ (ring)	–138.16	–98.22
$-\overset{\vert}{\mathrm{C}}=\mathrm{O}$ (nonring)	–133.22	–120.50
$-\overset{\vert}{\mathrm{C}}=\mathrm{O}$ (ring)	–164.50	–126.27
Oxygen Increments (*Cont.*)		
$-\mathrm{CHO}$ (aldehyde)	–162.03	–143.48
$-\mathrm{COOH}$ (acid)	–426.72	–387.87
$-\mathrm{COO}-$ (ester)	–337.92	–301.95
$=\mathrm{O}$ (except for above)	–247.61	–250.83
Nitrogen Increments		
$-\mathrm{NH_2}$	–22.02	14.07
$-\overset{\vert}{\mathrm{NH}}$ (nonring)	53.47	89.39
$-\overset{\vert}{\mathrm{NH}}$ (ring)	31.65	75.61
$-\overset{\vert}{\mathrm{N}}-$ (nonring)	123.34	163.16
$-\mathrm{N}=$ (nonring)	23.61	—
$-\mathrm{N}=$ (ring)	55.52	79.93
$=\mathrm{NH}$	93.70	119.66
$-\mathrm{CN}$	88.43	89.22
$-\mathrm{NO_2}$	–66.57	–16.83
Sulfur Increments		
$-\mathrm{SH}$	–17.33	–22.99
$-\mathrm{S}-$ (nonring)	41.87	33.12
$-\mathrm{S}-$ (ring)	39.10	27.76
Halogen Increments		
$-\mathrm{F}$	–251.92	–247.19
$-\mathrm{Cl}$	–71.55	–64.31
$-\mathrm{Br}$	–29.48	–38.06
$-\mathrm{I}$	21.06	5.74

ENTHALPY OF VAPORIZATION AND FUSION

Enthalpy of Vaporization The enthalpy (heat) of vaporization ΔH_V is defined as the difference of the enthalpies of a unit mole or mass of a saturated vapor and saturated liquid of a pure component; i.e., at a temperature (below the critical temperature) and corresponding vapor pressure. ΔH_V is related to vapor pressure by the thermodynamically exact Clausius-Clapeyron equation:

$$\Delta H_v = -R\,\Delta Z_V \frac{d \ln P^{\text{sat}}}{d\,(1/T)} \qquad (2\text{-}54)$$

where R = gas constant in energy units

$$\Delta Z_V = Z_G - Z_L \qquad (2\text{-}55)$$

Z_G = compressibility factor of the saturated vapor

Z_L = compressibility factor of the saturated liquid

P^{sat} = vapor pressure

T = absolute temperature

If accurate Z_G and Z_L data are available, excellent ΔH_V values can be obtained by differentiating a vapor pressure correlation and using Eq. (2-54). If not, ΔZ_V may be esimated by Haggenmacher's equation[34]:

TABLE 2-389 Standard-State Entropy of Elements at 298.15 K and 1 Atmosphere

Element	State	Absolute entropy J/mol K
C	crystal (graphite)	5.74
H_2	gas	130.571
O_2	gas	205.043
N_2	gas	191.500
S	crystal (rhombic)	32.054
F_2	gas	202.682
Cl_2	gas	222.972
Br_2	liquid	152.21
I_2	crystal	116.14

$$\Delta Z_v = \left(1 - \frac{P_r}{T_{r^3}}\right)^{1/2} \tag{2-56}$$

where P_r = reduced pressure = P/P_c
T_r = reduced temperature = T/T_c

However, Eq. (2-56) should be used only near or below the normal boiling point; even then, the accuracy of the resulting ΔH_V is significantly reduced.

The corresponding states approach suggested by Pitzer et al.[82] requires only the critical temperature and acentric factor of the compound. For a close approximation, an analytical representation of this method proposed by Reid et al.[86] for $0.6 < T_r < 1.0$ is:

$$\Delta H_V/RT_c = 7.08(1 - T_r)^{0.354} + 10.95\omega(1 - T_r)^{0.456} \tag{2-57}$$

where ΔH_V = enthalpy of vaporization, kJ/mol
R = gas constant = 0.008314 kJ/mol K
T_c = critical temperature, K
T_r = reduced temperature, T/T_c
T = temperature, K
ω = acentric factor

Maximum errors are in the order of 8 percent.

Example 12 Estimate ΔH_V of Propionaldehyde at 350 K. The required properties from Daubert et al.[24] are $T_c = 504.4$ K and $\omega = 0.2559$. $T_r = 350.0/504.4 = 0.6939$. Substituting in Eq. (2-57):

$$\Delta H_V/RT_c = (7.08)(1 - 0.6939)^{0.354} + (10.95)(0.2559)(1 - 0.6939)^{0.456} = 6.289$$

$$\Delta H_V = (6.289)(0.008314)(504.4) = 26.37 \text{ kJ/mol}$$

The reported value is 26.85 kJ/mol.[24]

The enthalpy of vaporization **at the normal boiling temperature** ΔH_{vb} (kJ/mol) can be estimated by an equation suggested by Riedel[90]:

$$\Delta H_{vb} = 1.093\ RT_c \left[T_{br} \frac{(\ln [P_c/101.325] - 1)}{0.930 - T_{br}}\right] \tag{2-58}$$

where R = gas constant = 0.008314 kJ/mol K.
T_c = critical temperature, K
T_{br} = reduced normal boiling temperature = T_b/T_r
T_b = normal boiling temperature, K
P_c = critical pressure, kPa

Average errors are about 2 percent.

Example 13 Estimate ΔH_{Vb} of Ethyl Acetate. The required properties for ethyl acetate are from Daubert et al.[24]: $T_c = 523.3$ K, $T_b = 350.2$ K, and $P_c = 3880.0$ kPa. $T_{br} = 350.2/523.3 = 0.6692$. Substituting in Eq. (2-58):

$$\Delta H_{Vb} = (1.093)(0.008314)(523.3)\left[(0.6692)\left(\frac{(\ln [3880.0/101.325] - 1)}{0.930 - 0.6692}\right)\right]$$

$$= 32.28 \text{ kJ/mol}$$

The value from Daubert et al.[24] is 32.23 kJ/mol.

The enthalpy of vaporization decreases with temperature and is zero at the critical point. If the value of an enthalpy of vaporization ΔH_{v_1} is known at temperature T_1, this temperature dependency can be represented by the Watson relation[127] to calculate another enthalpy of vaporization ΔH_{v_2} at any other temperature T_2:

$$\Delta H_{v_2} = \Delta H_{v_1}\left(\frac{1 - T_{r_2}}{1 - T_{r_1}}\right)^{0.38} \tag{2-59}$$

where $Tr_{1,2}$ = reduced temperature = T_1/T_c or T_2/T_c
$T_{1,2}$ = temperature, K
T_c = critical temperature, K

Equation (2-59) works best between the normal boiling and critical temperatures, producing values of engineering accuracy.

Example 14 Estimate ΔH_v of ethyl acetate at 450 K, using the normal boiling point values as a basis (see Example 13). $\Delta H_{v_1} = 32.23$ kJ/mol, $T_{r_1} = 0.6692$, and $T_{r_2} = 450.0/523.3 = 0.8599$. Substituting in Eq. (2-59):

$$\Delta H_{v(450)} = 32.23\left(\frac{1 - 0.8599}{1 - 0.6692}\right)^{0.38} = 23.25 \text{ kJ/mol}$$

A value of 23.16 kJ/mol is obtained from Daubert et al.[24]

Enthalpy of Fusion The enthalpy (heat) of fusion ΔH_{fus} is defined as the difference of the enthalpies of a unit mole or mass of a solid and liquid at its melting temperature and one atmosphere pressure of a pure component. There are no generally applicable estimation techniques that are very accurate. However, if the melting temperature is known, the atomic group contribution method of Chickos et al.[16] yields approximate results:

$$\Delta H_{\text{fus}} = T_{\text{mlt}}\Delta S_{\text{fus}} \tag{2-60}$$

where ΔH_{fus} = enthalpy of fusion at the melting temperature, J/mol
T_{mlt} = melting temperature, K
$\Delta S_{\text{fus}} = a + b$ = entropy of fusion at the melting temperature, J/mol K.

It should be noted that the methodology for a and b results in a ΔS_{fus} associated with the phase change from a solid at 0 K to the liquid at T_{mlt}. No entropy changes resulting from solid transitions are taken into account, and ΔS_{fus} for a substance that undergoes such a transition will be overestimated by this technique.

$$a = 35.19\ N_R + 4.289\ (N_{CH_2} - 3\ N_R) \tag{2-61}$$

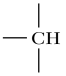
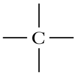
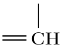
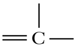
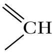
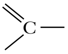
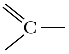
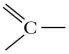
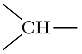
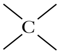
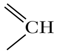
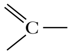
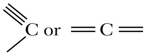
where N_R = number of nonaromatic rings
N_{CH_2} = number of —CH_2— atomic groups in nonaromatic ring(s) required to form a cyclic paraffin of the same ring size(s) as contained in the molecule of interest.

Example: For , $N_{CH_2} = 5$; $a = 0$ if there are no nonaromatic rings in the molecule of interest. If a nonaromatic ring in fact contains a —CH_2— atomic group, then no consideration of that group in the b term in Eq. (2-62) is required.

$$b = \sum_{i=1}^{n_g}(N_g)_i(\Delta_s)_i + \sum_{j=1}^{n_s}(N_s)_j(C_s)_j(\Delta_s)_j + \sum_{k=1}^{n_f}(N_f)_k(C_t)_k(\Delta_s)_k \tag{2-62}$$

where n_g = number of different nonring or aromatic C-H atomic groups bonded to other carbon atoms in the molecule of interest
$(N_g)_i$ = number of C-H atomic groups i bonded to other carbon atoms in the molecule of interest
n_s = number of different nonring or aromatic C-H atomic groups bonded to at least one functional group or atom in the molecule of interest
$(N_s)_j$ = number of C-H atomic groups j bonded to at least one functional group or atom in the molecule of interest
n_f = number of different functional groups or atoms in the molecule of interest
$(N_f)_k$ = number of functional groups or atoms k in the molecule of interest
$(C_s)_j$ = coefficient for C-H atomic group j bonded to at least one functional group or atom in the molecule of interest; numeric values for C-H atomic groups are found in Table 2-390
C_t = coefficient for the functional group or atom k in the molecule of interest, where t = the total number of functional groups or atoms in the molecule of interest. *Exception:* Molecules containing any number of fluorine atoms are treated as having only one functional fluorine atom. Numeric values of C_1–C_4 are in Table 2-391 for functional groups or atoms
$(\Delta_s)_{i,j,k}$ = contribution of the atomic group or atom i, j, or k to the entropy of fusion, J/mol K. Numeric values for C-H atomic groups are in Table 2-390; values for functional groups or atoms are in Table 2-391

TABLE 2-390 C_s and Δ_s Values for C-H Atomic Groups to Estimate ΔH_{fus}

	C_s	Δ_s
Nonring		
$-CH_3$	1.0	18.33
$-CH_2-$	1.0	9.41
	0.69	–16.19
	0.67	–38.70
$=CH_2$	1.0	14.56
	3.23	4.85
	1.0	–11.38
$\equiv CH$	1.0	10.88
$\equiv C-$	1.0	2.18
Aromatic		
	1.0	6.44
 (bonded to paraffinic C)	1.0	–10.33
 (bonded to olefinic C or non-C)	1.0	–4.27
 (bonded to acetylenic C)	1.0	–2.51
Ring		
	0.76	–15.98
	1.0	–32.97
	0.62	–4.35
	0.86	–11.72
	1.0	–5.36

Chickos et al.[16] report an average error of 2050 J/mol for monofunctional molecules and 3180 J/mol for multifunctional molecules when using their method to estimate ΔH_{fus}. Four **example** estimations are shown in Table 2-392.

SOLID AND LIQUID HEAT CAPACITY

The heat capacity is defined as the amount of energy required to change the temperature of a unit mass or mole one degree; typical units are J/kg·K or J/kmol·K.

Solid Heat Capacity Solid heat capacity increases with increasing temperature, with steep rises near the triple point for many compounds. When experimental data are available, a simple polynomial equation in temperature is often used to correlate the data. It should be noted that step changes in heat capacity occur if the compound undergoes crystalline state changes at different temperatures.

There are no reliable prediction methods for solid heat capacity as a function of temperature. However, the atomic element contribution method of Hurst and Harrison,[41] which is a modification of Kopp's Rule,[50] provides estimations at 298.15 K and is easy to use:

$$C_{pS} = \sum_{i=1}^{n} N_i \, \Delta_{Ei} \qquad (2\text{-}63)$$

where C_{pS} = solid heat capacity at 298.15 K, J/mol K
n = number of different atomic elements in the compound
N_i = number of atomic elements i in the compound
Δ_{Ei} = numeric value of the contribution of atomic element i found in Table 2-393

Average errors are in the 9–10 percent range.

Example 15 Estimate solid heat capacity of dibenzothiophene, $C_{12}H_8S$. The required atomic element contributions from Table 2-393 are: C = 10.89, H = 7.56, and S = 12.36. Substituting in Eq. (2-63):

$$C_{pS} = (12)(10.89) + (8)(7.56) + (1)(12.36) = 203.52 \text{ J/mol K}$$

Daubert et al.[24] report a value of 198.5 J/mol K.

Liquid Heat Capacity The two commonly used liquid heat capacities are either at constant pressure or at saturated conditions. There is negligible difference between them for most compounds up to a reduced temperature (temperature/critical temperature) of 0.7. Liquid heat capacity increases with increasing temperature, although a minimum occurs near the triple point for many compounds.

There are a number of reliable estimating techniques for obtaining **pure-component** liquid heat capacity as a function of temperature, including Ruzicka and Dolmalski,[93,94] Tarakad and Danner,[112] and Lee and Kesler.[55] These methods are somewhat complicated. The relatively simple atomic group contribution approach of Chueh and Swanson[17] for liquid heat capacity **at 293.15 K** is presented here:

$$C_{pL} = \sum_{i=1}^{n} N_i \, \Delta_{\text{cpi}} + 18.83m \qquad (2\text{-}64)$$

where C_{pL} = liquid heat capacity at 293.15 K, J/mol K.
n = number of different atomic groups in the compound
N_i = number of atomic groups i in the compound
Δ_{cpi} = numeric value of the contribution of atomic element i found in Table 2-394. The original units of cal/mol K have been converted to J/mol K by the conversion 1 cal/mol K = 4.184 J/mol K
m = number of carbon groups requiring an additional contribution, which are those that are joined by a single bond to a carbon group, which in turn is connected to a third carbon group by a double or triple bond. If a carbon group meets this criterion in more than one way, m should be increased by one for each of the ways. *Exceptions:* $-CH_3$ groups or carbon groups in a ring never require an additional contribution; and the *first* additional contribution for a $-CH_2-$ group is 10.46 J/mol K rather than 18.83 J/mol K. However, if the $-CH_2-$ group meets the criterion in a second way, the *second* additional contribution reverts to the 18.83 J/mol K value (see Example 17, below).

Errors should be less than 6 percent for all compounds except for acids, amines, and halides.

Example 16 Estimate the liquid heat capacity at 293.15 K of 2-butanol. The atomic groups are:

2 $-CH_3$
1 $-CH_2-$
1 $-CHOH$

Substituting in Eq. (2-64) the atomic group contributions from Table 2-394 with $m = 0$:

$$C_{pL} = (2)(36.82) + (1)(30.38) + (1)(76.15) = 180.17 \text{ J/mol K}$$

The value from Daubert et al.[24] is 190.3 J/mol K.

TABLE 2-391 C_i and Δ_s Values for Functional Groups and Atoms to Estimate ΔH_{fus}

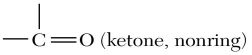
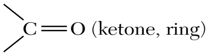
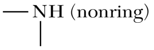
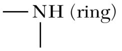
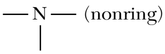
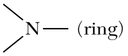
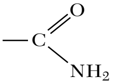
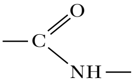
	C_1	C_2	C_3	C_4	Δ_s
—OH (alcohol)	1.0	12.6	18.9	26.4	1.13
—OH (phenol)	1.0	1.0	1.0	1.0	16.57
—O— (ether, nonring)	1.0	1.0	1.0	1.0	1.09
—O— (ether, ring)	1.0	1.0	1.0	1.0	1.34
 $-\overset{\vert}{C}{=}O$ (ketone, nonring)	1.0	1.0			3.14
 $>C{=}O$ (ketone, ring)	1.0	1.0			−1.88
—CHO (aldehyde)	1.0				19.66
—COOH (acid)	1.0	1.83	1.88	1.72	14.90
—COO— (ester)	1.0	1.0	1.0	1.0	3.68
$-NH_2$ (aliphatic)	1.0	1.82			16.23
$-NH_2$ (aromatic)	1.0	1.0			15.48
 $-\underset{\vert}{N}H$ (nonring)	1.0	1.0			−2.18
 $-\underset{\vert}{N}H$ (ring)	1.0				1.84
 $-\underset{\vert}{N}-$ (nonring)	1.0				−15.90
 $>N-$ (ring)	1.0	1.0			−17.07
=N— (ring)	1.0	1.0			1.67
=N— (aromatic)	1.0	1.0	1.0		7.32
—CN (nitrile)	1.0	1.4			9.62
$-NO_2$	1.0	1.0	1.0		17.36
 $-C(=O)NH_2$	1.0	1.0			26.19
 $-C(=O)NH-$	1.0	1.0			−0.42
—SH	1.0	1.0			17.99
—S— (nonring)	1.0			0.36	7.20
—S— (ring)	1.0	1.0			2.18
$-SO_2^-$ (nonring)	1.0				3.26
—F (on —C)	1.0	1.0	1.0	1.0	14.73
—F (on =C)	1.0	1.0	1.0	1.0	13.01
—F (on ring C)	1.0	1.0	1.0	1.0	15.90
—Cl	1.0	2.0	2.0	1.93	8.37
—Br	1.0	1.0	1.0	0.82	17.95
—I	1.0	1.0			16.95

TABLE 2-392 Examples of Estimations of ΔH_{fus}, J/mol

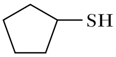
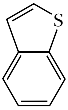
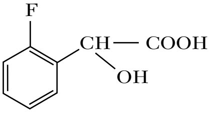
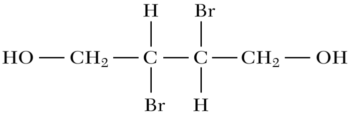
Molecule	Melting temp., K	Atomic group	Contribution		
 (t = 1)	155.4	cyclopentane	$(35.19)(1) + (4.289)[5 - (3)(1)]$	=	43.77
		$>$CH— (ring)	$(1)(0.76)(-15.98)$	=	−12.14
		—SH	$(1)(1.0)(17.99)$	=	17.99
			ΔS_{fus}	=	49.62
			$\Delta H_{fus} = (49.62)(155.4)$	=	7710.9
			ΔH_{fus} = (experimental)[16]	=	7802
 (t = 1)	304.5	cyclopentane	$(35.19)(1) + (4.289)[5 - (3)(1)]$	=	43.77
		=CH (aromatic)	$(4)(6.44)$	=	25.76
		=C— (ring)	$(1)(-11.72)$	=	−11.72
		=C— (ring)	$(1)(0.86)(-11.72)$	=	−10.08
		=CH (ring)	$(1)(-4.35)$	=	−4.35
		=CH (ring)	$(1)(0.62)(-4.35)$	=	−2.69
		—S— (ring)	$(1)(1.0)(2.18)$	=	2.18
			ΔS_{fus}	=	42.87
			$\Delta H_{fus} = (42.87)(304.5)$	=	13054
			ΔH_{fus} = (experimental)[16]	=	11823
 (t = 3)	363.0	=CH (aromatic)	$(4)(6.44)$	=	25.76
		=C— (aromatic)	$(1)(1.0)(-4.27)$	=	−4.27
		—F (on =C)	$(1)(1.0)(13.01)$	=	13.01
		=C— (aromatic)	$(1)(-10.33)$	=	−10.33
		$-\overset{\vert}{\underset{\vert}{\mathrm{C}}}\mathrm{H}$	$(1)(0.69)(-16.19)$	=	−11.17
		—COOH	$(1)(1.88)(14.90)$	=	28.01
		—OH (alcohol)	$(1)(18.9)(1.13)$	=	21.36
			ΔS_{fus}	=	62.37
			$\Delta H_{fus} = (62.37)(363.0)$	=	22640
			ΔH_{fus} = (experimental)[16]	=	20959
 $\mathrm{HO-CH_2-\underset{Br}{\overset{H}{C}}-\underset{H}{\overset{Br}{C}}-CH_2-OH}$ (t = 4)	338.2	$-\mathrm{CH_2}-$	$(2)(1.0)\ 9.41$	=	18.82
		$-\overset{\vert}{\underset{\vert}{\mathrm{C}}}\mathrm{H}$	$(2)(0.69)(-16.19)$	=	−22.34
		—OH (alcohol)	$(2)(26.4)(1.13)$	=	59.66
		—Br	$(2)(0.82)(17.95)$	=	29.44
			ΔS_{fus}	=	85.58
			$\Delta H_{fus} = (85.58)(338.2)$	=	28943
			ΔH_{fus} = (experimental)[16]	=	29291

TABLE 2-393 Atomic Element Contributions to Estimate Solid Heat Capacity at 298.15 K

Atomic element	Δ_E	Atomic element	Δ_E	Atomic element	Δ_E
C	10.89	Ba	32.37	Mo	29.44
H	7.56	Be	12.47	Na	26.19
O	13.42	Ca	28.25	Ni	25.46
N	18.74	Co	25.71	Pb	31.60
S	12.36	Cu	26.92	Si	17.00
F	26.16	Fe	29.08	Sr	28.41
Cl	24.69	Hg	27.87	Ti	27.24
Br	25.36	K	28.78	V	29.36
I	25.29	Li	23.25	W	30.87
Al	18.07	Mg	22.69	Zr	26.82
B	10.10	Mn	28.06	All other	26.63

Example 17 Estimate liquid heat capacity at 293.15 K of 1,4-pentadiene, $CH_2{=}CH{-}CH_2{-}CH{=}CH_2$. The atomic groups are:

2 $=CH_2$

2 $=\overset{|}{CH}$

1 $-CH_2-$

The $-CH_2-$ group is twice joined by a single bond to a carbon group, which in turn is connected to a third carbon group by a double bond, and $m = 2$. However, by the second exception, the first additional contribution is 10.46 J/mol K rather than 18.83 J/mol K. Substituting in Eq. (2-64) the atomic group contributions from Table 2-394:

$$C_{pL} = (2)(21.76) + (2)(21.34) + (1)(30.38) + 10.46 + 18.83 = 145.87 \text{ J/mol K}$$

TABLE 2-394 Atomic Group Contributions to Estimate Liquid Heat Capacity at 293.15 K

	Δ_{cp}		Δ_{cp}
Nonring Increments		**Oxygen Increments (*Cont.*)**	
$-CH_3$	36.82	$-CH_2OH$	73.22
$-CH_2-$	30.38	$-\underset{\vert}{C}HOH$	76.15
$-\overset{\vert}{\underset{\vert}{C}}H$	20.92	$-\overset{\vert}{\underset{\vert}{C}}OH$	111.29
$-\overset{\vert}{\underset{\vert}{C}}-$	7.36	$-OH$ (except for above)	44.77
$=CH_2$	21.76	$-ONO_2$	119.24
$=\overset{\vert}{C}H$	21.34	**Nitrogen Increments**	
$=\overset{\vert}{C}-$	15.90	$-NH_2$	58.58
$\equiv CH$	24.69	$-\underset{\vert}{N}H$	43.93
$\equiv C-$	24.69	$-N-$	31.38
Ring Increments		$-\underset{\vert}{N}=$ (ring)	18.83
$-CH_2-$	25.94	$-CN$	58.16
$-\overset{\vert}{\underset{\vert}{C}}H$	18.41	**Sulfur Increments**	
$-\overset{\vert}{\underset{\vert}{C}}-$ or $=\overset{\vert}{\underset{\vert}{C}}$	12.13	$-SH$	44.77
$=\overset{\vert}{C}H$	22.18	$-S-$	33.47
Oxygen Increments		**Halogen Increments**	
$-O-$	35.15	$-F$	16.74
$-\overset{\vert}{C}{=}O$	52.97	$-Cl$ (first or second on a carbon)	35.98
$-CHO$ (aldehyde)	52.97	$-Cl$ (third or fourth on a carbon)	25.10
$-COOH$ (acid)	79.91	$-Br$	37.66
$-COO-$ (ester)	60.67	$-I$	35.98
		Hydrogen Increment	
		$-H$ (for formic acid, formates, hydrogen cyanide, etc.)	14.64

Daubert et al.[24] report a value of 145.6 J/mol K.

For **liquid mixtures,** the values of the pure components can be mole-fraction-averaged. This procedure neglects any heat of mixing effects.

DENSITY

Density is defined as the mass of a substance contained in a unit volume. In the SI system of units, the ratio of the density of a substance to the density of water at 15°C is known as its relative density, while the older term *specific gravity* is the ratio relative to water at 60°F. Various units of density, such as kg/m^3, lb-mass/ft^3, and g/cm^3, are commonly used. In addition, molar densities, or the density divided by the molecular weight, is often specified. This section briefly discusses methods of correlation of density as a function of temperature and presents the most common accurate methods for prediction of vapor, liquid, and solid density.

Correlation Methods Vapor densities are not correlated as functions of temperature alone, as pressure and temperature are both important. At high temperatures and very low pressures, the ideal gas law can be applied; while at moderate temperature and low pressure, vapor density is usually correlated by the virial equation. Both methods will be discussed later.

Molar liquid density (ρ) is best correlated by an equation adopted from the Rackett predictor. The equation has the form of Eq. (2-65):

$$\rho = \frac{A}{B\left(1 - \dfrac{T}{C}\right)^{D}} \tag{2-65}$$

The regression constants A, B, and D are determined from the nonlinear regression of available data, while C is usually taken as the critical temperature. The liquid density decreases approximately linearly from the triple point to the normal boiling point and then nonlinearly to the critical density (the reciprocal of the critical volume). A few compounds such as water cannot be fit with this equation over the entire range of temperature. Liquid density data to be regressed should be at atmospheric pressure up to the normal boiling point, above which saturated liquid data should be used. Constants for 1500 compounds are given in the DIPPR compilation.[24]

Solid density data are sparse and usually only available over a narrow temperature range, for which the general decrease in density with temperature is approximately linear.

Vapor Density Prediction A myriad of methods exist for prediction of vapor density as a function of temperature and pressure. This section will only present the most accurate and generally used methods.

For simple molecules at temperatures above the critical and at pressures no more than a few atmospheres, the ideal gas law, Eq. (2-66), may be used to estimate vapor density.

$$\rho = \frac{1}{V} = \frac{P}{RT} \tag{2-66}$$

At slightly higher pressures up to a reduced pressure of about 0.4, the truncated virial equation, Eq. (2-67), is commonly used for all types of organic fluids.

$$Z = \frac{PV}{RT} = 1 + \frac{B}{V} \tag{2-67a}$$

$$Z = \frac{P}{\rho RT} = 1 + B\rho \tag{2-67b}$$

Second virial coefficients, B, are a function of temperature and are available for about 1500 compounds in the DIPPR compilation.[24] The second virial coefficient can be regressed from experimental PVT data or can be reasonably and accurately predicted. Tsonopoulos[117] proposed a prediction method for nonpolar compounds that requires the critical temperature, critical pressure, and acentric factor. Equations (2-68) through (2-70) describe the method.

$$\frac{BP_c}{RT_c} = B_0 + \omega B_1 \tag{2-68}$$

$$B_0 = 0.1445 - \left(\frac{0.330}{T_r}\right) - \left(\frac{0.1385}{T_r^2}\right) - \left(\frac{0.0121}{T_r^3}\right) - \left(\frac{0.000607}{T_r^5}\right) \tag{2-69}$$

$$B_1 = 0.0637 + \left(\frac{0.0331}{T_r^2}\right) - \left(\frac{0.423}{T_r^3}\right) - \left(\frac{0.008}{T_r^8}\right) \tag{2-70}$$

For non-hydrogen-bonding polar compounds such as carbonyls and ethers, Tsonopoulos[117] recommends that Eq. (2-68) be expanded to a third term that is a function of the reduced dipole moment (μ_r) as described by Eqs. (2-71) through (2-73):

$$\frac{BP_c}{RT_c} = B_0 + \omega B_1 + B_2 \tag{2-71}$$

$$B_2 = -0.0002410\lambda_r - 4.308 \times 10^{-21}\lambda_r^8 \tag{2-72}$$

$$\lambda_r = \frac{10^5 \lambda_p^2 P_c}{T_c^2} \tag{2-73}$$

The dipole moment λ_p in Eq. (2-73) is in debyes, while P_c is in atm and T_c is in K. Units must be watched carefully. For hydrogen-bonding molecules, Eq. (2-71) can be used with a value of B_2 calculated by Eq. (2-74).

$$B_2 = \frac{a}{T_r^6} - \frac{b}{T_r^8} \tag{2-74}$$

Variables a and b are specific constants reported by Tsonopoulos[117] for some alcohols and water (e.g., methanol: $a = 0.0878$, $b = 0.0560$; and water: $a = 0.0279$, $b = 0.0229$). Tsonopoulos also gives specific prediction methods for haloalkanes[118] and water pollutants.[119]

Example 18 Estimate the molar volume of isobutane at 155°C and 1.0 MPa pressure. Properties of isobutane are $T_c = 135.0°\text{C}$, $P_c = 3.647$ MPa, and $\omega = 0.1170$.

$$T_r = \frac{155 + 273.1}{135 + 273.1} = 1.05 \qquad P_r = \frac{1.0}{3.647} = 0.274$$

Since reduced pressure is below 0.4, use virial equation (2-67*a*). Calculate B by the Tsonopoulos method, Eq. (2-68).

$$\frac{BP_c}{RT_c} = B_0 + \omega B_1$$

Using Eq. (2-69):

$$B_0 = 0.1445 - \left(\frac{0.330}{1.05}\right) - \left(\frac{0.1385}{1.05^2}\right) - \left(\frac{0.0121}{1.05^3}\right) - \left(\frac{0.000607}{1.05^5}\right)$$

$$B_0 = 0.1445 - 0.3143 - 0.1256 - 0.0105 - 0.0005 = -0.3064$$

Using Eq. (2-70):

$$B_1 = 0.0637 + \left(\frac{0.0331}{1.05^2}\right) - \left(\frac{0.423}{1.05^3}\right) - \left(\frac{0.008}{1.05^8}\right)$$

$$B_1 = 0.0637 + 0.0300 - 0.3654 - 0.0054 = -0.2771$$

$$B = \frac{[-0.3064 + (0.1770)(-0.2771)](8314)(408.1)}{(3.647 \times 10^6)} = -0.3307$$

$$\frac{PV}{RT} = 1 + \frac{B}{V}$$

$$\frac{10^6 V}{(8314)(428.1)} = 1 - \frac{0.3307}{V}$$

Trial and error or the quadratic formula can be used for the solution. If you opt for trial and error, start with the ideal gas value ($B = 0$) where $V = 3.559$ m^3/kmole [Eq. (2-66)].

Solving, $V = 3.190$ m^3/kmole.

For prediction of vapor density of **pure hydrocarbon and nonpolar gases,** the corresponding states method of Pitzer et al.[82] is the most accurate method, with errors of less than 1 percent except in the critical region where errors of up to 30 percent can occur. The method correlates the compressibility factor by Eq. (2-75), after which the density can be calculated by Eq. (2-75):

$$Z = Z^{(0)} + \omega Z^{(1)} \tag{2-75}$$

$$\rho = \frac{P}{ZRT} = \frac{1}{V} \tag{2-76}$$

$Z^{(0)}$ is the compressibility factor for the simple fluid, while $Z^{(1)}$ is the correction term for molecular acentricity, both of which are functions of T_r and P_r. Both plots and detailed tabulations of the functions are available in the *Technical Data Book.*[23] Critical temperature and pressure and the acentric factor from tabulations or as predicted are required. For hydrogen, T_c and P_c should be taken as 41.7 K and 2100 kPa, respectively. For approximate calculations, Figs. 2-35 and 2-36 should be used for calculating $Z^{(0)}$ and $Z^{(1)}$, respectively, for superheated vapors with $0.2 \le P_r \le 10$. $Z^{(0)}$ will approach 1, and $Z^{(1)}$ will approach 0 for $P_r < 0.2$. More accurately, Eq. (2-77) can be used for P_r between 0 and 0.2.

$$Z = 1 + \frac{P_r}{T_r}[(0.1445 + 0.073\omega) - (0.330 - 0.46\omega)T_r^{-1} - (0.1385 + 0.50\omega)T_r^{-2} - (0.0121 + 0.097\omega)T_r^{-3} - 0.0073\omega T_r^{-8}] \quad (2\text{-}77)$$

Extension of the pressure range to P_r = 14 is available in the *Technical Data Book.* For saturated vapor densities, the values of $Z^{(0)}$ and $Z^{(1)}$ are tabulated as a

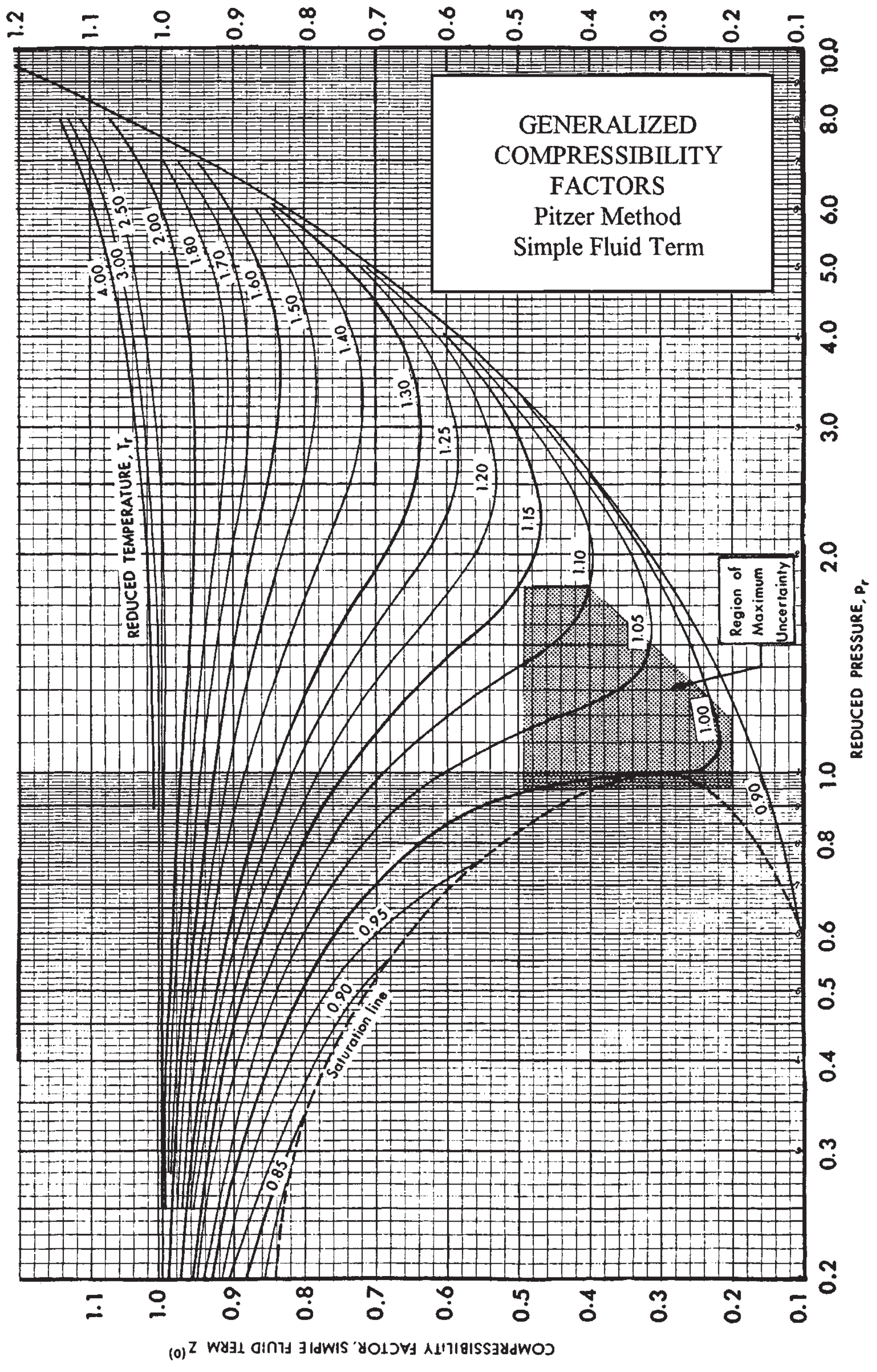


FIG. 2-35 Generalized compressibility factors—Pitzer Method, simple fluid term.

function of reduced pressure in Table 2-395. If the saturation temperature rather than the saturation pressure is known, the vapor pressure of the compound can be determined either from data or the vapor pressure prediction methods discussed earlier.

Example 19 Estimate the molar volume of isobutane at 155°C and 8.6 MPa pressure.

As high pressure, use Eq. (2-75) to calculate Z and then Eq. (2-76) to estimate the molar volume.

The properties of isobutane necessary are $T_c = 135.0°\text{C}$, $P_c = 3.647$ MPa, and $\omega = 0.1770$.

$$T_r = \frac{155 + 273.1}{135 + 273.1} = 1.05 \qquad P_r = \frac{8.6}{3.647} = 2.36$$

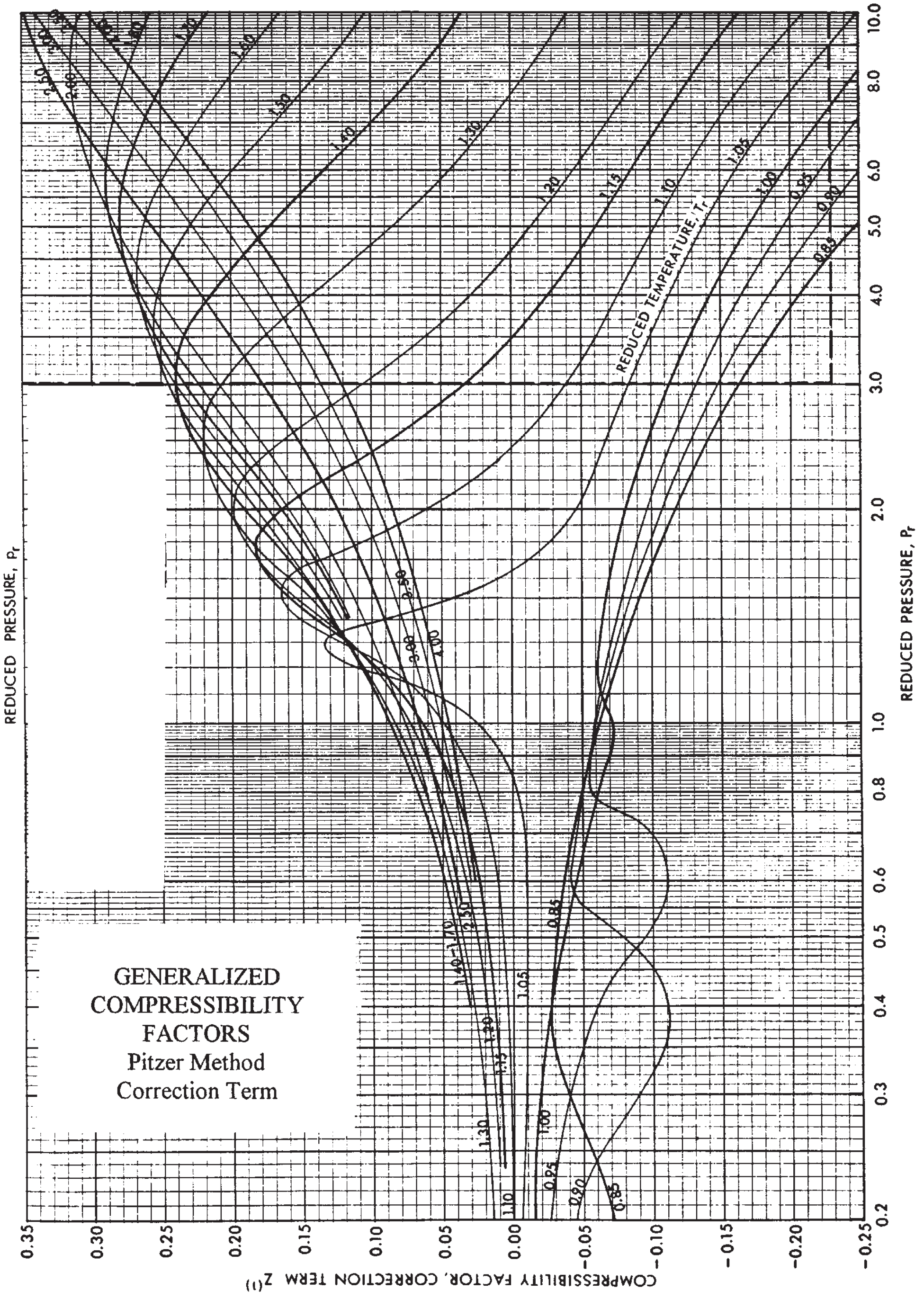


FIG. 2-36 Generalized compressibility factors—Pitzer Method, correction term.

TABLE 2-395 Saturated Vapor Density Parameters

P_r	$Z^{(0)}$	$Z^{(1)}$	P_r	$Z^{(0)}$	$Z^{(1)}$
1.00	0.291	−0.080	0.65	0.615	−0.069
0.99	0.35	−0.083	0.60	0.64	−0.063
0.98	0.38	−0.085	0.55	0.665	−0.056
0.97	0.40	−0.087	0.50	0.688	−0.049
0.96	0.41	−0.088	0.45	0.711	−0.041
0.95	0.42	−0.089	0.40	0.734	−0.033
0.94	0.43	−0.089	0.35	0.758	−0.025
0.92	0.45	−0.090	0.30	0.783	−0.018
0.90	0.47	−0.091	0.25	0.809	−0.012
0.85	0.50	−0.090	0.20	0.835	−0.008
0.80	0.53	−0.087	0.15	0.864	−0.005
0.75	0.56	−0.081	0.10	0.896	−0.002
0.70	0.59	−0.075	0.05	0.935	0.000

Using Fig. 2-35, $Z^{(0)} = 0.385$. Using Fig. 2-36, $Z^{(1)} = -0.063$.

$$Z = Z^{(0)} + \omega Z^{(1)}$$

$$Z = 0.385 + 0.1770(-0.063) = 0.374$$

$$V = \frac{ZRT}{P} = \frac{(0.374)(8314)(428.1)}{8.6 \times 10^6}$$

$$V = 0.155 \text{ m}^3\text{/kmol}$$

An experimental value for Z is 0.377.

Note that use of the Lee-Kesler fit [Eq. (2-78)] would give a slightly more accurate answer than the graphical method, and this fit is used for any computer applications.

Lee and Kesler[55] fit the entire Pitzer method to equations, rewriting the basic Eq. (2-75) with respect to a heavy reference fluid (*n*-octane) as shown by Eq. (2-78).

$$Z = Z^{(0)} + \frac{\omega}{\omega^{(h)}}(Z^{(h)} - Z^{(0)}) \tag{2-78}$$

where h specifies the heavy reference fluid with an acentric factor of 0.3978.

The parameters in the equation are calculated for the simple fluid and the heavy reference fluid with an acentric factor of 0.3978. The parameters in the equation are calculated for the simple fluid and the heavy reference fluid from Eq. (2-79)

$$Z^{(i)} = \frac{P_r V_r}{T_r} = 1 + \frac{B}{V_r} + \frac{C}{V_r^2} + \frac{D}{V_r^5} + \frac{c_4}{T_r^3 V_r^2}\left[\beta + \frac{\gamma}{V_r^2}\right]\exp\left[\frac{-\gamma}{V_r^2}\right] \tag{2-79}$$

$$B = b_1 - \left(\frac{b_2}{T_r}\right) - \left(\frac{b_3}{T_r^2}\right) - \left(\frac{b_4}{T_r^3}\right)$$

$$C = c_1 - \left(\frac{c_2}{T_r}\right) - \left(\frac{c_3}{T_r^3}\right)$$

$$D = d_1 + \left(\frac{d_2}{T_r}\right)$$

where $Z^{(i)} = Z^{(0)}$ when the constants in the equation correspond to the simple fluid and $Z^{(h)}$ when the constants in the equation correspond to the heavy reference fluid

P = pressure, kPa

P_c = critical pressure of the compound whose density is sought, kPa

V = molar volume of the simple fluid or the heavy reference fluid, as the case may be, in m³/kmole.

R = gas constant = 8.3140 m³ kPa/k mole K

T_c = critical temperature of the compound whose density is sought, K

T = temperature, K

Constant	Simple fluid	Heavy reference fluid
b_1	0.1181193	0.2026579
b_2	0.265728	0.331511
b_3	0.154790	0.027655
b_4	0.030323	0.203488
c_1	0.0236744	0.0313385
c_2	0.0186984	0.0503618
c_3	0.0	0.016901
c_4	0.042724	0.041577
$d_1 \times 10^4$	0.155488	0.48736
$d_2 \times 10^4$	0.623689	0.0740336
β	0.65392	1.226
γ	0.060167	0.03754

For **hydrocarbon and nonpolar gas mixtures,** the Pitzer pure component method can be used to predict vapor density by replacing the true critical properties with pseudocritical properties defined in Eqs. (2-80) and (2-81) by Kay.[47]

$$T_{pc} = \sum_{i=1}^{n} x_i T_{c_i} \tag{2-80}$$

$$P_{pc} = \sum_{i=1}^{n} x_i P_{c_i} \tag{2-81}$$

The mixture acentric factor, Eq. (2-82), can also be used.

$$\omega = \sum_{i=1}^{n} x_i \omega_i \tag{2-82}$$

Errors in compressibility factors tabulated for over 6500 data points rarely exceed 2 percent except in the critical region, where 15 percent errors may be expected and 50 percent errors can occur. For mixtures near the critical point, special techniques are available as discussed in the sixth chapter of the *Technical Data Book.*

For **pure organic vapors,** the Lydersen et al.[63] corresponding states method is the most accurate technique for predicting compressibility factors and, hence, vapor densities. Critical temperature, critical pressure, and critical compressibility factor defined by Eq. (2-21) are used as input parameters. Figure 2-37 is used to predict the compressibility factor at $Z_c = 0.27$, and the result is corrected to the Z_c of the desired fluid using Eq. (2-83).

$$Z = Z_{@Z_c = 0.27} + D_i(Z_c - 0.27) \tag{2-83}$$

D_i is equal to D_a read from Fig. 2-38 if $Z_c > 0.27$; and D_i is equal to D_b read from Fig. 2-39 if $Z_c < 0.27$. At reduced temperatures less than 0.9, D_i can be taken as 0. The density is then calculated from Eq. (2-76). All families of organic compounds except mercaptans and carboxylic acids are predicted within an average deviation of 5 percent.

No specific mixing rules have been tested for predicting compressibility factors for **defined organic mixtures.** However, the Lydersen method using pseudocritical properties as defined in Eqs. (2-80), (2-81), and (2-82) in place of true critical properties will give a reasonable estimate of the compressibility factor and hence the vapor density.

Vapor densities for pure compounds can also be predicted by cubic equations of state. For hydrocarbons, relatively accurate Redlich-Kwong-type equations such as the Soave[98] and Peng-Robinson[81] equations are often used. Both require only T_c, P_c, and ω as inputs. For organic compounds, the Lee-Erbar-Edmister[54] equation (which requires the same input parameters) has been used with errors essentially equivalent to those determined for the Lydersen method. While analytical equations of state are not often used when only densities are required, values from equations of state are used as inputs to equation of state formulations for thermal and equilibrium properties.

Liquid Density Prediction Methods for the prediction of pure saturated hydrocarbons and nonhydrocarbon organics, compressed hydrocarbon liquids, and defined and undefined hydrocarbon mixtures were evaluated. Only the most accurate and convenient methods are included here.

The most convenient method for predicting the saturated liquid density of both **pure hydrocarbons and pure organic liquids** is the method of Rackett[84] as modified by Spencer and Danner.[99] Equation (2-84) is used to calculate the saturated liquid molar density at any temperature using input parameters of T_c, P_c, and Z_{RA}. Z_{RA} is a parameter regressed from experimental data. Values for some common substances are given in Table 2-396. Extensive tabulations are given in the *Technical Data Book*[23] for hydrocarbons and nonhydrocarbons as well as organic and inorganic gases. Additional values are given in the *Data Prediction Manual*[22] for nonhydrocarbons.

$$\frac{1}{\rho_{\text{sat}}} = V_{\text{sat}} = \left(\frac{RT_c}{P_c}\right) Z_{RA}^{n} \tag{2-84}$$

$$n = 1.0 + (1.0 - T_r)^{2/7}$$

Errors for hydrocarbons between the triple and critical points average about 0.7 percent, with organics averaging about 1.2 percent. The cor-

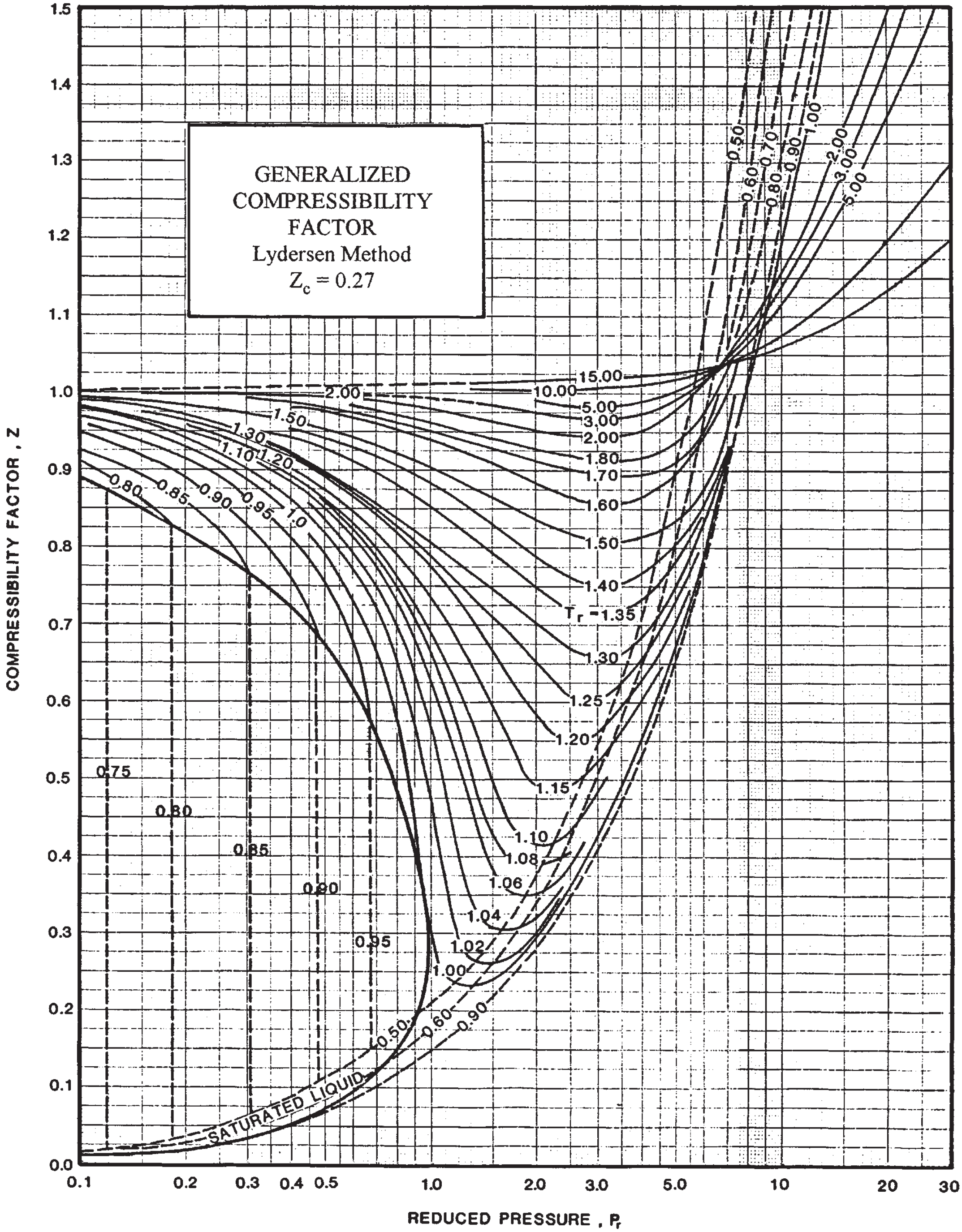


FIG. 2-37 Generalized compressibility factor—Lydersen Method, $Z_c = 0.27$.

relation is especially sensitive to the value of Z_{RA} near the critical point.

If no value of Z_{RA} is available or derivable, the critical compressibility factor can be used in Eq. (2-84) as originally proposed by Rackett. Use of Z_c increases the average error to about 3.0 percent.

Example 20 Estimate the density of saturated liquid propane at 0°C. Use Eq. (2-84).

$$\rho_{\text{sat}} = \left(\frac{P_c}{RT_c}\right)\left(\frac{1}{Z_{\text{RA}}^n}\right)$$

$$n = 1.0 + (1.0 - T_r)^{2/7}$$

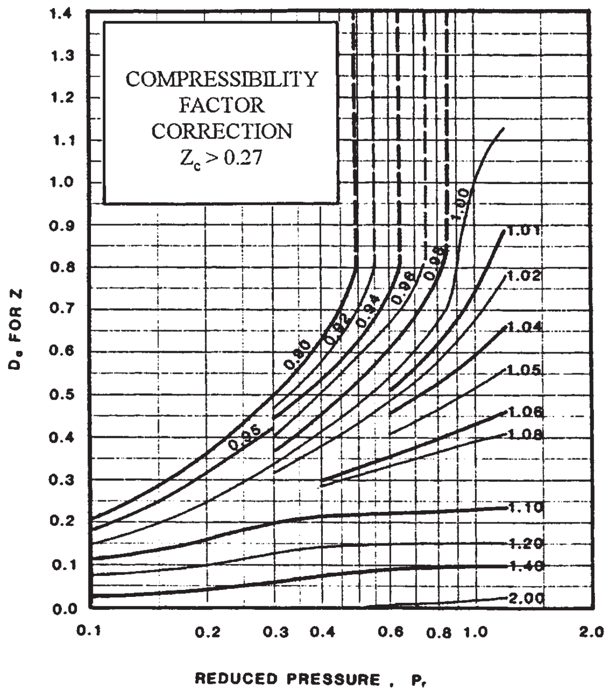


FIG. 2-38 Compressibility factor correction for Lydersen Method, $Z_c > 0.27$.

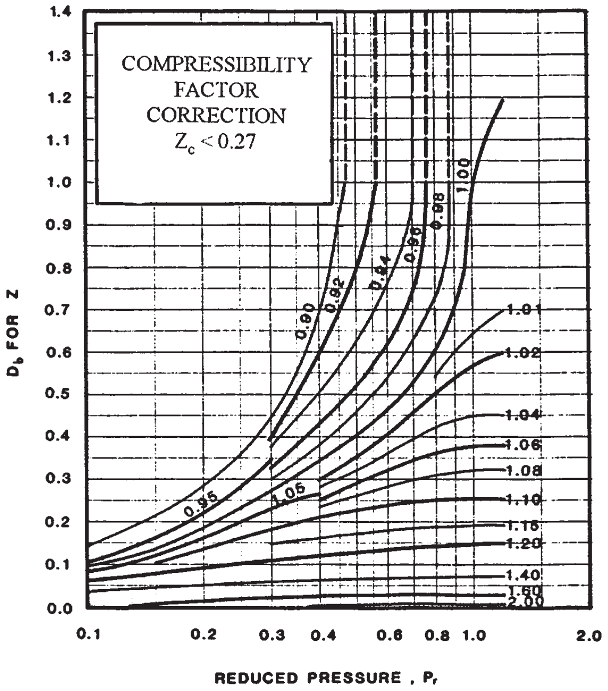


FIG. 2-39 Compressibility factor correction for Lydersen Method, $Z_c < 0.27$.

Pure component properties of propane are $M = 44.1$, $T_c = 96.7°C$, and $P_c = 4.246$ MPa. From Table 2-388, $Z_{RA} = 0.2763$.

$$T_r = \frac{273.1}{369.8} = 0.739, \quad n = 1.0 + (1.0 - 0.739)^{2/7} = 1.6813$$

$$n = 1.6813$$

$$\rho_{\text{sat}} = \frac{(4.246 \times 10^6)}{(8314)(369.8)}\left(\frac{1}{0.2763^{1.6813}}\right)$$

$$\rho_{\text{sat}} = 1.201 \text{ kmole/m}^3 = 529.6 \text{ kg/m}^3$$

An accepted experimental value is 531 kg/m^3.

An alternate method with approximately the same accuracy as the Rackett method is the COSTALD method of Hankinson and Thomson.[35] The critical temperature, a characteristic volume near the critical volume, and an acentric factor optimized for vapor pressure prediction by the Soave[98] equation of state are required input parameters. The method is detailed in the *Technical Data Book*.[23]

Prediction of the density of **compressed pure liquid hydrocarbons** and their defined mixtures are readily and accurately predicted by the method of Lu.[62] One value of low pressure liquid density and the critical temperature and pressure are required to predict the density at higher pressures from Eq. (2-85).

$$\rho_2 = \left(\frac{C_2}{C_1}\right)\rho_1 \tag{2-85}$$

The constants C_1 and C_2 are both obtained from Fig. 2-40: C_1, usually from the saturated liquid line; and C_2, at the higher pressure. Errors should be less than 1 percent for pure hydrocarbons except at reduced temperatures above 0.95 where errors of up to 10 percent may occur. The method can be used for defined mixtures substituting pseudocritical properties for critical properties. For mixtures, the *Technical Data Book—Petroleum Refining* gives a more complex and accurate mixing rule than merely using the pseudocritical properties. The saturated low pressure value should be obtained from experiment or from prediction procedures discussed in this section for both pure and mixed liquids.

Example 21 Estimate the liquid density of *n*-nonane at 104.5°C and 6.893 MPa pressure.

A tabulated value of liquid density at 60°F (15.5°C) and 1 atm is 719.8 kg/m^3. Pure component properties are $T_c = 321.5°C$ and $P_c = 2.288$ MPa.

Use Eq. (2-85) to correct a low pressure density.

$$\rho_2 = \left(\frac{C_2}{C_1}\right)\rho_1$$

where ρ_1 is a reference density. C_2 and C_1 are functions of T_r and P_r.

$$T_{r_1} = \frac{288.6}{594.6} = 0.485 \qquad T_{r_2} = \frac{377.6}{594.6} = 0.635$$

$$P_{r_1} = \frac{0.1013}{2.288} = 0.0443 \qquad P_{r_2} = \frac{6.893}{2.288} = 3.013$$

From Fig. 2-40, $C_1 = 1.08$ and $C_2 = 0.998$.

$$\rho_2 = \left(\frac{0.998}{1.08}\right)(719.8) = 665.1 \text{ kg/m}^3$$

An accepted experimental value at this temperature is 658.5 kg/m^3, a 1 percent difference.

An analytical method for the prediction of compressed liquid densities was proposed by Thomson et al.[114] The method requires the saturated liquid density at the temperature of interest, the critical temperature, the critical pressure, an acentric factor (preferably the one optimized for vapor pressure data), and the vapor pressure at the temperature of interest. All properties not known experimentally may be estimated. Errors range from about 1 percent for hydrocarbons to 2 percent for nonhydrocarbons.

For prediction of the densities of a **defined liquid mixture at its bubble point** (ρ_{bp}), the method of Spencer and Danner[100] is the simplest. The density is calculated from Eq. (2-86) using inputs from Eqs. (2-87) and (2-88). For hydrocarbons, T_{mc} is calculated by Eqs. (2-89) through (2-92) if high accuracy is desired or by Eq. (2-93) for a less accurate answer.

$$\frac{1}{\rho_{bp}} = R\left(\sum_{i=1}^{n} x_i \frac{T_{c_i}}{P_{c_i}}\right) Z_{RA_m}^{[1+(1-T_r)^{2/7}]} \tag{2-86}$$

$$Z_{RA_m} = \sum_{i=1}^{n} x_i Z_{RA_i} \tag{2-87}$$

$$T_r = \frac{T}{T_{mc}} \tag{2-88}$$

$$T_{mc} = \sum_{i=1}^{n}\sum_{j=i}^{n} \phi_i \phi_j T_{c_{ij}} \tag{2-89}$$

TABLE 2-396 The Modified Rackett Equation Input Parameters for Calculating Pure Saturated Liquid Densities

Liquid	Z_{RA}
Hydrocarbons	
Methane	0.2880
Ethane	0.2819
Propane	0.2763
n-Butane	0.2730
2-Methylpropane (isobutane)	0.2760
n-Pentane	0.2685
n-Hexane	0.2637
n-Heptane	0.2610
n-Octane	0.2569
n-Nonane	0.2555
n-Decane	0.2527
n-Dodecane	0.2471
n-Tetradecane	0.2270
n-Hexadecane	0.2386
n-Octadecane	0.2292
n-Eicosane	0.2281
Cyclopentane	0.2709
Methylcyclopentane	0.2712
Cyclohexane	0.2729
Methylcyclohexane	0.2702
Ethene (ethylene)	0.2813
Propene (propylene)	0.2783
1-Butene	0.2735
cis-2-Butene	0.2705
trans-2-Butene	0.2722
2-Methylpropene (isobutylene)	0.2727
1-Hexene	0.2654
1,3-Butadiene	0.2713
2-Methyl-1,3-butadiene	0.2680
Ethyne (acetylene)	0.2707
Propyne (methylacetylene)	0.2703
Benzene	0.2696
Methylbenzene (toluene)	0.2645
Ethylbenzene	0.2619
1,2-Dimethylbenzene (*o*-xylene)	0.2626
1,3-Dimethylbenzene (*m*-xylene)	0.2594
1,4-Dimethylbenzene (*p*-xylene)	0.2590
Isopropylbenzene (cumene)	0.2616
Biphenyl	0.2746
Naphthalene	0.2611
Organics	
Acetic acid	0.2242
Methanol	0.2340
Ethanol	0.2523
2-Propanol	0.2508
Acetaldehyde	0.2387
Acetone	0.2448
Methyl ethyl ketone	0.2524
Methyl isobutyl ketone	0.2589
Ethylamine	0.2640
Aniline	0.2607
Methyl formate	0.2581
Methyl acetate	0.2553
Ethyl acetate	0.2538
Ethyl acrylate	0.2583
Methyl-*n*-butyl ether	0.2655
Diethyl ether	0.2643
Diisopropyl ether	0.2699
Halogen Compounds	
Methyl chloride	0.2679
Dichloromethane	0.2619
Chloroform	0.2751
Tetrachloromethane	0.2721
Chlorobenzene	0.2650
Propionitrile	0.2156
Inorganics	
Ammonia	0.2466
Argon	0.2933
Carbon dioxide	0.2729
Carbon disulfide	0.2850
Carbon monoxide	0.2898
Chlorine	0.2781
Hydrogen	0.3218
Hydrogen chloride	0.2673
Hydrogen sulfide	0.2818
Nitrogen	0.2893
Oxygen	0.2890
Sulfur dioxide	0.2667
Sulfur trioxide	0.2513

$$\phi_i = \frac{x_i V_{c_i}}{\sum_{j=1}^{n} x_j V_{c_j}} \tag{2-90}$$

$$T_{c_{ij}} = \sqrt{T_{c_i} T_{c_j}}\,(1 - k_{ij}) \tag{2-91}$$

$$k_{ij} = 1.0 - \left[\frac{\sqrt{V_{c_i}^{1/3} V_{c_j}^{1/3}}}{(V_{c_i}^{1/3} + V_{c_j}^{1/3})/2}\right]^3 \tag{2-92}$$

$$T_{mc} = \sum_{i=1}^{n} x_i T_{c_i} \tag{2-93}$$

Errors for binary hydrocarbon systems average about 2.5 percent except near the critical, where errors can approach 20 percent. If inorganic gases are included, errors average 4 percent except at high concentrations of carbon dioxide or hydrogen, where higher errors would be expected. If the simplified method for predicting T_{mc} is used, average errors of 5 to 7 percent should be expected for both binary hydrocarbon and nonhydrocarbon systems. No data are available to test the method for systems with more than two components.

A similarly accurate but slightly more complex method for prediction of densities of defined liquid hydrocarbon mixtures at their bubble points was published by Hankinson and Thomson[35] and was previously cited for prediction of pure liquid hydrocarbons.

For undefined hydrocarbon mixtures, the liquid density may be predicted at any temperature (T) from the mean average boiling point (MeABP) and the specific gravity (sp gr) by Eq. (2-94), adopted from Ritter et al.[92]

$$P = 62.3636\left[(\text{sp gr})^2 - \frac{(1.2655)(\text{sp gr}) - 0.5098 + 8.011 \times 10^{-5}\text{MeABP}(T - 519.67)}{\text{MeABP}}\right]^{1/2} \tag{2-94}$$

The density is calculated in $\text{lb}_\text{m}/\text{ft}^3$ if the temperatures are both in °R. Errors average about 0.3 percent at atmospheric pressure. At high pressures, the liquid density of undefined hydrocarbon mixtures can be predicted from the low pressure value by the method of Wright[131] fully outlined in the *Technical Data Book.*[23]

Solid Density Prediction The prediction of solid density is an inexact science and sometimes is taken as the liquid density at the triple point, although the solid density normally is higher than this value with a discontinuity at the triple point. Based on solid density data reviewed for the DIPPR compilation,[24] the solid density at the triple point can be estimated for organic compounds as 1.17 times the liquid density at the triple point. As liquid density at low temperatures varies little with temperature, the density of the liquid at the lowest estimable point above the triple point can be used with little degradation of the result. As solid density only decreases very slightly with increasing temperature and very little data on solid density as a function of temperature exist, no methods have been developed for predicting the solid density vs. temperature.

VISCOSITY

Viscosity is defined as the shear stress per unit area at any point in a confined fluid divided by the velocity gradient in the direction perpendicular to the direction of flow. If this ratio is constant with time at a given temperature and pressure for any species, the fluid is called a Newtonian fluid. This section is limited to Newtonian fluids, which include all gases and most nonpolymeric liquids and their mixtures. Most polymers, pastes, slurries, waxy oils, and some silicate esters are examples of non-Newtonian fluids.

The absolute viscosity (μ) is defined as the sheer stress at a point

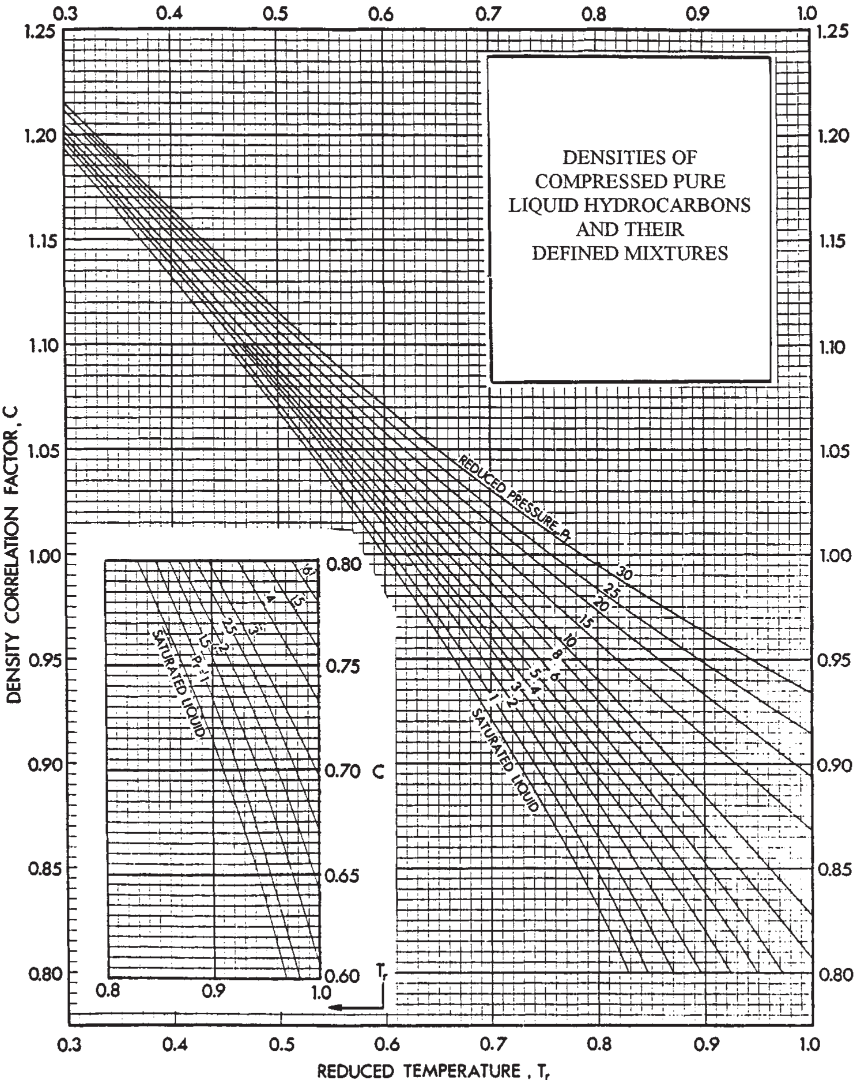


FIG. 2-40 Densities of compressed pure liquid hydrocarbons and their defined mixtures.

divided by the velocity gradient at that point. The most common unit is the poise (1 g/cm sec). The SI unit is the Pa·sec (1 kg/m sec). As many common fluids have viscosities in the hundredths of a poise the centipoise (cp) is often used. One centipoise is then equal to one mPa sec.

The kinematic viscosity (ν) is defined as the ratio of the absolute viscosity to density at the same temperature and pressure. The most common unit corresponding to the poise is the stoke (1 cm^2/sec). The SI unit would be m^2/sec.

Correlation Methods This section briefly discusses methods for correlating viscosities as a function of temperature and presents the most common accurate methods for prediction of vapor and liquid viscosity.

Vapor viscosity is accurately correlated as a function of temperature by Eq. (2-95).

$$\mu_v = \frac{AT^B}{1 + \frac{C}{T} + \frac{D}{T^2}} \tag{2-95}$$

If data are available over a wide range, all four regression constants (*A*, *B*, *C*, and *D*) are usually used. Over narrow temperature ranges, only constants *A* and *B* are necessary.

Liquid viscosity is accurately correlated as a function of temperature by the modified Riedel equation previously discussed for correlation of vapor pressure and shown by Eq. (2-96).

$$\mu_\ell = \exp\left(A + \frac{B}{T} + C\ln(T) + DT^E\right) \tag{2-96}$$

For most systems, only the first three terms are used. Only the first two terms are used for narrow ranges. If data are available in a wide range extending far above the normal boiling point, all four terms are used, with values of *E* varying in integers from −10 to 10 (excluding 0 and −1).

Constants for about 1500 compounds for both viscosities are available in the DIPPR compilation.[24]

Vapor Viscosity Methods for prediction of vapor viscosity abound such that only the most accurate and generally used methods are included.

For prediction of the vapor viscosity of **pure hydrocarbons at low pressure** (below T_r of 0.6), the method of Stiel and Thodos[101] is the most accurate. Only the molecular weight, the critical temperature, and the critical pressure are required. Equation (2-97) with values of N from Eqs. (2-98) and (2-99) is used.

$$\mu_v = 4.60 \times 10^{-4}\,\frac{NM^{1/2}P_c^{2/3}}{T_c^{1/6}} \tag{2-97}$$

$$N = 0.0003400T_r^{0.94} \quad \text{for } T_r \le 1.5 \tag{2-98}$$

$$N = 0.0001778(4.58T_r - 1.67)^{0.625} \quad \text{for } T_r > 1.5 \tag{2-99}$$

The resultant viscosity is in centipoise (mPa·sec) if T_c and P_c are given in K and Pa, respectively. This method can also be used for light nonhydrocarbon gases except for hydrogen where, special N's are required. For hydrocarbons below ten carbon atoms, average errors of about 3 percent can be expected, with errors increasing to 5–10 percent for heavier hydrocarbons.

Example 22 Estimate the vapor viscosity of propane at 101.3 kPa and 80°C.

Use Eq. (2-97).

$$\mu_v = 4.60 \times 10^{-4}N\,\frac{M^{1/2}P_c^{2/3}}{T_c^{1/6}}$$

$$T_c = 96.7°\text{C}, \quad P_c = 4.246 \text{ MPa}, \quad \text{and } M = 44.1.$$

To determine whether Eq. (2-98) or (2-99) should be used to calculate N, calculate T_r.

$$T_r = \frac{80 + 273.1}{96.7 + 273.1} = 0.955$$

Use Eq. (2-98): $\qquad N = 0.0003400T_r^{0.94}$

Thus, $N = 3.255 \times 10^{-4}$.

$$\mu_v = \frac{(4.60 \times 10^{-4})(3.255 \times 10^{-4})(44.1)^{1/2}(4.246 \times 10^6)^{2/3}}{(369.8)^{1/6}}$$

$$\mu_v = 0.0097 \text{ cp}$$

An experimental value of 0.0095 cp compares favorably.

For prediction of the vapor viscosity of **gaseous mixtures of hydrocarbons and nonhydrocarbon gases at low pressures** below a T_r of 0.6, the method of Bromley and Wilke[13] is recommended.

The mixing rule is given by Eq. (2-100) with the interaction parameter Q for each pair of components defined by Eq. (2-101).

$$\mu_m = \sum_{i=1}^{n} \frac{\mu_i}{1 + \sum\limits_{\substack{j=1\\ j\neq 1}}^{n}\left(Q_{ij}\,\dfrac{x_j}{x_i}\right)} \tag{2-100}$$

$$Q_{ij} = \frac{1 + \left[\left(\dfrac{\mu_i}{\mu_j}\right)^{1/2}\left(\dfrac{M_j}{M_i}\right)^{1/4}\right]^2}{\sqrt{8}\left[1 + \dfrac{M_i}{M_j}\right]^{1/2}} \tag{2-101}$$

Errors, when tested against binary and multicomponent mixtures of both hydrocarbons and nonhydrocarbon gas mixtures, average about 3 percent.

For prediction of the vapor viscosity of **gaseous hydrocarbons and mixtures of hydrocarbons at high pressures** (not applicable to nonhydrocarbon gases) above a T_r of 0.6, low pressure values are calculated from Eq. (2-97) and/or (2-100) and then corrected for pressure by the method of Dean and Stiel[25] given by Eq. (2-102).

$$\mu - \mu_o = 5.0 \times 10^{-8}\,\frac{M^{1/2}P_c^{2/3}}{T_c^{1/6}}\,[\exp(1.439\rho_r) - \exp(-1.11\rho_r^{1.858})] \tag{2-102}$$

If critical pressure and critical temperature are given in Pa and K, respectively, viscosities in centipoise result. The variable μ_o is either the low pressure pure component or mixture viscosity according to whether a pure component or mixture is being considered. For mixtures, simple molar average pseudocritical temperature (Kay's rule), pressure, and density, and molar average molecular weight are used. The vapor density can be predicted by the methods previously discussed. Errors of above 5 percent are common for hydrocarbons and their mixtures. Experimental densities will reduce the errors slightly.

Example 23 Estimate the vapor viscosity of a mixture of propane and methane. Assume 60 mole percent methane and 40 mole percent propane at 125°C and 10.34 MPa total pressure. The low pressure viscosity is 0.0123 cp.

Use Eq. (2-102):

$$\mu - \mu_o = 5.0 \times 10^{-8}\,\frac{M^{1/2}P_c^{2/3}}{T_c^{1/6}}\,[\exp(1.439\rho_r) - \exp(-1.11\rho_r^{1.858})]$$

Properties of the pure components are:
Methane. $M = 16.04$, $T_c = -110.4°\text{C}$, $P_c = 4.593$ MPa
Propane. $M = 44.10$, $T_c = 96.7°\text{C}$, $P_c = 4.246$ MPa

For the mixture:
$T_{pc} = (0.60)(-110.4 + 273.1) + (0.40)(96.7 + 273.1) = 245.5$ K
$P_{pc} = (0.60)(4.593) + (0.40)(4.246) = 4.454$ MPa
$M_m = (0.60)(16.04) + (0.40)(44.10) = 27.26$

To calculate ρ_r, use Eq. (2-76) to calculate ρ using Pitzer corresponding states first to calculate Z. Then calculate $\rho_r = \rho/\rho_c = \rho V_{pc}$

Additional properties required are:
Methane $\omega = 0.0115$, $V_c = 0.0986$ m³/kmole
Propane $\omega = 0.1523$, $V_c = 0.2002$ m³/kmole

For the mixture:
$\omega_m = (0.60)(0.0115) + (0.40)(0.1523) = 0.0678$
$V_{pc} = (0.60)(0.0986) + (0.40)(0.2002) = 0.1392$ m³/kmole

Using Eq. (2-58): $\qquad Z = Z^{(0)} + \omega Z^{(1)}$

$$T_r = \frac{398.1}{245.5} = 1.62 \qquad P_r = \frac{10.34}{4.454} = 2.32$$

From Fig. 2-35: $\qquad Z^{(0)} = 0.87$

From Fig. 2-36: $\qquad Z^{(0)} \cong 0.20$

$$Z = 0.87 + (0.0678)(.20) = 0.88$$

Hence: $$\rho = \frac{P}{ZRT} = \frac{(10.34)}{(0.88)(8.314 \times 10^{-3})(398.1)}$$

$$\rho = 3.55 \text{ kmole/m}^3$$

$$\rho_r = \rho V_{pc} = (3.55)(.1392) = 0.494$$

$$\mu - \mu_o = \frac{(5.0 \times 10^{-8})(27.26)^{1/2}(4.454 \times 10^6)^{2/3}}{(245.5)^{1/6}}[e^{1.439(.494)} - e^{-1.11(.494)^{1.858}}]$$

$$\mu - \mu_o = \frac{(5.08 \times 10^{-8})(5.22)(27{,}085)}{(2.503)}[2.0358 - 0.7413]$$

$$\mu - \mu_o = 0.0037$$

$$\mu = 0.0037 + 0.0123 = 0.0160 \text{ cp}$$

An experimental value of 0.0167 cp compares favorably.

For **pure nonhydrocarbon polar gases at low pressures,** the viscosity can be estimated by the method of Reichenberg[85] given by Eq. (2-103).

$$\mu = \frac{AT_r}{[1 + 0.36T_r(T_r - 1)]^{1/6}} \tag{2-103}$$

For organic compounds:

$$A = \frac{M^{1/2}T_c}{\sum n_iC_i} \tag{2-104}$$

For inorganic gases:

$$A = 1.6104 \times 10^{-10}\left[\frac{M^{1/2}P_c^{2/3}}{T_c^{1/6}}\right] \tag{2-105}$$

Viscosities are calculated in Pa sec (10³ cp = 1 Pa sec) with T_c in K and P_c in Pa. Group contributions based on atomic structure for organic compounds necessary for Eq. (2-104) are tabulated in Table 2-397. Errors average about 5 percent for most organics, with slightly higher errors for inorganic gases. For pure nonhydrocarbon nonpolar gases, an alternate method is the method of Yoon and Thodos,[132] which requires the same input parameters as the Reichenberg method. The method, when evaluated for the *Technical Data Manual*, showed errors of about 3 percent for compounds with low dipole moments and requires special correlations for hydrogen and helium.

Example 24 Estimate the vapor viscosity of isopropyl alcohol at 251°C and atmospheric pressure.

Use Eq. (2-103) with A determined from Eq. (2-104).

$$\mu = \frac{AT_r}{[1 + 0.36T_r(T_r - 1)]^{1/6}}$$

$$A = \frac{M^{1/2}T_c}{\sum n_iC_i}$$

TABLE 2-397 Group Contribution Values for Eq. (2-104)

Group	Contribution $C_i \times 10^{-8}$ m·s·K/kg
$-CH_3$	0.904
$>CH_2$ (nonring)	0.647
$>CH-$ (nonring)	0.267
$>C<$ (nonring)	−0.153
$=CH_2$	0.768
$=CH-$ (nonring)	0.553
$>C=$ (nonring)	0.178
$\equiv CH$	0.741
$\equiv C-$ (nonring)	0.524
$>CH_2$ (ring)	0.691
$>CH-$ (ring)	0.116
$>C<$ (ring)	0.023
$=CH-$ (ring)	0.590
$>C=$ (ring)	0.359
$-F$	0.446
$-Cl$	1.006
$-Br$	1.283
$-OH$ (alcohols)	0.796
$>O$ (nonring)	0.359
$>C=O$ (nonring)	1.202
$-CHO$ (aldehydes)	1.402
$-COOH$ (acids)	1.865
$-COO-$ (esters) or $HCOO-$ (formates)	1.341
$-NH_2$	0.971
$>NH$ (nonring)	0.368
$=N-$ (ring)	0.497
$-CN$	1.813
$>S$ (ring)	0.886

Pure component properties are $T_c = 508.3$ K and $M = 60.1$.

Isopropyl alcohol group contributions for $\sum n_i C_i$ are calculated using Table 2-397.

$$2 \; -CH_3 \text{ groups} = (2)(.904 \times 10^8) +$$

$$1 \; >CH- \text{ group} = (1)(.267 \times 10^8) +$$

$$1 \; -OH \text{ group} = (1)(.796 \times 10^8) = 2.871 \times 10^8$$

$$T_r = \frac{524.1}{508.3} = 1.031$$

$$A = \frac{60.1^{1/2}(508.3)}{2.871} \times 10^8 = 1.373 \times 10^{-5} \text{ Pa sec}$$

$$\mu = \frac{(1.373 \times 10^{-5})(1.031)}{[1 + 0.36(1.031)(.031)]^{1/6}} = 1.413 \times 10^{-5} \text{ Pa sec}$$

(An experimental value of 1.380×10^{-5} Pa sec compares favorably.)

For **pure nonhydrocarbon polar and nonpolar gases at high pressure,** a method of prediction attributed to Stiel and Thodos[102] depending on the reduced density as a corrector to the low pressure gas viscosity (μ^o) takes various forms for polar gases according to the reduced density (ρ_r) as shown in Eqs. (2-106) through (2-109).

$$\rho_r \le 0.1 \qquad (\mu - \mu^o)B = 1.656 \times 10^{-7}\rho_r^{1.111} \qquad (2\text{-}106)$$

$$0.1 \le \rho_r \le 0.9 \qquad (\mu - \mu^o)B = 6.07 \times 10^{-9}(9.045\rho_r + 0.63)^{1.739} \qquad (2\text{-}107)$$

$$0.9 \le \rho_r < 2.2 \qquad \log\{4 - \log_{10}[(\mu - \mu^o)10^7 B]\} = 0.6439 - 0.1005\rho_r \qquad (2\text{-}108)$$

$$2.2 \le \rho_r < 2.6 \qquad \log\{4 - \log_{10}[(\mu - \mu^o)10^7 B]\} = 0.6439 - 0.1005\rho_r - 4.75 \times 10^{-4}(\rho_r^3 - 10.65)^2 \qquad (2\text{-}109)$$

$$B = 2173.424\, T_c^{1/6} M^{-1/2} P_c^{-2/3} \qquad (2\text{-}110)$$

For nonpolar gases, Jossi et al.[45] extended the method as shown in Eq. (2-111) for $0.1 < \rho_r < 3.0$.

$$[(\mu - \mu^o)B10^7 + 1]^{1/4} = 1.0230 + 0.23364\rho_r + 0.58533\rho_r^2 - 0.40758\rho_r^3 + 0.093324\rho_r^4 \qquad (2\text{-}111)$$

In all cases viscosities are in Pa sec with T_c in K and P_c in Pa. For nonpolars, errors are very small; while for polars, average errors reach 11 percent.

Example 25 Estimate the vapor viscosity of carbon dioxide at 350 K and a total pressure of 20 MPa. An experimental low pressure viscosity at 350 K is 1.7386×10^{-5} Pa sec.

Use Eq. (2-111) with B calculated by Eq. (2-110).

The pure component properties necessary are T_c = 304.19 K, P_c = 7.3815 MPa, $V_c = 0.094$ m^3/kmole, and $M = 44.01$.

Using the Lee-Kesler form of the Pitzer method [Eq. (2-78)], $Z = 0.4983$.

$$\rho_r = \frac{V_c}{V} = \frac{V_c P}{ZRT} = \frac{(0.094)(2 \times 10^7)}{(0.4983)(8314)(350)} = 1.2965$$

$$B = \frac{2173.424 T_c^{1/6}}{M^{1/2} P_c^{2/3}} = \frac{(2173.424)(304.19)^{1/6}}{(44.01)^{1/2}(7.3815 \times 10^6)^{2/3}}$$

$$B = 2.2411 \times 10^{-2}$$

$$[(\mu - \mu^o)B10^7 + 1]^{1/4} = 1.0230 + 0.23364(1.2965) + 0.58533(1.2965)^2 - 0.40758(1.2965)^3 + 0.093324(1.2965)^4 = 1.6852$$

$$(\mu - 1.7386 \times 10^{-5})(2.2411 \times 10^{-2})(10^7) + 1 = 8.0659$$

$$\mu - 1.7386 \times 10^{-5} = 3.1529 \times 10^{-5}$$

$$\mu = 4.89 \times 10^{-5} \text{ Pa sec}$$

An experimental value of 4.73×10^{-5} Pa sec compares favorably.

For both polar and nonpolar **nonhydrocarbon gaseous mixtures at low pressures,** the most accurate viscosity prediction method is the method of Brokaw.[10,11] The method is quite accurate but requires the dipole moment and the Stockmayer energy parameter (ε/k) for polar components as well as pure component viscosities, molecular weights, the normal boiling point, and the liquid molar volume at the normal boiling point. The *Technical Data Manual* should be consulted for the full method.

For nonpolar, nonhydrocarbon vapor mixtures at high pressures, the method of Dean and Stiel[25] [Eq. (2-102)] discussed earlier can be used. The accuracy of the method is excellent and dependent on the pure component viscosity values used as input parameters.

Liquid Viscosity The viscosity of both **pure hydrocarbon and pure nonhydrocarbon liquids** are most accurately predicted by the method of van Velzen et al.[122] The basic equation (2-112) depends on group contributions which are dependent on structure for the calculation of compound-specific constants B and T_o.

$$\log \mu = B\left(\frac{1}{T} - \frac{1}{T_o}\right) - 3.0 \tag{2-112}$$

Resultant viscosities are in Pa sec. If the −3.0 on the right is deleted, answers are in cp. T_o is calculated by Eq. (2-114) or (2-115) according to the value of an adjusted carbon number N^* calculated by Eq. (2-113) using the actual carbon number N and group contributions from Table 2-398.

$$N^* = N + \sum_i \Delta N_i \tag{2-113}$$

$$N^* \le 20 \quad T_o = 28.86 + 37.439N^* - 1.3547N^{*2} + 0.02076N^{*3} \tag{2-114}$$

$$N^* > 20 \quad T_o = 8.164N^* + 238.59 \tag{2-115}$$

TABLE 2-398 Group Contribution Values for Liquid Viscosity Prediction

Structures or functional group	ΔN_i	ΔB_i	Remarks
n-Alkanes	0	0	
Isoalkanes	$1.389 - 0.238N$	15.51	
Saturated hydrocarbons with two methyl groups in isoposition	$2.319 - 0.238N$	15.51	
n-Alkanes	$-0.152 - 0.042N$	$-44.94 + 5.410N^*$	
n-Alkadienes	$-0.304 - 0.084N$	$-44.94 + 5.410N^*$	
Isoalkanes	$1.237 - 0.280N$	$-36.01 + 5.410N^*$	
Isoalkadienes	$1.085 - 0.322N$	$-36.01 + 5.410N^*$	
Hydrocarbon with one double bond and two methyl groups in isoposition	$2.626 - 0.518N$	$-36.01 + 5.410N^*$	For any additional CH_3 groups in isoposition, increase ΔN by $1.389 - 0.238N$
Hydrocarbon with two double bonds and two methyl groups in isoposition	$2.474 - 0.560N$	$-36.01 + 5.410N^*$	For any additional CH_3 groups in isoposition, increase ΔN by $1.389 - 0.238N$
Cyclopentanes	$0.205 + 0.069N$	$-45.96 + 2.224N^*$	$N \le 16$; not recommended for $N = 5,6$
	$3.971 - 0.172N$	$-339.67 + 23.135N^*$	$N \ge 16$
Cyclohexanes	1.48	$-272.85 + 25.041N^*$	$N < 17$; not recommended for $N = 6,7$
	$6.517 - 0.311N$	$-272.85 + 25.041N^*$	$N \ge 17$
Alkyl benzenes	0.60	$-140.04 + 13.869N^*$	$N < 16$; not recommended for $N = 6,7$[a,e,f]
	$3.055 - 0.161N$	$-140.04 + 13.869N^*$	$N \ge 16$[a,e,f]
Polyphenols	$-5.340 + 0.815N$	$-188.40 + 9.558N^*$	[a]
Alcohols			
Primary	$10.606 - 0.276N$	$-589.44 + 70.519N^*$	[b]
Secondary	$11.200 - 0.605N$	497.58	[b]
Tertiary	$11.200 - 0.605N$	928.83	[b]
Diols (correction)	See remarks	557.77	For ΔN, use alcohol contributions and add $N - 2.50$ [a,c,d]
Phenols (correction)	$16.17 - N$	213.68	
—OH on side chain to aromatic ring (correction)	−0.16	213.68	
Acids	$6.795 + 0.365N$	$-249.12 + 22.449N^*$	$N < 11$, not recommended for $N = 1,2$
	10.71	$-249.12 + 22.449N^*$	$N \ge 11$
Isoacids	See remarks	$-249.12 + 22.449N^*$	Calculate ΔB as for straight-chain acid; calculate ΔN for straight-chain acid but reduce ΔN by 0.24 for each methyl group in isoposition
Acids with aromatic nucleus in structure (correction)	4.81	$-188.40 + 9.558N^*$	
Esters	$4.337 - 0.230N$	$-149.13 + 18.695N^*$	If hydrocarbon groups have isoconfiguration, see [e]
Esters with aromatic nucleus in structure (correction)	$-1.174 + 0.376N$	$-140.04 + 13.869N^*$	Add to values of ΔN, ΔB calculated for ester
Ketones	$3.265 - 0.122N$	$-117.21 + 15.781N^*$	If hydrocarbon groups have isoconfiguration, see [e]
Ketones with aromatic nucleus in structure (correction)	2.70	$-760.65 + 50.478N^*$	Add to values of ΔN, ΔB calculated for ketone
Ethers	$0.298 + 0.209N$	$-9.39 + 2.848N^*$	If hydrocarbon groups have isoconfiguration, see [e]
Aromatic ethers	$11.5 - N$	$-140.04 + 13.869N^*$	The ΔN value is not a correction to regular ether value, but the ΔB value is a correction to regular ether[c]
Amines			
Primary	$3.581 + 0.325N$	$25.39 + 8.744N^*$	If hydrocarbon groups have isoconfiguration, see [e]
Primary amine in side chain of aromatic compound (correction)	−0.16	0	Corrections to be added to amine calculation[e]
Secondary	$1.390 - 0.461N$	$25.39 + 8.744N^*$	If hydrocarbon groups have isoconfiguration, see [e]
Tertiary	3.27	$25.39 + 8.744N^*$	If hydrocarbon groups have isoconfiguration, see [e]
Primary amines with NH_2 group on aromatic nucleus	$15.04 - N$	0	The ΔN value is not a correction to regular amine value; to find ΔB, use primary amine value[a,c]
Secondary or tertiary amine with at least one aromatic group attached to amino nitrogen	[f]	[f]	
Nitro compounds			
1-Nitro	$7.812 - 0.236N$	$-213.14 + 18.330N^*$	
2-Nitro	5.84	$-213.4 + 18.330N^*$	Note alkene contribution is necessary
3-Nitro	5.56	$-338.01 + 25.086N^*$	
4-Nitro; 5-Nitro	5.36	$-338.01 + 25.086N^*$	
Aromatic nitrocompounds	$7.182 - 0.236N$	$-213.14 + 18.330N^*$	For aromatic correction, see [f]
Nitrile	$4.039 - 0.0103N$	$-241.66 + 27.937N^*$	

TABLE 2-398 Group Contribution Values for Liquid Viscosity Prediction (*Concluded*)

Structures or functional group	ΔN_i	ΔB_i	Remarks
Amines (*Cont.*)			
Isomethyl on nitrile	$-0.7228 + 0.1755N$	$286.26 - 31.009N^*$	
Aromatic nitrile	$2.321 - 0.2357N$	$-26.063 - 11.516N^*$	
Dinitrile	$10.452 - 1.1276N$	$3599.9 - 199.96N^*$	
Halogenated compounds			
Fluoride	1.43	5.75	
Chloride	3.21	−17.03	e,f
Bromide	4.39	$-101.97 + 5.954N^*$	e,f
Iodide	5.76	−85.32	e,f
Special configurations (corrections)			
$C(Cl)_x$	$1.91 - 1.459x$	−26.38	
—CCl—CCl—	0.96	0	
$—C(Br)_x—$	0.50	$81.34 - 86.850x$	
—CBr—CBr—	1.60	−57.73	
CF_3			
In alcohols	−3.93	341.68	
In other compounds	−3.93	25.55	
Aldehydes	3.38	$146.45 - 25.11N^*$	
Aldehydes with an aromatic nucleus in structure (correction)	2.70	$-760.65 + 50.478N^*$	
Anhydrides	$7.97 - 0.50N$	−33.50	
Anhydrides with an aromatic nucleus in structure (correction)	2.70	$-760.65 + 50.478N^*$	
Amides	$13.12 + 1.49N$	$524.63 - 20.72N^*$	
Amides with an aromatic nucleus in structure (correction)	2.70	$-760.65 + 50.478N^*$	
Sulfide	$3.9965 - 0.1861N$	$-76.676 + 8.1403N^*$	
Isomethyl on sulfide	0.1601	−25.026	

[a] For substitutions on an aromatic nucleus in more than one position, additional corrections are required:

Ortho	$\Delta N = 0.51$	$\Delta B = \begin{cases} -571.94 \text{ (with —OH)} \\ 54.84 \text{ (without —OH)} \end{cases}$
Meta	$\Delta N = 0.11$	$\Delta B = 27.25$
Para	$\Delta N = -0.04$	$\Delta B = 17.57$

[b] For alcohols, if there is a methyl group in the isoposition, increase ΔN by 0.24 and ΔB by 94.23.

[c] If the compound has an aromatic —OH or —NH_2, or if there is an aromatic ether, use ΔN contribution in table but neglect other substituents on the ring such as halogen, CH_3, NO_2, and the like. For the calculation of ΔB, however, such substituents must be taken into account.

[d] For aromatic alcohols and compounds with an —OH on a side chain, the alcohol contribution (primary, etc.) must be included. For example, *o*-chlorophenol:

$\Delta B = \Delta B$ (primary alcohol) $+ \Delta B$ (chlorine) $+ \Delta B$ (phenol) $+ \Delta B$ (ortho correction—see footnote *a*)

With $N^* = 16.17$ (see footnote *c*):

$\Delta B = (-589.44 + 70.519 \times 16.17) + (-17.03) + (213.68) + (-571.94) = 175.56$

$B_a = 745.94 \quad B = B_a + \Delta B = 921.50$

2-Phenylethanol:

$N = 8$; $\Delta N = \Delta N$ (primary alcohol) $+ \Delta N$ (correction) $= [10.606 - (0.276)(8)] + (-0.16) = 8.24$

$N^* = N + \Delta N = 8 + 8.24 = 16.24$

$\Delta B = \Delta B$ (primary alcohol) $+ \Delta B$ (correction) $= [-589.44 + (70.519)(16.24)] + 213.68 = 769.47$

$B_a = 747.43 \quad B = B_a + \Delta B = 1516.9$

[e] For esters, alkylbenzenes, halogenated hydrocarbons, and ketones: If the hydrocarbon chain has a methyl group in an isoposition, decrease ΔN by 0.24 and increase ΔB by 8.93 for each such grouping. For ethers and amines, decrease ΔN by 0.50 and increase ΔB by 8.93 for each isogroup.

[f] For alkylbenzenes, nitrobenzenes, halogenated benzenes and for secondary or tertiary amines where at least one aromatic group is connected to an amino nitrogen, add the following corrections for each aromatic nucleus. If $N < 16$, increase ΔN by 0.60; if $N \geq 16$, increase ΔN by $3.055 - 0.161N$ for each aromatic group. For any N, increase ΔB by $(-140.04 + 13.869N^*)$.

From van Velzen et al. (122).

B is calculated by Eq. (2-116) using values of B_a calculated from Eq. (2-117) or (2-118) according to the value of N^* and group contributions from Table 2-398.

$$B = B_a + \sum_i \Delta B_i \tag{2-116}$$

$$N^* \leq 20 \quad B_a = 24.79 + 66.885N^* - 1.3173N^{*2} - 0.00377N^{*3} \tag{2-117}$$

$$N^* > 20 \quad B_a = 530.59 + 13.740N^* \tag{2-118}$$

The method should not be used for the first member of a homologous series or for temperatures much above the normal boiling point ($T_r \approx 0.75$). Errors for both hydrocarbons and nonhydrocarbons average 15 percent for a wide variety of compounds. Higher errors are noted for amines, diols, ethers, and fluorides. Table 2-398 gives ΔN and ΔB contributions for most common groups. Space prohibits examples for each type of compound or inclusion of specialized cases that are more fully discussed in the *Technical Data Manual.*

Example 26 Estimate the liquid viscosity of *cis*-1,4-dimethylcyclohexane at 0°C.

Use Eq. (2-112) with N^* calculated from Eq. (2-113) and B calculated from Eq. (2-116).

Determine group contributions from Table 2-398.

		ΔN_i	ΔB_i
Cyclohexanes	(1)	1.48	$-272.85 + 25.041\,N^*$
n-Alkanes	(2)	0	0

$$N^* = N + \sum_i n_i \Delta N_i$$

$$N^* = 8 + (1)(1.48) + (2)(0) = 9.48$$

Use Eq. (2-114) to calculate T_o:

$$T_o = 28.86 + 37.439(9.48) - 1.3547(9.48)^2 + (.02076)(9.48)^3$$

$$T_o = 279.72$$

$$B = B_a + \sum_i n_i \Delta B_i$$

Use Eq. (2-117) to calculate B_a:

$$B_a = 24.79 + 66.885(9.48) - 1.3173(9.48)^2 - 0.00377(9.48)^3$$

$$B_a = 537.26$$

$$B = 537.26 + (1)[-272.85 + 25.041\ (9.48)]$$

$$B = 501.80$$

$$\log \mu = B\left(\frac{1}{T} - \frac{1}{T_o}\right) - 3.0$$

$$\log \mu = 501.80\left(\frac{1}{273.15} - \frac{1}{279.72}\right) - 3.0$$

$$\log \mu = -2.9569$$

$$\mu = 0.001104 \text{ Pa sec} = 1.104 \text{ cp}$$

An experimental value at 0°C is 1.224 cp.

A mixing rule developed by Kendall and Monroe[48] is useful for determining the **liquid viscosity of defined hydrocarbon mixtures.** Equation (2-119) depends only on the pure component viscosities at the given temperature and pressure and the mixture composition.

$$\mu_m = \left(\sum_{i=1}^{n} x_i \mu_i^{1/3}\right)^3 \qquad (2\text{-}119)$$

For mixtures of the same chemical family, errors average less than 3 percent, while errors overall average 5–6 percent, with errors of mixed families averaging from 10–15 percent.

For estimating the liquid viscosity of **defined nonhydrocarbon mixtures,** a mixing rule shown by Eq. (2-120) was recommended by the *Technical Data Manual.*

$$\ln \mu_m = \sum_i x_i \ln \mu_i \qquad (2\text{-}120)$$

Errors average near 15 percent.

For interpolating viscosities of hydrocarbon mixtures within a limited range knowing viscosities at two temperatures, ASTM Procedure D341-89, including both charts and equations, is recommended. Several recommended methods for predicting the viscosity of undefined hydrocarbon mixtures, such as petroleum fractions and coal liquids, are presented and evaluated in the *Technical Data Book—Petroleum Refining.* In addition, several methods for determining the liquid viscosity of blends of hydrocarbon mixtures and a method for liquid viscosity of pure hydrocarbons blended with undefined mixtures are given.

The most accurate method for predicting the liquid viscosity of **hydrocarbons containing fewer than 20 carbon atoms at high pressure** is a corresponding states method developed by Graboski and included in the *Technical Data Book—Petroleum Refining.* Critical temperature, critical pressure, the acentric factor, and knowing or being able to calculate at least one viscosity at a reference temperature and pressure are required. Errors average about 5 percent. For high molecular weight hydrocarbons at high pressure, low pressure viscosities can be converted instead of using the method of Kouzel,[51] which requires a low pressure liquid viscosity as input. Compounds of more than 20 carbon atoms and their mixtures are treated in this way.

For predicting the **liquid viscosity of pure hydrocarbon mixtures at high temperatures,** the method of Letsou and Stiel[58] is available. Error analyses with only a small amount of data shows errors averaging 34 percent in the reduced temperature range of 0.76 to 0.98. Equation (2-121) defines the method with inputs of Eqs. (2-122) and (2-123).

$$\mu\left(2173.424\,\frac{T_c^{1/6}}{M^{1/2}P_c^{2/3}}\right) = \mu^{(0)} + \omega\mu^{(1)} \qquad (2\text{-}121)$$

$$\mu^{(0)} = 1.5174 \times 10^{-5} - 2.135 \times 10^{-5} T_r + 7.5 \times 10^{-6} T_r^2 \qquad (2\text{-}122)$$

$$\mu^{(1)} = 4.2552 \times 10^{-5} - 7.674 \times 10^{-5} T_r + 3.4 \times 10^{-5} T_r^2 \qquad (2\text{-}123)$$

Results are in Pa sec with inputs of T_c in K and P_c in Pa.

VAPOR AND LIQUID THERMAL CONDUCTIVITY

Thermal conductivity describes the ease with which conductive heat can flow through a vapor, liquid, or solid layer of a substance. It is defined as the proportionality constant in Fourier's law of heat conduction in units of energy · length/time · area · temperature; e.g., W/m K.

Gases For **pure component, low pressure** (<350 kPa) **hydrocarbon** gases, Misic and Thodos[70,71] recommend the following equations. For **methane** and **cyclic compounds** below reduced temperatures of 1.0:

$$k_G = 4.45 \times 10^{-7}\, T_r \frac{C_p}{\lambda} \qquad (2\text{-}124)$$

For these hydrocarbons above reduced temperatures of 1.0 and for other hydrocarbons at any temperature:

$$k_G = 10^{-7}\,(14.52\,T_r - 5.14)^{2/3}\left(\frac{C_p}{\lambda}\right) \qquad (2\text{-}125)$$

In these equations,

$$\lambda = T_c^{1/6}\, M^{1/2}\left(\frac{101.325}{P_c}\right)^{2/3} \qquad (2\text{-}126)$$

where k_G = vapor thermal conductivity, W/m K
T_r = reduced temperature, T/T_c
T = temperature, K
T_c = critical temperature, K
C_p = heat capacity at constant pressure, J/kmol K
M = molecular weight
P_c = critical pressure, kPa

C_p may be assumed to be the ideal gas heat capacity, C_p^o. Average errors can be expected to be less than 5 percent.

Example 27 Estimate thermal conductivity for *n*-hexane. For *n*-hexane at 373.15 K and low pressure, the required properties from Daubert et al.[24] are: $T_c = 507.6$ K, $M = 86.18$, $P_c = 3025.0$ kPa, and $C_p^o = 1.721 \times 10^5$. $T_r = 373.15/507.6 = 0.7351$. Using Eq. (2-126):

$$\lambda = (507.6)^{1/6}\,(86.18)^{1/2}\left(\frac{101.325}{3025.0}\right)^{2/3}$$

$$\lambda = 2.724$$

Substituting into Eq. (2-125):

$$k_G = 10^{-7}\,[(14.52)(0.7351) - 5.14]^{2/3}\left(\frac{1.721 \times 10^5}{2.724}\right)$$

$$k_G = 0.01977 \text{ W/m K}$$

The reported value is 0.02025 W/m K.[24]

For **pure nonhydrocarbon** gases at low pressures (up through 1 atm), the following equations may be used at temperature T (K):

Monatomic gases[12]: $$k_G = 2.5\,\frac{\eta_G C_v}{M} \qquad (2\text{-}127)$$

Linear molecules[12]: $$k_G = \frac{\eta_G}{M}\left(1.30\,C_v + 14644.0 - \frac{2928.8}{T_r}\right) \qquad (2\text{-}128)$$

Nonlinear molecules[102]: $$k_G = \frac{\eta_G}{M}\,(1.15\,C_v + 16903.36) \qquad (2\text{-}129)$$

where k_G = vapor thermal conductivity, W/m K
η_G = vapor viscosity, Pa·s
C_v = heat capacity at constant volume, J/kmol K
M = molecular weight
T_r = reduced temperature, T/T_c
T_c = critical temperature, K

C_v may be calculated as $C_p^o - R$, where C_p^o is the ideal gas heat capacity in J/kmol K and R is the gas constant, 8314 J/kmol K. Average errors are in the 8–10 percent range but may be higher for polar compounds. This method should not be used for molecules that associate; e.g., organic acids.

Example 28 Estimate thermal conductivity of carbon dioxide at 370 K and low pressure. For carbon dioxide (a linear molecule) at 370.0 K and low pressure, the required properties from Daubert et al.[24] are: $T_c = 304.2$ K, $\eta_G = 1.828 \times 10^{-5}$ Pa·s, $M = 44.01$, and $C_p^o = 40520$ J/kmol K. $T_r = 370.0/304.2 = 1.2163$, and $C_v = 40520 - 8314 = 32206$ J/kmol K. Substituting in Eq. (2-128):

$$k_G = \frac{1.828 \times 10^{-5}}{44.01}\left[(1.30)\,(32206) + 14644.0 - \frac{2928.8}{1.2163}\right]$$

$$k_G = 0.02247 \text{ W/m K}$$

A value of 0.0220 W/m K is obtained from Vargaftik et al.[124]

For pure gases **above atmospheric pressure,** the method of Stiel and Thodos[102] may be used:

$$k_G = k'_G + \frac{A \times 10^{-4}(e^{B\rho_r} + C)}{\left(\dfrac{T_c^{1/6} M^{1/2}}{P_c^{2/3}}\right) Z_c^5} \qquad \text{(2-130)}$$

$$\begin{array}{rlll}
\rho_r < 0.5 & A = 2.702 & B = 0.535 & C = -1.000 \\
0.5 < \rho_r > 2.0 & A = 2.528 & B = 0.670 & C = -1.069 \\
2.0 < \rho_r > 2.8 & A = 0.574 & B = 1.155 & C = 2.016
\end{array}$$

where k_G = vapor thermal conductivity at the temperature T (K) and pressure P of interest, W/m K
k'_G = vapor thermal conductivity at T and atmospheric pressure, W/m K
ρ_r = reduced density = V_c/V
V_c = critical molar volume, m^3/kmol
V = molar volume at T and P, m^3/kmol
T_c = critical temperature, K
M = molecular weight
P_c = critical pressure, MPa
Z_c = critical compressibility factor = P_cV_c/RT_c
R = gas constant = 0.008314 MPa m^3/kmol K

Errors in the range of 5–6 percent are typical with this method but may be higher for branched compounds.

Example 29 Estimate the thermal conductivity of carbon dioxide at 370 K and 10 MPa pressure. The required properties from Daubert et al.[24] are: $T_c = 304.2$ K, $M = 44.01$, $P_c = 7.383$ MPa, and $V_c = 0.0940$ m^3/kmol; $Z_c = (7.383) \times (0.0940)/(0.008314)(304.2) = 0.274$. $k'_G = 0.0220$ W/m K[123], and $V = 0.22809$ m^3/kmol[3]; $\rho_r = 0.0940/0.22809 = 0.4121$. Substituting in Eq. (2-130) using the equation constants A, B, and C for $\rho_r < 0.5$:

$$k_G = 0.0220 + \frac{(2.702 \times 10^{-4})(e^{(0.535)(0.4121)} - 1.000)}{\left(\dfrac{(304.2)^{1/6}(44.01)^{1/2}}{(7.383)^{2/3}}\right)(0.274)^5} = 0.0315 \text{ W/m K}$$

Vargaftik et al.[124] report a value of 0.0308 W/m K.

The thermal conductivity of **low pressure** (1 atm or less) **gas mixtures** can be determined from the relation of Wassiljewa[126]:

$$k_m = \sum_{i=1}^{n} \frac{y_i k_i}{\sum\limits_{j-1}^{n} y_j A_{ij}} \qquad \text{(2-131)}$$

where k_m = mixture thermal conductivity, W/m K
n = number of components
$y_{i,j}$ = mole fraction of component i or j in the vapor mixture
k_i = thermal conductivity of pure component i at the temperature of interest

The binary interaction parameter A_{ij} is obtained by the method of Lindsay and Bromley[61]:

$$A_{ij} = \frac{1}{4}\left\{1 + \left[\left(\frac{\mu_i}{\mu_j}\right)\left(\frac{M_j}{M_i}\right)^{3/4}\left(\frac{T + S_i}{T + S_j}\right)\right]^{1/2}\right\}^2 \left(\frac{T + S_{ij}}{T + S_i}\right) \qquad \text{(2-132)}$$

where $\mu_{i,j}$ = vapor viscosity of pure component i or j at the temperature T of interest and low pressure, Pa·s
$M_{i,j}$ = molecular weight of pure component i or j
T = temperature, K
$S_{ij} = S_{ji}$; see Eq. (2-133)
C = 1.0 except when either or both components i and j are very polar; then $C = 0.73$
$S_{i,j}$ = 79 K for helium, hydrogen, and neon; for all others, see Eq. (2-134)
$T_{bi,j}$ = normal boiling temperature of pure component i or j, K

$$S_{ji} = C(S_iS_j)^{1/2} \qquad \text{(2-133)}$$

$$S_{i,j} = 1.5T_{bi,j} \qquad \text{(2-134)}$$

Expected errors for this method are 4–5 percent. At **higher pressures,** a pressure correction using Eq. (2-130) may be used. The mixture is treated as a hypothetical pure component with mixture critical properties obtained via Eqs. (2-5), (2-8), and (2-17) and with the molecular weight being mole-averaged.

Example 30 Estimate thermal conductivity of a mixture of 0.23 mole fraction dimethylether (1) and 0.77 mole fraction methyl chloride (2) at 373.15 K and low pressure. The required pure component properties from Daubert et al.[24] are: $k_1 = 0.02504$ W/m K, $k_2 = 0.01587$ W/m K, $\mu_1 = 1.161 \times 10^{-5}$ Pa·s, $\mu_2 = 1.361 \times 10^{-5}$ Pa·s, $M_1 = 46.07$, $M_2 = 50.49$, $T_{b1} = 248.3$ K, and $T_{b2} = 248.9$ K. By Eq. (2-134), $S_1 = (1.5)(248.3) = 372.45$, and $S_2 = (1.5)(248.9) = 373.35$. By Eq. (2-133), $S_{12} = S_{21} = (1.0)[(372.45)(373.35)]^{1/2} = 372.90$. Substituting in Eq. (2-132):

$$A_{11} = A_{22} = 1.0$$

$$A_{12} = \frac{1}{4}\left\{1 + \left[\left(\frac{1.161 \times 10^{-5}}{1.361 \times 10^{-5}}\right)\left(\frac{50.49}{46.07}\right)^{3/4}\left(\frac{373.15 + 372.45}{373.15 + 373.35}\right)\right]^{1/2}\right\}^2 \times \left(\frac{373.15 + 372.90}{373.15 + 372.45}\right) = 0.956$$

$$A_{21} = \frac{1}{4}\left\{1 + \left[\left(\frac{1.361 \times 10^{-5}}{1.161 \times 10^{-5}}\right)\left(\frac{46.07}{50.49}\right)^{3/4}\left(\frac{373.15 + 373.35}{373.15 + 372.45}\right)\right]^{1/2}\right\}^2 \times \left(\frac{373.15 + 372.90}{373.15 + 373.35}\right) = 1.047$$

Using Eq. (2-131):

$$k_m = \frac{(0.23)(0.02504)}{(0.23)(1.0) + (0.77)(0.956)} + \frac{(0.77)(0.01587)}{(0.23)(1.047) + (0.77)(1.0)} = 0.01805 \text{ W/m K}$$

The experimental value is 0.01778 W/m K.[66]

Liquids For **pure component hydrocarbon** liquids at reduced temperatures between 0.25 and 0.8 and at pressures below 3.4 MPa, an equation based on the methods of Pachaiyappan et al.[79] and Riedel[88] may be used:

$$k_L = C\rho M^n \left[\frac{3 + 20(1 - T_r)^{2/3}}{3 + 20\left(1 - \dfrac{293.15}{T_c}\right)^{2/3}}\right] \qquad \text{(2-135)}$$

where k_L = liquid thermal conductivity, W/m K
M = molecular weight
ρ = molar density at 293.15 K, kmol/m^3
T_r = reduced temperature, T/T_c
T = temperature, K
T_c = critical temperature, K

For unbranched, straight chain hydrocarbons, $n = 1.001$ and $C = 1.811 \times 10^{-4}$.

For branched and cyclic hydrocarbons, $n = 0.7717$ and $C = 4.407 \times 10^{-4}$.

Average errors are 5 percent when this equation is used. For pressures greater than 3.4 MPa, the thermal conductivity from Eq. (2-135) may be corrected by the technique suggested by Lenoir.[57] The correction factor is the ratio of conductivity factors F/F', where F is at the desired temperature and higher pressure, and F' is at the same temperature and lower pressure (usually atmospheric). The conductivity factors are calculated from:

$$F = 17.77 + 0.065P_r - 7.764T_r - \frac{2.054T_r^2}{e^{0.2\,P_r}} \qquad \text{(2-136)}$$

where T_r = reduced temperature as in Eq. (2-135)
P_r = reduced pressure, P/P_c
P = pressure, MPa
P_c = critical pressure, MPa

The average error in the pressure correction alone is typically 3 percent.

Example 31 Estimate thermal conductivity of n-octane at 373.15 K and pressures of 0.1 MPa and 20.0 MPa. The required properties from Daubert et al.[24] are: ρ at 293.15 K = 6.155 kmol/m^3, $M = 114.2$, $T_c = 568.7$ K, and $P_c = 2.490$ MPa. $T_r = 373.15/568.7 = 0.6561$, $n = 1.001$, and $C = 1.811 \times 10^{-4}$. Substituting in Eq. (2-135) for the thermal conductivity at 0.1 MPa:

$$k_L = (1.811 \times 10^{-4})(6.155)(114.2)^{1.001}\left[\frac{3 + (20)(1 - 0.6561)^{2/3}}{3 + (20)\left(1 - \dfrac{293.15}{568.7}\right)^{2/3}}\right]$$

$$= 0.107 \text{ W/m K}$$

The reported value is 0.111 W/m K.[123] To correct to 20 MPa, $P_r = 20.0/2.490 = 8.032$, and $P'_r = 0.1/2.490 = 0.04016$. Substituting in Eq. (2-136) to calculate F and F':

$$F = 17.77 + (0.065)(8.032) - (7.764)(0.6561) - \frac{(2.054)(0.6561)^2}{e^{(0.2)(8.032)}}$$

$$F = 13.02$$

$$F' = 17.77 + (0.065)(0.04016) - (7.764)(0.6561) - \frac{(2.054)(0.6561)^2}{e^{(0.2)(0.04016)}}$$

$$F' = 11.80$$

Thus, the thermal conductivity of n-octane at 373.15 K and 20.0 MPa is estimated to be (0.111)(13.02/11.80) = 0.122 W/m K as compared with an experimental value of 0.121 W/m K.[123]

For pure component hydrocarbon liquids **above the normal boiling point and all pressures,** the method of Kanitkar and Thodos[46] is recommended:

$$k_L = \frac{\alpha\, e^{\beta\rho_r}}{\lambda} \qquad P < 10{,}000 \text{ kPa} \tag{2-137}$$

$$k_L = \frac{2.596 \times 10^{-4}\, P_r^{1.6} + \alpha\, e^{\beta\rho_r}}{\lambda} \qquad P > 10{,}000 \text{ kPa} \tag{2-138}$$

where k_L = liquid thermal conductivity at the temperature T (K) and pressure P (kPa) of interest, W/m K

$$\alpha = 0.0112\, \beta^{-3.322} \tag{2-139}$$

$$\beta = 0.40 + 0.986 e^{-0.64\lambda} \tag{2-140}$$

$$\lambda = T_c^{1/6} M^{1/2} \left(\frac{101.325}{P_c}\right)^{2/3} \tag{2-141}$$

ρ_r = reduced density = V_c/V
V_c = critical molar volume, m³/kmol
V = molar volume at T and P, m³/kmol
T_c = critical temperature, K
M = molecular weight
P_c = critical pressure, kPa
P_r = reduced pressure, P/P_c

Average errors can be expected to be in the order of 10 percent.

Example 32 Estimate thermal conductivity of n-octane at 473.15 K and 15,000 kPa. The required properties from Daubert et al.[24] are: T_c = 568.7 K, M = 114.2, P_c = 2490.0 kPa, and V_c = 0.4860 m³/kmol. The specific volume at 473.15 K and 15,000 kPa is 0.001717 m³/kg[123]; V = (0.001717)(114.2) = 0.1961 m³/kmol. Thus, P_r = 15000/2490 = 6.024, and ρ_r = 0.4860/0.1961 = 2.478. Substituting in Eqs. (2-141), (2-140), and (2-139):

$$\lambda = (568.7)^{1/6}\,(114.2)^{1/2} \left(\frac{101.325}{2490}\right)^{2/3} = 3.639$$

$$\beta = 0.40 + 0.986 e^{-(0.64)(3.639)} = 0.496$$

$$\alpha = (0.0112)(0.496)^{-3.322} = 0.115$$

Using Eq. (2-138):

$$k_L = \frac{(2.596 \times 10^{-4})(6.024)^{1.6} + 0.115 e^{(0.496)(2.478)}}{3.639} = 0.109 \text{ W/m K}$$

The reported value is 0.106 W/m K.[123]

The thermal conductivity of **pure component nonhydrocarbon** liquids may be estimated by the method of Baroncini et al.,[5] with a modification by Myers[75] for silicon compounds, at reduced temperatures between 0.3 and 0.8 and at pressures below 3.5 MPa:

$$k_L = \left(\frac{abc}{m}\right)\left(\frac{(1 - T_r)^{0.38}}{T_r^{1/6}}\right) \tag{2-142}$$

where k_L = liquid thermal conductivity, W/m K
T_r = reduced temperature, T/T_c
T = temperature, K
T_c = critical temperature, K
a = constant parameter
b = constant parameter = function of normal boiling temperature T_b, K
c = constant paramerer = function of critical temperature T_c, K
m = constant parameter = function of molecular weight M

Values of a, b, c, and m for various compound classes are found in Table 2-399. Average errors are about 8 percent.

TABLE 2-399 Values of Constant Parameters in Eq. (2-142) for Various Compound Classes

Compound class	a	b	c	m
Acids*	0.00319	$T_b^{6/5}$	$T_c^{-1/6}$	$M^{1/2}$
Alcohols, phenols	0.00339	$T_b^{6/5}$	$T_c^{-1/6}$	$M^{1/2}$
Esters†	0.0415	$T_b^{6/5}$	$T_c^{-1/6}$	M
Ethers	0.0385	$T_b^{6/5}$	$T_c^{-1/6}$	M
Halides‡	0.494	1.0	$T_c^{1/6}$	$M^{1/2}$
Refrigerants R20–R23	0.562	1.0	$T_c^{1/6}$	$M^{1/2}$
Ketones	0.00383	$T_b^{6/5}$	$T_c^{-1/6}$	$M^{1/2}$
Alkoxysilanes	0.00482	$T_b^{6/5}$	$T_c^{-1/6}$	$M^{1/2}$
Alkyl-(aryl)-chlorosilanes	0.6510	1.0	$T_c^{1/6}$	$M^{1/2}$

*Do not use for formic, myristic, or oleic acids.
†Do not use for butyl stearate.
‡Do not use for refrigerants R20–R23 ($CHCl_3$, $CHFCl_2$, $CHClF_2$, or CHF_3).

Example 33 Estimate thermal conductivity of n-butanol. The properties required to estimate the liquid thermal conductivity of n-butanol at 360.0 K and 0.1 MPa from Daubert et al.[24] are: T_c = 563.0 K, M = 74.12, and T_b = 390.8 K. T_r = 360.0/563.0 = 0.6394. From Table 2-399, a = 0.00339, $b = (T_b)^{6/5} = (390.8)^{6/5} = 1289.3$, $c = (T_c)^{-1/6} = (563.0)^{-1/6} = 0.3480$, and $m = M^{1/2} = (74.12)^{1/2} = 8.609$. Substituting in Eq. (2-142):

$$k_L = \left[\frac{(0.00339)(1289.3)(0.3480)}{8.609}\right]\left[\frac{(1 - 0.6394)^{0.38}}{(0.6394)^{1/6}}\right] = 0.1292 \text{ W/m K}$$

The reported value is 0.1429 W/m K.[123]

For pure component nonhydrocarbon liquids **for which Eq. (2-142) is not applicable,** the method of Missenard[72,73] may be used at temperature T (K) and below pressures of 3.5 MPa:

$$k_L = k_L^r \left[\frac{3 + 20\,(1 - T_r)^{2/3}}{3 + 20\left(1 - \dfrac{273.15}{T_c}\right)^{2/3}}\right] \tag{2-143}$$

$$k_L^r = 2.656 \times 10^{-7}\, \frac{(T_b \rho^r)^{1/2}\, C_p^r}{M^{1/2}\, N^{1/4}} \tag{2-144}$$

where k_L = liquid thermal conductivity, W/m K
k_L^r = liquid thermal conductivity at 273.15 K, W/m K
T_r = reduced temperature, T/T_c
T_c = critical temperature, K
T_b = normal boiling temperature, K
ρ^r = molar density at 273.15 K, kmol/m³
C_p^r = molar heat capacity at 273.15 K, J/kmol K
M = molecular weight
N = number of atoms in the molecule

Errors in the order of 8 percent can be expected.

Example 34 Estimate the thermal conductivity of n-propionaldehyde (CH_3CH_2CHO) at 318.15 K and low pressure (0.1 MPa); the necessary properties from Daubert et al.[24] are: T_c = 504.4 K, T_b = 321.1 K, ρ^r = 14.11 kmol/m³, $C_p^r = 1.309 \times 10^5$ J/kmol K, and M = 58.08. N = 10, and T_r = 318.15/504.4 = 0.6307. Substituting in Eq. (2-144):

$$k_L^r = (2.656 \times 10^{-7})\, \frac{[(321.1)\,(14.11)]^{1/2}\,(1.309 \times 10^5)}{(58.08)^{1/2}\,(10)^{1/4}} = 0.1727 \text{ W/m K}$$

Using Eq. (2-143):

$$k_L = 0.1727\left[\frac{3 + 20\,(1 - 0.6307)^{2/3}}{3 + 20\,(1 - 273.15/504.4)^{2/3}}\right] = 0.1542 \text{ W/m K}$$

A value from the literature is 0.1541 W/m K.[24]

For **pressures greater than 3.5 MPa,** the correction factor suggested by Missenard[74] may be used to obtain the thermal conductivity of pure component nonhydrocarbon liquids. Thus:

$$k_L = k'_L \left[0.98 + 0.0079\, P_r T_r^{1.4} + 0.63\, T_r^{1.2}\left(\frac{P_r}{30 + P_r}\right)\right] \tag{2-145}$$

where k_L = liquid thermal conductivity at the desired temperature T (K) and pressure P (MPa), W/m K
k'_L = liquid thermal conductivity at T and pressure of 0.1 MPa, W/m K
P_r = reduced pressure, P/P_c
P_c = critical pressure, MPa
T_r = reduced temperature, T/T_c
T_c = critical temperature, K

Average errors are in the range of 5–20 percent.

Example 35 Estimate thermal conductivity of n-butanol. The required properties at 360 K and 15 MPa from Daubert et al.[24] are: T_c = 563.0 K and

P_c = 4.423 MPa. $T_r = 360.0/563.0 = 0.6394$ and $P_r = 15.0/4.423 = 3.391$. k'_L = 0.1429 W/m K.[123] Substituting in Eq. (2-145):

$$k_L = 0.1429\left[0.98 + (0.0079)\,(3.391)\,(0.6394)^{1.4} + (0.63)\,(0.6394)^{1.2}\left(\frac{3.391}{30 + 3.391}\right)\right]$$

$$= 0.1474 \text{ W/m K}$$

Vargaftik[123] reports a value of 0.1494 W/m K.

For both aqueous and nonaqueous **liquid mixtures,** the method of Li[59] is suggested for pressures below 3.5 MPa:

$$k_m = \sum_{i=1}^{n}\sum_{j=1}^{n} \phi_i\,\phi_j\,k_{ij} \tag{2-146}$$

$$\phi_i = \frac{x_i\,V_i}{\sum_{j=1}^{n} x_j\,V_j} \tag{2-147}$$

$$k_{ij} = \frac{2}{(1/k_i) + (1/k_j)} \tag{2-148}$$

where k_m = mixture liquid thermal conductivity at temperature T (K), W/m K
n = number of components
$x_{i,j}$ = mole fraction of component i or j in the liquid mixture
$V_{i,j}$ = liquid molar volume of pure component i or j at temperature T, m^3/kmol
$k_{i,j}$ = liquid thermal conductivity of pure component i or j at temperature T, W/m K

Expected errors are in the 4–6 percent range. At **pressures greater than 3.5 MPa,** a pressure correction using Eq. (2-145) may be used. The mixture is treated as a hypothetical pure component with mixture critical properties obtained via Eqs. (2-5) and (2-8).

Example 36 Estimate thermal conductivity of a mixture of 0.302 mole fraction diethyl ether (1) and 0.698 mole fraction methanol (2) at 273.15 K and 0.1 MPa. The required properties from Daubert et al.[24] are: V_1 = 0.1007 m^3/kmol, V_2 = 0.03942 m^3/kmol, k_1 = 0.1383 W/m K, and k_2 = 0.2069 W/m K. Substituting in Eq. (2-148):

$$k_{12} = \frac{2}{1/0.1383 + 1/0.2069} = 0.1658$$

Then, using Eq. (2-147) to obtain ϕ_1 and ϕ_2:

$$\phi_1 = \frac{(0.302)(0.1007)}{(0.302)(0.1007) + (0.698)(0.03942)} = \frac{0.03041}{0.05793} = 0.525$$

$$\phi_2 = \frac{(0.698)(0.03942)}{0.05793} = 0.475$$

Substituting in Eq. (2-146):

$$k_m = (0.525)^2(0.1383) + 2(0.525)(0.475)(0.1658) + (0.475)^2(0.2069) = 0.167 \text{ W/m K}$$

Jamieson and Hastings[42] report a value of 0.173 W/m K for this mixture.

DIFFUSIVITY

Diffusion is the molecular transport of mass without flow. The diffusivity (D) or diffusion coefficient is the proportionality constant between the diffusion and the concentration gradient causing diffusion. It is usually defined by Fick's first law for one-dimensional, binary component diffusion for molecular transport without turbulence shown by Eq. (2-149)

$$\frac{N_1}{A} = -D_{12}\,\frac{dC_1}{dL} \tag{2-149}$$

The molar flow of species 1(N_1) per unit area (A) is directly proportional to the change in concentration of species 1 (C_1) per distance diffused (L). The usual units of diffusivity are m^2/sec.

In chemical engineering, the primary application of the diffusivity is to calculate the Schmidt number ($\mu/\rho D$) used to correlate mass transfer properties. This number is also used in reaction rate calculations involving transport to and away from catalyst surfaces.

Experimental diffusion coefficients are scarce and not highly accurate, especially in the liquid phase, leading to prediction methods with marginal accuracy. However, use of the values predicted are generally suitable for engineering calculations. At concentrations above about 10 mole percent, predicted values should be used with caution. Diffusivities in liquids are 10^4–10^5 times lower than those in gases.

Gas Diffusivity For prediction of the gas diffusivity of **binary hydrocarbon-hydrocarbon gas systems at low pressures** (below about 500 psia [3.5 MPa]) the method of Gilliland[32] given by Eq. (2-150) is recommended.

$$D_{12} = \frac{0.1014T^{1.5}\left(\dfrac{1}{M_1} + \dfrac{1}{M_2}\right)^{0.5}}{P(V_1^{1/3} + V_2^{1/3})^2} \tag{2-150}$$

Component 1 is the solute, while component 2 is the solvent. Units of T, P, and V are °R, psia, and cm^3/gmole, respectively. Diffusivity is then in ft^2/hr. The molar volumes V_1 and V_2 at the normal boiling point are estimated by Tyn and Calus,[120] Eq. (2-151).

$$V_i = 0.285V_{c_i}^{1.048} \tag{2-151}$$

The method gives average errors of less than 4 percent.

For prediction of the gas diffusivity of **binary air-hydrocarbon or nonhydrocarbon gas mixtures at low pressures,** the method of Fuller et al.[30] given by Eq. (2-152) is recommended.

$$D_{12} = \frac{0.1013T^{1.75}\left(\dfrac{1}{M_1} + \dfrac{1}{M_2}\right)^{0.5}}{P[(\sum v_1)^{1/3} + (\sum v_2)^{1/3}]^2} \tag{2-152}$$

Units of T and P are K and Pa, respectively, with the resulting diffusivity in m^2/sec. All v_i are group contribution values for the subscript component summed over atoms, groups, and structural features given in Table 2-400.

For air-hydrocarbon systems, average deviations do not exceed 9 percent. For general nonhydrocarbon gas systems, the average deviation is about 6 percent.

Example 37 Estimate the diffusivity of benzene vapor diffusing into air at 30°C and 96.5 kPa total pressure.

Use Eq. (2-152).

$$D_{12} = \frac{0.1013T^{1.75}\left(\dfrac{1}{M_1} + \dfrac{1}{M_2}\right)^{0.5}}{P[(\sum v_1)^{1/3} + (\sum v_2)^{1/3}]^2}$$

$$T = 303.1 \text{ K},\ M_1 = 78.1,\ M_2 = 28.86, \text{ and } P = 96{,}500 \text{ Pa.}$$

Now consult Table 2-400. For benzene (C_6H_6):

$$\sum v_1 = 6(16.5) + 6(1.98) - 20.2$$

$$\sum v_1 = 90.68$$

For air, $\sum v_2 = 20.1$:

$$D_{12} = \frac{(.01013)303.1^{1.75}\left(\dfrac{1}{78.1} + \dfrac{1}{28.86}\right)^{0.5}}{(96{,}500)(90.68^{1/3} + 20.1^{1/3})^2}$$

$$D_{12} = 9.68 \times 10^{-6} \text{ m}^2\text{/sec}$$

This value is within 1 percent of an available experimental value.

TABLE 2-400 Atomic Diffusion Volumes for Use in Eq. (2-153)

Atomic and structural diffusion-volume increments ν			
C	16.5	Cl	(19.5)
H	1.98	S	(17.0)
O	5.481	Aromatic ring	−20.2
N	(5.69)	Heterocyclic ring	−20.2
Diffusion volumes for simple molecules			
H_2	7.07	CO	18.9
D_2	6.70	CO_2	26.9
He	2.88	N_2O	35.9
N_2	17.9	NH_3	14.9
O_2	16.6	H_2O	12.7
Air	20.1	CCl_2F_2	(114.8)
Ar	16.1	SF_6	(69.7)
Kr	22.8	CI_2	(37.7)
Xe	(37.9)	Br_2	(67.2)
		SO_2	(41.1)

Parentheses indicate that the value listed is based only on a few data points.

TABLE 2-401 Parameters for Eq. (2-153)

P_r	$(D_{12}P)_R$	A	B	C	E
0.1	1.01	0.38042	1.52267	0.0	
0.2	1.01	0.067433	2.16794	0.0	
0.3	1.01	0.098371	2.42910	0.0	
0.4	1.01	0.137610	2.77605	0.0	
0.5	1.01	0.175081	2.98256	0.0	
0.6	1.01	0.216376	3.11384	0.0	
0.8	1.01	0.314051	0.50264	0.0	
1.0	1.02	0.385736	3.07773	0.141211	13.45454
1.2	1.02	0.514553	3.54744	0.278407	14.00000
1.4	1.02	0.599184	3.61216	0.372683	10.00900
1.6	1.02	0.557725	3.41882	0.504894	8.57519
1.8	1.03	0.593007	3.18415	0.678469	10.37483
2.0	1.03	0.696001	3.3760	0.0665702	11.21674
2.5	1.04	0.790770	3.27984	0.0	
3.0	1.05	0.502100	2.39031	0.602907	6.19043
4.0	1.06	0.837452	3.23513	0.0	
5.0	1.07	0.890390	3.13001	0.0	

An alternate method for gas diffusivity of binary gas mixtures at low pressures is the method of Hirschfelder et al.[40] The method requires several molecular parameters and, when evaluated, gives an average absolute error of about 10 percent. The method is discussed in detail in the *Data Prediction Manual.*

For predicting the diffusivity of *binary gas mixtures at high pressures,* the method of Takahashi,[109] Eq. (2-153), applies.

$$D_{12} = 1.013 \times 10^5 \frac{D'_{12}}{P}(D_{12}P)_R(1 - AT_r^{-B})(1 - CT_r^{-E}) \tag{2-153}$$

D'_{12} is the low pressure diffusivity at the temperature of interest. $(D_{12}P)_R$ is a reduced diffusivity pressure product at infinite reduced temperature; and A, B, C, and E are constants. All are a function of P_r tabulated in Table 2-401. Component 1 is the diffusing species, while component 2 is the concentrated species. Critical properties are for the solvent. The pressure is given in Pa. The diffusivity is in m²/sec. Errors from evaluation average near 15 percent.

Example 38 Estimate the diffusivity of hydrogen (1) in nitrogen (2) at 60°C and 17.23 MPa. A value of the low pressure diffusivity obtained using Eq. (2-152) is $D'_{12} = 9.2 \times 10^{-5}$ m²/sec. Use Eq. (2-153):

$$D_{12} = 1.013 \times 10^5 \frac{D'_{12}}{P}(D_{12}P)_R(1 - AT_r^{-B})(1 - CT_r^{-E})$$

For nitrogen, $T_c = 126.2$ K and $P_c = 3.394$ MPa.

$$T_r = \frac{333.2}{126.2} = 2.640 \qquad P_r = \frac{17.23}{3.394} = 5.077$$

From Table 2-401:

$$(D_{12}P)_R = 1.07, \quad A = 0.89039, \quad B = 3.1300, \quad C = 0$$

$$D_{12} = 1.013 \times 10^5 \left(\frac{9.2 \times 10^{-5}}{1.723 \times 10^7}\right)(1.07)[1 - .89039(2.64)^{-3.13}]$$

$$D_{12} = 5.54 \times 10^{-7} \text{ m}^2/\text{sec}$$

An available experimental value is 4.89×10^{-7} m²/sec.

For prediction of gas phase diffusion coefficients in **multicomponent hydrocarbon/nonhydrocarbon gas systems,** the method of Wilke[128] shown in Eq. (2-154) is used.

$$D_{im} = \frac{1 - y_i}{\sum\limits_{\substack{j \\ j \neq 1}} y_j / D_{ij}} \tag{2-154}$$

This mixing rule is used to determine the diffusivity of any component in a $j + 1$ component mixture and requires binary diffusivities of component i with all other components. It has been estimated that errors are about 5 percent greater than the greatest error in the binary diffusivities. Fairbanks and Wilke,[28] using the same Eq. (2-154), made the same recommendation with essentially the same errors.

For prediction of the diffusivity of a **dilute dissolved gas (hydrocarbon or nonhydrocarbon) in a liquid,** the standard method is that of Wilke and Chang[129] shown by Eq. (2-155).

$$D_{12} = 1.1728 \times 10^{-16} \frac{T(\chi_2 M_2)^{1/2}}{\mu_2 V_1^{0.6}} \tag{2-155}$$

Component 1 is the diffusing gas, while component 2 is the solvent. The solvent viscosity μ_2 in Pa sec, the solute molar volume at the normal boiling point V_1 in m³/kmole, and the solvent association parameter χ_2 multiplied by the solvent molecular weight are required input parameters. For the common solvents, χ decreases to 1 as polarity decreases, with values of 2.6 for water, 1.9 for methanol, 1.5 for ethanol, and 1.0 for less polar solvents. When tested with both hydrocarbon and nonhydrocarbon systems, average errors are about 25 percent—not excessive, considering the magnitude of the diffusivity.

Example 39 Estimate the infinite dilution diffusivity of propane (1) in chlorobenzene (2) at 25°C. Use Eq. (2-113):

$$D_{12} = 1.1728 \times 10^{-16} \frac{T(\chi_2 M_2)^{1/2}}{\mu_2 V_1^{0.6}}$$

For chlorobenzene, $M_2 = 112.56$, $\chi_2 = 1.0$, μ_2 @ 25°C $= 7.548 \times 10^{-4}$ Pa sec, and $V_1 = 0.0745$ m³/kmole.

$$D_{12} = \frac{(1.1728 \times 10^{-16})(298.15)(1.0 \times 112.56)^{1/2}}{(7.548 \times 10^{-4})(0.0745)^{0.6}}$$

$$D_{12} = 2.33 \times 10^{-9} \text{ m}^2/\text{sec}$$

An experimental value of 2.77×10^{-9} m²/sec is available.

Liquid Diffusivity Liquid diffusivities are in general not as accurately predicted as vapor diffusivities, and specialized methods have been developed. References to each method determined to be accurate are given, but only the most common methods will be presented.

For predicting liquid diffusivities of **binary nonpolar liquid systems at high solute dilution,** Umesi[120] developed a method that only depends on the viscosity of the solvent (2) and the radius of gyration of the solvent (2) and the solute (1). The *Technical Data Book—Petroleum Refining* gives the method and values of the radii of gyration for common hydrocarbons. Errors average 16 percent but reach 30 percent at times.

For predicting diffusivities in **binary polar or associating liquid systems at high solute dilution,** the method of Wilke and Chang[129] defined in Eq. (2-156) can be utilized. The Tyn and Calus equation (2-152) can be used to determine the molar volume of the solute at the normal boiling point. Errors average 20 percent, with occasional errors of 35 percent. The method is not considered to be accurate above a solute concentration of 5 mole percent.

For **concentrated binary nonpolar liquid systems** (more than 5 mole percent solute), the diffusivity can be estimated by a molar average mixing rule developed by Caldwell and Babb,[14] Eq. (2-156).

$$D_{1m} = x_1 D_{21} + (1 - x_1) D_{12} \tag{2-156}$$

D_{21} and D_{12} are dilute solution binary diffusivities. Errors depend on the procedure used to determine the dilute solution diffusivities.

For **multicomponent nonpolar liquid systems,** Leffler and Cullinan[56] developed a mixing rule, Eq. (2-157).

$$D_{1m}\mu_m = (D_{12}\mu_2)^{x_2}(D_{13}\mu_3)^{x_3} \ldots \tag{2-157}$$

The diffusivity of solute 1 in the mixture is related to the binary infinite dilution diffusivities for each of the other components calculated from Eq. (2-155) or the Umesi method. The viscosities are calculated by the methods in the previous section. Errors are not quantifiable, as little experimental data exist, although these errors would be related to those assumed for the binary pairs.

For **concentrated binary liquid nonhydrocarbon systems,** the method of Caldwell and Babb,[14] Eq. (2-156) has been modified by introduction of a thermodynamic correction term as shown in Eq. (2-158).

$$D_{1m}\mu_m = [x_i D_{21} + (1 - x_1) D_{12}]\left(1 + \frac{d \ln \gamma_1}{d \ln x_1}\right) \tag{2-158}$$

The activity coefficient (γ) based corrector is calculated using any applicable activity correlating equation such as the van Laar (slightly polar) or Wilson (more polar) equations. The average absolute error is 20 percent.

An alternate method for **binary concentrated liquid systems** where activity coefficients are not available or estimable is the method of Leffler and Cullinan[56] previously given in Eq. (2-156). Absolute errors average 25 percent.

For estimating the diffusivity of the **dilute solute (10 mole percent) in water,** the method of Hayduk and Laudie,[37] Eq. (2-159), applies.

$$D_{12} = \frac{8.621 \times 10^{-14}}{\mu_2^{1.14} V_1^{0.589}} \qquad (2\text{-}159)$$

Component 1 is the solute, while component 2 is water. The molar volume of the solute in m^3/kmole is at the solute normal boiling point, while the viscosity of water in Pa sec is at the temperature of the system resulting in a diffusivity in m^2/sec. The average error is about 9 percent when tested on 36 experimental systems.

For estimating the diffusivity of a **dilute solute (<10 mole percent) in any solvent except water,** the method of King et al.,[49] Eq. (2-160), applies.

$$D_{12} = 4.4 \times 10^{-15} \frac{T}{\mu_2}\left(\frac{V_2}{V_1}\right)^{1/6}\left(\frac{\lambda_2}{\lambda_1}\right)^{1/2} \qquad (2\text{-}160)$$

Component 1 is the solute, while component 2 is the solvent. The latent heats, λ, are at the normal boiling point, as are the molar volumes. Using T in K and μ in Pa sec yields a diffusivity in m^2/sec. The average error is 21 percent when tested on 237 experimental systems.

For prediction of the **liquid diffusivity of a solute in a pair of mixed solvents,** the method of Tang and Himmelblau,[111] Eq. (2-161), is recommended.

$$\ln (D_{1m}\mu_m^{1/2}) = x_2 \ln (D^*_{12}\mu_2^{1/2}) + x_3 \ln (D^*_{13}\mu_3^{1/2}) \qquad (2\text{-}161)$$

The solute 1 is dissolved in a solvent pair of 2 and 3. D^* are infinite dilution binary diffusivities estimated by the proper method discussed previously. The mixture viscosity can be predicted by methods of the previous section. The average absolute error when tested on 40 systems is 25 percent. The method gives higher errors if the solute is gaseous.

SURFACE TENSION

The molecules in a gas-liquid interface are in tension and tend to contract to a minimum surface area. This tension may be quantified by the surface tension, which is defined as the force in the plane of the surface per unit length. Jasper[43] has made a critical evaluation of experimental surface tension data for approximately 2200 pure chemicals. He correlates surface tension σ (mN/m = dyn/cm) with temperature T (°C) over a specified temperature range as

$$\sigma = a - bT \qquad (2\text{-}162)$$

where a and b are listed for most of the substances. To obtain values at a higher temperature than the upper temperature limit indicated by Jasper, the following expression may be used:

$$\sigma = d(1 - T_r)^e \qquad (2\text{-}163)$$

where d and e are determined such that σ and $d\sigma/dT$ at the upper temperature limit T_{HI} have the same values when calculated from both Eqs. (2-162) and (2-163):

$$e = \frac{b(T_c - T_{HI})}{a - b\,T_{HI}} \qquad (2\text{-}164)$$

$$d = (a - b\,T_{HI})(1 - T_{HI})^{-e} \qquad (2\text{-}165)$$

where T_c = critical temperature, °C
T_r = reduced temperature = $(T + 273.15)/(T_c + 273.15)$

Eq. (2-163) correctly predicts that the surface tension becomes zero at the critical point.[87]

For **nonpolar, nonhydrocarbon** chemicals not found in Jasper,[43] use can be made of the corresponding states approach of Brock and Bird[9] as modified by Miller[69] at temperature T (K):

$$\sigma = 4.601 \times 10^{-4}\, P_c^{2/3}\, T_c^{1/3}\, Q\, (1 - T_r)^{11/9} \qquad (2\text{-}166)$$

$$Q = 0.1207\left[1 + \frac{T_{br}(\ln P_c - 11.5261)}{1 - T_{br}}\right] - 0.281 \qquad (2\text{-}167)$$

where σ = surface tension, mN/m
P_c = critical pressure, Pa
T_c = critical temperature, K
T_r = reduced temperature, T/T_c
T_b = normal boiling temperature, K
T_{br} = reduced normal boiling temperature, T_b/T_c

Errors are usually less than 5 percent.

Example 40 Estimate surface tension for ethyl mercaptan. The required properties from Daubert et al.[24] are $P_c = 5.49 \times 10^6$ Pa, $T_c = 499.15$ K, and $T_b = 308.15$ K. For $T = 303.15$ K, $T_r = 303.15/499.15 = 0.6073$, and $T_{br} = 308.15/499.15 = 0.6173$. Substituting into Eqs. (2-167) and (2-166):

$$Q = 0.1207\left[1 + \frac{0.6173\,(\ln 5.49 \times 10^6 - 11.5261)}{1 - 0.6173}\right] - 0.281$$

$$Q = 0.6170$$

$$\sigma = 4.601 \times 10^{-4}(5.49 \times 10^6)^{2/3}(499.15)^{1/3}(0.6170)(1 - 0.6073)^{11/9}$$

$$\sigma = 22.36 \text{ mN/m}$$

The reported experimental value is 22.68 mN/m.[43]

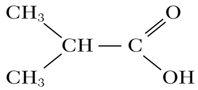
For **hydrocarbon and polar** chemicals, the approach originally suggested by Macleod[65] as further developed by Sugden[106,107] can be used:

$$\sigma = \left\{\frac{[P]}{1000}(\rho_L - \rho_G)\right\}^4 \qquad (2\text{-}168)$$

where σ = surface tension, mN/m
ρ_L = liquid density, kmol/m^3
ρ_G = vapor density, kmol/m^3

The temperature-independent parachor $[P]$ may be calculated by the additive scheme proposed by Quale.[83] The atomic group contributions for this method, with contributions for silicon, boron, and aluminum from Myers,[75] are shown in Table 2-402. At low pressures, where $\rho_L >> \rho_G$, the vapor density term may be neglected. Errors using Eq. (2-168) are normally less than 5 to 10 percent.

Example 41 Estimate surface tension for isobutyric acid. For isobutyric acid, the liquid density from Daubert et al.[24] is 10.77 kmol/m^3 at 293.15 K. $[P]$ is determined from Table 2-402:



is made up of the two groups CH_3—$CH(CH_3)$— and —COOH. Therefore, $[P] = 133.3 + 73.8 = 207.1$. With Eq. (2-168), neglecting the vapor density,

$$\sigma = \left[\frac{207.1}{1000}(10.77)\right]^4 = 24.75 \text{ mN/m}$$

Jasper[43] quotes a value of 25.04 mN/m at 293.15 K.

In general, the surface tension of a **liquid mixture** is not a simple function of the pure component surface tensions because the composition of the mixture surface is not the same as the bulk. For **nonaqueous** solutions of n components, the method of Winterfeld, Scriven, and Davis[130] is applicable:

$$\sigma_m = \sum_{i=1}^{n}\sum_{j=1}^{n} \rho^2 \left(\frac{x_i}{\rho_{Li}}\right)\left(\frac{x_j}{\rho_{Lj}}\right)(\sigma_i\sigma_j)^{1/2} \qquad (2\text{-}169)$$

$$\frac{1}{\rho} = \sum_{i=1}^{n} \frac{x_i}{\rho_{Li}} \qquad (2\text{-}170)$$

where σ_m = mixture surface tension, mN/m
$x_{i,j}$ = mole fraction of component i or j in the liquid mixture
$\rho_{Li,j}$ = pure component liquid density of component i or j, kmol/m^3
$\sigma_{i,j}$ = pure component surface tension of component i or j, mN/m

Accuracies of 3–4 percent average deviation are typical when using this method.

Example 42 Estimate surface tension of a mixture. At 298.15 K, Daubert et al.[24] report the liquid density of n-pentane to be 8.617 kmol/m^3 and its surface tension to be 15.47 mN/m. From the same source, the corresponding values for dichloromethane are 15.52 kmol/m^3 and 27.22 mN/m. Using Eqs. (2-170) and (2-169) for a mixture of 0.1606 mole fraction n-pentane and 0.8394 mole fraction dichloromethane:

$$\frac{1}{\rho} = \frac{0.1606}{8.617} + \frac{0.8394}{15.52}$$

$$\rho = 13.75 \text{ kmol/m}^3$$

TABLE 2-402 Atomic Group Contributions for Calculation of the Parachor [*P*]

Atomic group	[*P*]
Carbon-hydrogen	
C	9.0
H	15.5
CH_3—	55.5
(—CH_2—)$_n$	
$n = 1 - 12$	40.0
$n > 12$	40.3
CH_3—$CH(CH_3)$—	133.3
CH_3—CH_2—$CH(CH_3)$—	171.9
CH_3—CH_2—CH_2—$CH(CH_3)$—	211.7
CH_3—$CH(CH_3)$—CH_2—	173.3
CH_3—CH_2—$CH(C_2H_5)$—	209.5
CH_3—$C(CH_3)_2$—	170.4
CH_3—CH_2—$C(CH_3)_2$—	207.5
CH_3—$CH(CH_3)$—$CH(CH_3)$—	207.9
CH_3—$CH(CH_3)$—$C(CH_3)_2$—	243.5
C_6H_5—	189.6
Special Groups	
H in OH	10.0
H in HN	12.5
O	19.8
—OH	29.8
O_2 in acids, esters	54.8
—COO—	63.8
—COOH	73.8
N	17.5
—NH_2	42.5
S	49.1
P	40.5
Si	30.3
Si (silanes)	43.3

Atomic group	[*P*]
Special Groups (*Cont.*)	
B	13.2
Al	34.9
F	26.1
Cl	55.2
Br	68.0
I	90.3
Ethylenic Bond	
Terminal*	19.1
2,3-position	17.7
3,4-position†	16.3
Triple Bond	40.6
Ring Closure	
3-membered	12.5
4-membered	6.0
5-membered	3.0
6-membered	0.8
7-membered	4.0
=0 (ketone)	
3 carbon atoms	22.3
4 carbon atoms	20.0
5 carbon atoms	18.5
6 carbon atoms	17.3
7 carbon atoms	17.3
8 carbon atoms	15.1
9 carbon atoms	14.1
10 carbon atoms	13.0
11 carbon atoms	12.6

*Use the value for double bonds in cyclic compound. Assume 3 double bonds for the aromatic ring.
† Use 16.3 for double bonds in the 3, 4 or higher positions.

$$\sigma_m = (13.75)^2\left(\frac{0.1606}{8.617}\right)^2(15.47) + 2(13.75)^2\left(\frac{0.1606}{8.617}\right)\left(\frac{0.8394}{15.52}\right)[(15.47)(27.22)]^{1/2} + (13.75)^2\left(\frac{0.8394}{15.52}\right)^2(27.22)$$

$$\sigma_m = 23.89 \text{ mN/m}$$

De Soria et al.[26] give an experimental value of 24.24 mN/m for this mixture.

Surface tensions for **aqueous** solutions are more difficult to predict than those for nonaqueous mixtures because of the nonlinear dependence on mole fraction. Small concentrations of the organic material may significantly affect the mixture surface tension value. For many binary organic-water mixtures, the method of Tamura, Kurata, and Odani[110] may be used:

$$\sigma_m^{1/4} = \psi_w\sigma_w^{1/4} + \psi_o\sigma_o^{1/4} \qquad (2\text{-}171)$$

where σ_m = mixture surface tension, mN/m
σ_w = surface tension of pure water, mN/m
σ_o = surface tension of pure organic component, mN/m
$\psi_o = 1 - \psi_w$ (2-172)

ψ_w is defined by the relation:

$$\log_{10}\frac{(\psi_w)^q}{(1-\psi_w)} = \log_{10}\left[\frac{(x_wV_w)^q}{x_oV_o}(x_wV_w + x_oV_o)^{1-q}\right] + 44.1\frac{q}{T}\left[\frac{\sigma_oV_o^{2/3}}{q} - \sigma_wV_w^{2/3}\right] \qquad (2\text{-}173)$$

where x_w = bulk mole fraction of pure water
x_o = bulk mole fraction of pure organic component
V_w = molar volume of pure water, m^3/kmol
V_o = molar volume of pure organic component, m^3/kmol
T = temperature, K
q = constant depending upon the size and type of the organic component; see table:

Organic component	*q*	Example
Fatty acids, alcohols	Number of carbon atoms	Acetic acid: $q = 2$
Ketones	One less than the number of carbon atoms	Acetone: $q = 2$
Halogen derivatives of fatty acids	Number of carbon atoms times the ratio of the molar volume of the halogen derivative to the parent fatty acid	Chloroacetic acid

$$q = 2\,\frac{V(\text{chloroacetic acid})}{V(\text{acetic acid})}$$

Expected errors are less than 10 percent when q is less than 5 and within 20 percent when q is greater than 5.

Example 43 Estimate surface tension of a water-methanol mixture. Equation (2-171) can be used with a water-methanol mixture at 303.15 K when the methanol mole fraction is 0.122. From Jasper,[43] σ_w = 71.40 mN/m, and σ_o = 21.73 mN/m. The density of water (per Ref. 24) is 55.16 kmol/m^3; V_w = 0.01813 m^3/kmol. The density of methanol is 24.49 kmol/m^3 (Ref. 24); V_o = 0.04083 m^3/kmol. For methanol, $q = 1$. Using Eq. (2-173) to obtain ψ_w:

$$\log_{10}\frac{\psi_w}{1-\psi_w} = \log_{10}\left[\frac{(0.878)(0.01813)}{(0.122)(0.04083)}\right] + \frac{44.1}{303.15}[(21.73)(0.04083)^{2/3} - (71.40)(0.01813)^{2/3}]$$

$$= 0.505 - 0.342 = 0.163$$

$$\frac{\psi_w}{1-\psi_w} = 10^{0.163} = 1.455$$

$$\psi_w = \frac{1.455}{2.455} = 0.593$$

Using Eq. (2-172): $\psi_o = 1 - 0.593 = 0.407$. Substituting into Eq. (2-171):

$$\sigma_m^{1/4} = (0.593)(71.40)^{1/4} + (0.407)(21.73)^{1/4}$$

$$\sigma_m^{1/4} = 2.603$$

$$\sigma_m = 45.91 \text{ mN/m}$$

The reported experimental value is 46.1 mN/m.[110]

FLAMMABILITY PROPERTIES

Flash points, lower and upper flammability limits, and autoignition temperatures are the three properties used to indicate safe operating limits of temperature when processing organic materials. Prediction methods are somewhat erratic, but, together with comparisons with reliable experimental values for families or similar compounds, they are valuable in setting a conservative value for each of the properties. The DIPPR compilation includes evaluated values for over 1000 common organics. Detailed examples of most of the methods discussed are available in Danner and Daubert.[22]

The flash point is the lowest temperature at which a liquid gives off sufficient vapor to form an ignitable mixture with air near the surface of the liquid or within the vessel used. ASTM test methods include procedures using a closed cup (ASTM D56, ASTM D93, and ASTM D3828), which is preferred, and an open cup (ASTM D92 and ASTM D1310). When several values are available, the *lowest* temperature is usually taken in order to assure safe operation of the process.

The method of Shebeko et al.[96] is the preferred flash point prediction method. The formula of the compound, the system pressure, and vapor pressure data for the compound must be available or estimable. Equation (2-174) is the basic equation.

$$P^{\text{sat}} = \frac{P}{1 + 4.76(2\beta - 1)} = 0 \qquad (2\text{-}174)$$

$$\beta = N_C + N_S + \frac{(N_H - N_X)}{4} - \frac{N_O}{2}$$

N's are the numbers of **atoms** of carbon (C), sulfur (S), hydrogen (H), halogens (X), and oxygen (O) in the molecule. *P* is the total system pressure. P^{sat} is the vapor pressure of the compound at the flash point temperature.

If P^{sat} is available as a function of temperature, Eq. (2-174) can be solved directly for the flash point temperature. Otherwise, trial and error with a table of P^{sat} vs. *T* is required. Errors average about 5°C but may be as much as 15°C.

An alternate method for flash point prediction is the method of Gmehling and Rasmussen[33] and depends on the lower flammability limit (discussed later). Vapor pressure as a function of temperature is also required. The method is generally not as accurate as the preceding method as flammability limit errors are propagated. The authors have also extended the method to defined mixtures of organics.

The upper and lower flammability limits are the boundary-line mixtures of vapor or gas with air, which, if ignited, will just propagate flame and are given in terms of percent by volume of gas or vapor in the air. Each of these limits also has a temperature at which the flammability limits are reached. The temperature corresponding to the lower-limit partial vapor pressure should equal the flash point. The temperature corresponding to the upper-limit partial vapor pressure is somewhat above the lower limit and is usually considerably below the autoignition temperature. Flammability limits are calculated at one atmosphere total pressure and normally are considered synonymous with explosive limits. Limits in oxygen rather than air are sometimes measured and available. Limits are generally reported at 298 K and 1 atm. If temperature or pressure are increased, the lower limit will decrease while the upper limit will increase, giving a wider range of compositions over which flame will propagate.

The most generally applicable method for prediction of the property is the method of Seaton,[95] which depends only on the molecular structure of the molecule and utilizes second order (Benson-type) groups to construct the molecule. Equation (2-175) sums the groups' number of each type group (n_i) to get both the upper and lower limits.

$$z_u \quad \text{or} \quad z_l = \frac{\sum (n_i f_i)}{\sum \left(\frac{n_i f_i}{g_i} \right)} \qquad (2\text{-}175)$$

Two sets of f_i and g_i are given in the article for each second-order group to cover both upper (*u*) and lower (*l*) limits (*z*) in volume percent units. A study of this method for about 80 organic compounds in 14 families shows absolute errors of 0.15 percent and 2.3 percent for the lower and upper limits, respectively. The upper limit prediction should not be used for ethers.

Alternate group contribution methods dependent only on molecular structure are the method of Shebeko et al.[97] modified by High and Siegel[39] for lower flammability limit and the method of High and Danner[38] for upper flammability limit. Both methods are detailed by Danner and Daubert.[22] A study comparing these methods with the Seaton method shows slightly higher absolute errors of 0.23 percent and 2.9 percent for the lower and upper limits, respectively. The upper limit prediction should not be used for ethers. Both methods are recommended to be used only for qualitative guidance. Lower flammability limits can also be back-calculated from a known flash point by the method of Gmehling and Rasmussen[33] discussed earlier.

The autoignition temperature is the minimum temperature for a substance to initiate self-combustion in air in the absence of a spark or flame. The temperature is no lower than and is generally considerably higher than the temperature corresponding to the upper flammability limit. Large differences can occur in reported values determined by different procedures. The lowest reasonable value should be accepted in order to assure safety. Values are also sometimes given in oxygen rather than in air.

Values for hydrocarbons other than alkynes and alkadienes can be predicted by the method of Suzuki et al.[108] The best model includes the descriptors T_c, P_c, the parachor, the molecular surface area (which can be approximated by the van der Waals area), and the zero-order connectivity index. Excluding alkynes and alkadienes, a study for 58 alkanes, aromatics, and cycloalkanes showed an average deviation from experimental values of about 30 K.

Another method of estimating autoignition temperatures is to compare values for a compound with other members of its homologous series on a plot vs. carbon number as the temperature decreases and carbon number increases. Affens[1] gives a formal procedure for such estimation.