

APPENDIX D

PHYSICAL PROPERTIES OF VARIOUS ORGANIC AND INORGANIC SUBSTANCES

General Sources of Data for Tables on the Physical Properties, Heat Capacities, and Thermodynamic Properties in Appendices D, E, and F

1. Kobe, Kenneth A., and Associates. "Thermochemistry of Petrochemicals." Reprint from *Petroleum Refiner*, Houston: Gulf Publishing (January 1949–July 1958). (Enthalpy tables D.2–D.7 and heat capacities of several gases in Table E.1, Appendix E.)
2. Lange, N. A. *Handbook of Chemistry*, 12th ed. New York: McGraw-Hill (1979).
3. Maxwell, J. B. *Data Book on Hydrocarbons*. New York: Van Nostrand Reinhold (1950).
4. Perry, J. H., and C. H. Chilton, eds. *Chemical Engineers' Handbook*, 5th ed. New York: McGraw-Hill (1973).
5. Rossini, Frederick D., et al. "Selected Values of Chemical Thermodynamic Properties." From *National Bureau of Standards Circular 500*. Washington, DC: U.S. Government Printing Office (1952).
6. Rossini, Frederick D., et al. "Selected Values of Physical and Thermodynamic Properties of Hydrocarbons and Related Compounds." American Petroleum Institute Research Project 44 (1953 and subsequent years).
7. Weast, Robert C. *Handbook of Chemistry and Physics*, 59th ed. Boca Raton, FL: CRC Press (1979).

TABLE D.1 Physical Properties of Various Organic and Inorganic Substances* (additional compounds are on the disk in the back of this book, provided by Professor Carl L. Yaws)

To convert to kcal/g mol, multiply by 0.2390; to Btu/lb mol multiply by 430.2.

Compound	Formula	Formula Wt	Sp Gr	Melting Temp. (K)	$\Delta \hat{H}$ Fusion (kJ/g mol)	Normal b.p. (K)	$\Delta \hat{H}$ Vap. at b.p. (kJ/g mol)	T_c (K)	p_c (atm)	$\hat{V}_c$ (cm ³ /g mol)	z_c
Acetaldehyde	C ₂ H ₄ O	44.05	0.783 ^{18°/4°}	149.5		293.2		461.0			
Acetic acid	CH ₃ CHO ₂	60.05	1.049	289.9	12.09	390.4	24.4	594.8	57.1	171	0.200
Acetone	C ₃ H ₆ O	58.08	0.791	178.2	5.69	329.2	30.2	508.0	47.0	213	0.238
Acetylene	C ₂ H ₂	26.04	0.9061(A)	191.7	3.7	191.7	17.5	309.5	61.6	113	0.274
Air			1.00					132.5	37.2		
Ammonia	NH ₃	17.03	0.817–79°	195.40	5.653	239.73	23.35	405.5	111.3	72.5	0.243
Ammonium carbonate	(NH ₄) ₂ CO ₃ ·H ₂ O	114.11	0.597(A)								
Ammonium chloride	NH ₄ Cl	53.50	2.53 ^{17°}								
Ammonium nitrate	NH ₄ NO ₃	80.05	1.725 ^{25°}	442.8	5.4			(decomposes at 483.2 K)			
Ammonium sulfate	(NH ₄) ₂ SO ₄	132.14	1.769	786				(decomposes at 786 K after melting)			
Aniline	C ₆ H ₇ N	93.12	1.022	266.9		457.4		699	52.4		
Benzaldehyde	C ₆ H ₅ CHO	106.12	1.046	247.16		452.16	38.40				
Benzene	C ₆ H ₆	78.11	0.879	278.693	9.837	353.26	30.76	562.6	48.6	260	0.274
Benzoic acid	C ₇ H ₆ O ₂	122.12	1.316 ^{28°/4°}	395.4		523.0					
Benzyl alcohol	C ₇ H ₈ O	108.13	1.045	257.8		478.4					
Boron oxide	B ₂ O ₃	69.64	1.85	723	22.0						
Bromine	Br ₂	159.83	3.119 ^{20°}	265.8	10.8	331.78	31.0	584	102	144	0.306
1, 2-Butadiene	C ₄ H ₆	54.09	5.87(A)								
1, 3-Butadiene	C ₄ H ₆	54.09	0.652 ^{20°}	136.7		283.3		446			
Butane	n-C ₄ H ₁₀	58.12	0.621	164.1		268.6		425	42.7	221	0.271
iso-Butane	iso-C ₄ H ₁₀	58.12	0.579	134.83	4.661	272.66	22.31	425.17	37.47	255	0.374
			0.557	113.56	4.540	261.43	21.29	408.1	36.0	263	0.283

*Sources of data are listed at the beginning of Appendix D.
Sp gr = 20°C/4°C unless specified. Sp gr for gas referred to air (A).

TABLE D.1 (cont.)

Compound	Formula	Formula Wt	Sp Gr	Melting Temp. (K)	$\Delta\hat{H}$ Fusion (kJ/g mol)	Normal b.p. (K)	$\Delta\hat{H}$ Vap. at b.p. (kJ/g mol)	T_c (K)	p_c (atm)	$\hat{V}_c$ (cm ³ /g mol)	z_c
1-Butene	C ₄ H ₈	56.10	0.60	87.81	3.848	266.91	21.92	419.6	39.7	240	0.277
Butyl phthalate	<i>see</i> Dibutyl phthalate										
<i>n</i> -Butyric acid	<i>n</i> -C ₄ H ₈ O ₂	88.10	0.958	267		437.1		628	52.0	290	0.293
iso-Butyric acid	iso-C ₄ H ₈ O ₂	88.10	0.949	226		427.7		609			
Calcium arsenate	Ca ₃ (AsO ₄) ₂	398.06		1723							
Calcium carbide	Ca ₂ C ₂	64.10	2.2218°	2573							
Calcium carbonate	CaCO ₃	100.09	2.93	(decomposes at 1098 K)							
Calcium chloride	CaCl ₂	110.99	2.15215°	1055	28.4						
	CaCl ₂ ·H ₂ O	129.01									
	CaCl ₂ ·2H ₂ O	147.03									
	CaCl ₂ ·6H ₂ O	219.09	1.7817°	303.4	37.3	(-6H ₂ O at 473 K)					
Calcium cyanamide	CaCN ₂	80.11	2.29								
Calcium cyanide	Ca(CN) ₂	92.12									
Calcium hydroxide	Ca(OH) ₂	74.10	2.24	(-H ₂ O at 853 K)							
Calcium oxide	CaO	56.08	2.62	2873	50	3123					
Calcium phosphate	Ca ₃ (PO ₄) ₂	310.19	3.14	1943							
Calcium silicate	CaSiO ₃	117.17	2.915	1803	48.62						
Calcium sulfate (gypsum)	CaSO ₄ ·2H ₂ O	172.18	2.32	(-1½ H ₂ O at 301° K)							
Carbon	C	12.010	2.26	3873	46.0	4473					
Carbon dioxide	CO ₂	44.01	1.53(A) 1.229 satd. liq. at 5162 kPa	217.0 ^{5.2atm} 304.2 (sublimes at 195 K)	8.32	(sublimes at 195 K)		304.2	72.9	94	0.275

Carbon disulfide	CS ₂	76.14	1.261 ^{22°/20°} 2.63(A)	161.1	4.39	319.41	26.8	552.0	78.0	170	0.293
Carbon monoxide	CO	28.01	0.968(A)	68.10	0.837	81.66	6.042	133.0	34.5	93	0.294
Carbon tetrachloride	CCl ₄	153.84	1.595	250.3	2.5	349.9	30.0	556.4	45.0	276	0.272
Chlorine	Cl ₂	70.91	2.49(A)	172.16	6.406	239.10	20.41	417.0	76.1	124	0.276
Chlorobenzene	C ₆ H ₅ Cl	112.56	1.107	228		405.26	36.5	632.4	44.6	308	0.265
Chloroform	CHCl ₃	119.39	1.489 ^{20°}	209.5		334.2		536.0	54.0	240	0.294
Chromium	Cr	52.01	7.1								
Copper	Cu	63.54	8.92	1356.2	13.0	2855	305				
Cumene	C ₉ H ₁₂	120.19	0.862	177.125	7.1	425.56	37.5	636	31.0	440	0.260
Cupric sulfate	CuSO ₄	159.61	3.605 ^{15°}	(decomposes at 873 K)							
Cyclohexane	C ₆ H ₁₂	84.16	0.779	279.83	2.677	353.90	30.1	553.7	40.4	308	0.274
Cyclopentane	C ₅ H ₁₀	70.13	0.745	179.71	0.6088	322.42	27.30	511.8	44.55	260	0.27
Decane	C ₁₀ H ₂₂	142.28	0.730 ^{20°}	243.3		447.0		619.0	20.8	602	0.2476
Dibutyl phthalate	C ₈ H ₂₂ O ₄	278.34	1.045 ^{21°}			613					
Diethyl ether	(C ₂ H ₅) ₂ O	74.12	0.708 ^{25°}	156.86	7.301	307.76	26.05	467	35.6	281	0.261
Ethane	C ₂ H ₆	30.07	1.049(A)	89.89	2.860	184.53	14.72	305.4	48.2	148	0.285
Ethanol	C ₂ H ₆ O	46.07	0.789	158.6	5.021	351.7	38.6	516.3	63.0	167	0.248
Ethyl acetate	C ₄ H ₈ O ₂	88.10	0.901	189.4		350.2		523.1	37.8	286	0.252
Ethyl benzene	C ₈ H ₁₀	106.16	0.867	178.185	9.163	409.35	36.0	619.7	37.0	360	0.260
Ethyl bromide	C ₂ H ₅ Br	108.98	1.460	154.1		311.4		504	61.5	215	0.320
Ethyl chloride	CH ₃ CH ₂ Cl	64.52	0.903 ^{10°}	134.83	4.452	285.43	25	460.4	52.0	199	0.274
3-Ethyl hexane	C ₈ H ₁₈	114.22	0.7169			391.69	34.3	567.0	26.4	466	0.264
Ethylene	C ₂ H ₄	28.05	0.975(A)	103.97	3.351	169.45	13.54	283.1	50.5	124	0.270
Ethylene glycol	C ₂ H ₆ O ₂	62.07	1.113 ^{19°}	260	11.23	470.4	56.9				
Ferric oxide	Fe ₂ O ₃	159.70	5.12	1833		(decomposes at 1833 K)					
Ferric sulfide	Fe ₂ S ₃	207.90	4.3	(decomposes)							

*Sources of data are listed at the beginning of Appendix D.
Sp gr = 20°C/4°C unless specified. Sp gr for gas referred to air (A).

TABLE D.1 (cont.)

Compound	Formula	Formula Wt	Sp Gr	Melting Temp. (K)	$\Delta\hat{H}$ Fusion (kJ/g mol)	Normal b.p. (K)	$\Delta\hat{H}$ Vap. at b.p. (kJ/g mol)	T_c (K)	p_c (atm)	$\hat{V}_c$ (cm ³ /g mol)	z_c
Ferrous sulfide	FeS	87.92	4.84	1466	(decomposes)						
Formaldehyde	H ₂ CO	30.03	0.815 ^{-20°}	154.9		253.9	24.5				
Formic acid	CH ₂ O ₂	46.03	1.220	281.46	12.7	373.7	22.3				
Glycerol	C ₃ H ₈ O ₃	92.09	1.260 ^{50°}	291.36	18.30	563.2					
Helium	He	4.00	0.1368(A)	3.5	0.02	4.216	0.084	5.26	2.26	58	0.304
Heptane	C ₇ H ₁₆	100.20	0.684	182.57	14.03	371.59	31.69	540.2	27.0	426	0.260
Hexane	C ₆ H ₁₄	86.17	0.659	177.84	13.03	341.90	28.85	507.9	29.9	368	0.264
Hydrogen	H ₂	2.016	0.06948(A)	13.96	0.12	20.39	0.904	33.3	12.8	65	0.304
Hydrogen chloride	HCl	36.47	1.268(A)	158.94	1.99	188.11	16.15	324.6	81.5	87	0.266
Hydrogen fluoride	HF	20.01	1.15	238		293		503.2			
Hydrogen sulfide	H ₂ S	34.08	1.1895(A)	187.63	2.38	212.82	18.67	373.6	88.9	98	0.284
Iodine	I ₂	253.8	4.93 ^{20°}	386.5		457.4		826.0			
Iron	Fe	55.85	7.7	1808	15	3073	353				
Iron oxide	Fe ₃ O ₄	231.55	5.2	1867	138	(decomposes at 1867 K after melting)					
Lead	Pb	207.21	11.337 ^{20°}	600.6	5.10	2023	180				
Lead oxide	PbO	223.21	9.5	1159	11.7	1745	213				
Magnesium	Mg	24.32	1.74	923	9.2	1393	132				
Magnesium chloride	MgCl ₂	95.23	2.325 ^{25°}	987	43.1	1691	137				
Magnesium hydroxide	Mg(OH) ₂	58.34	2.4	(decomposes at 623 K)							
Magnesium oxide	MgO	40.32	3.65	3173	77.4	3873					
Mercury	Hg	200.61	13.546 ^{20°}								
Methane	CH ₄	16.04	0.554(A)	90.68	0.941	111.67	8.180	190.7	45.8	99	0.290
Methanol	CH ₃ OH	32.04	0.792	175.26	3.17	337.9	35.3	513.2	78.5	118	0.222
Methyl acetate	C ₃ H ₆ O ₂	74.08	0.933	174.3		330.3		506.7	46.3	228	0.254

TABLE D.1 (cont.)

Compound	Formula	Formula Wt	Sp Gr	Melting Temp. (K)	$\Delta \hat{H}_f$ Fusion (kJ/g mol)	Normal b.p. (K)	$\Delta \hat{H}_v$ Vap. at b.p. (kJ/g mol)	T_c (K)	p_c (atm)	$\hat{V}_c$ (cm ³ /g mol)	z_c
Phenyl hydrazine	C ₆ H ₈ N ₂	108.14	1.097 ^{23°}	292.76	16.43	51.66					
Phosphoric acid	H ₃ PO ₄	98.00	1.834 ^{18°}	315.51	10.5	(-1/2 H ₂ O at 486 K)					
Phosphorus (red)	P ₄	123.90	2.20	863	81.17	863	41.84				
Phosphorus (white)	P ₄	123.90	1.82	317.4	2.5	553	49.71				
Phosphorus pentoxide	P ₂ O ₅	141.95	2.387	(sublimes at 523 K)							
Propane	C ₃ H ₈	44.09	1.562(A)	85.47	3.524	231.09	18.77	369.9	42.0	200	0.277
Propene	C ₃ H ₆	42.08	1.498(A)	87.91	3.002	255.46	18.42	365.1	45.4	181	0.274
Propionic acid	C ₃ H ₆ O ₂	74.08	0.993	252.2		414.4		612.5	53.0		
n-Propyl alcohol	C ₃ H ₈ O	60.09	0.804	146		370.2		536.7	49.95	220	0.251
iso-Propyl alcohol	C ₃ H ₈ O	60.09	0.785	183.5		355.4		508.8	53.0	219	0.278
n-Propyl benzene	C ₉ H ₁₂	120.19	0.862	173.660	8.54	432.38	38.2	638.7	31.3	429	0.257
Silicon dioxide	SiO ₂	60.09	2.25	1883	8.54	2503					
Sodium bisulfate	NaHSO ₄	120.07	2.742	455							
Sodium carbonate (sal soda)	Na ₂ CO ₃ ·10H ₂ O	286.15	1.46	306.5		(-H ₂ O at 306.5 K)					
Sodium carbonate (soda ash)	Na ₂ CO ₃	105.99	2.533	1127	33.4	(decomposes)					
Sodium chloride	NaCl	58.45	2.163	1081	28.5	1738	171				
Sodium cyanide	NaCN	49.01		835	16.7	1770	155				
Sodium hydroxide	NaOH	40.00	2.130	592	8.4	1663					
Sodium nitrate	NaNO ₃	85.00	2.257	583	15.9	(decomposes at 653 K)					
Sodium nitrite	NaNO ₂	69.00	2.168 ^{0°}	544		(decomposes at 593 K)					
Sodium sulfate	Na ₂ SO ₄	142.05	2.698	1163	24.3						
Sodium sulfide	Na ₂ S	78.05	1.856	1223	6.7						
Sodium sulfite	Na ₂ SO ₃	126.05	2.633 ^{15°}	(decomposes)							

Sodium thiosulfate	$\text{Na}_2\text{S}_2\text{O}_3$	158.11	1.667						
Sulfur (rhombic)	S_8	256.53	2.07	386	10.0	717.76	84		
Sulfur (monoclinic)	S_8 $\swarrow$	256.53	1.96	392	14.17	717.76	84		
Sulfur chloride (mono)	S_2Cl_2	135.05	1.687	193.0		411.2	36.0		
Sulfur dioxide	SO_2	64.07	2.264(A)	197.68	7.402	263.14	24.92	430.7	77.8 122
Sulfur trioxide	SO_3	80.07	2.75(A)	290.0	24.5	316.5	41.8	491.4	83.8 126
Sulfuric acid	H_2SO_4	98.08	1.834 ^{18°}	283.51	9.87			(decomposes at 613 K)	
Toluene	$\text{C}_6\text{H}_5\text{CH}_3$	92.13	0.866	178.169	6.619	383.78	33.5	593.9	40.3 318
Water	H_2O	18.016	1.004°	273.16	6.009	373.16	40.65	647.4	218.3 56
m-Xylene	C_8H_{10}	106.16	0.864	225.288	11.57	412.26	34.4	619	34.6 390
o-Xylene	C_8H_{10}	106.16	0.880	247.978	13.60	417.58	36.8	631.5	35.7 380
p-Xylene	C_8H_{10}	106.16	0.861	286.423	17.11	411.51	36.1	618	33.9 370
Zinc	Zn	65.38	7.140	692.7	6.673	1180	114.8		
Zinc sulfate	ZnSO_4	161.44	3.74 ^{15°}	(decomposes at 1013 K)					

*Sources of data are listed at the beginning of Appendix D.
 Sp gr = 20°C/4°C unless specified. Sp gr for gas referred to air (A).

TABLE D.2 Enthalpies of Paraffinic Hydrocarbon Vapors, C_1 – C_6 (J/g mol) (at 1 atm)

To convert to Btu/lb mol, multiply by 0.4306.

K	C_1	C_2	C_3	n - C_4	i - C_4	n - C_5	n - C_6
273	0						
291	630	912	1,264	1,709	1,658	2,125	2,545
298	879	1,277	1,771	2,394	2,328	2,976	3,563
300	950	1,383	1,919	2,592	2,522	3,222	3,858
400	4,740	7,305	10,292	13,773	13,623	17,108	20,463
500	9,100	14,476	20,685	27,442	27,325	34,020	40,622
600	14,054	22,869	32,777	43,362	43,312	53,638	64,011
700	19,585	32,342	46,417	61,186	61,220	75,604	90,123
800	25,652	42,718	61,337	80,600	80,767	99,495	118,532
900	32,204	53,931	77,404	101,378	101,754	125,101	148,866
1,000	39,204	65,814	94,432	123,428	123,971	152,213	181,041
1,100	46,567	78,408	112,340	146,607	147,234	180,665	214,764
1,200	54,308	91,504	131,042	170,707	171,418	210,246	249,868
1,300	62,383	105,143	150,331	195,727	196,480	240,872	286,143
1,400	70,709	119,202	170,205	221,375	222,212	272,378	323,465
1,500	79,244	133,678	190,581	247,650	248,571	304,595	361,539
1,600	88,031						
1,800	106,064						
2,000	124,725						
2,200	143,804						
2,500	173,050						

TABLE D.3 Enthalpies of Other Hydrocarbon Vapors (J/g mol) (at 1 atm)

To convert to Btu/lb mol, multiply by 0.4306.

K	Ethylene	Propylene	i -Butene	iso-Butene	Acetylene	Benzene
273	0	0	0	0	0	0
291	753	1,104	1,536	1,538	769	1,381
298	1,054	1,548	2,154	2,154	1,075	1,945
300	1,125	1,665	2,313	2,322	1,163	2,109
400	6,008	8,882	12,455	12,367	5,899	11,878
500	11,890	17,572	24,765	24,468	11,125	24,372
600	18,648	27,719	38,911	38,425	16,711	39,150
700	26,158	39,049	54,643	53,889	22,556	55,840
800	34,329	51,379	71,755	70,793	28,686	74,015
900	43,053	64,642	89,997	88,826	35,074	93,471
1,000	52,258	78,742	109,286	107,947	41,635	113,972
1,100	61,923	93,470	129,494	123,846	48,388	135,394
1,200	71,964	108,825	150,456	148,866	55,271	157,611
1,300	82,341	124,683	172,087	170,414	62,342	180,456
1,400	92,968	141,000	194,304	188,363	69,622	203,844
1,500	103,888	157,736	217,065	215,183	76,944	227,777

TABLE D.4 Enthalpies of Nitrogen and Some of its Oxides (J/g mol) (at 1 atm)
To convert to Btu/lb mol, multiply by 0.4306.

K	N ₂	NO	N ₂ O	NO ₂	N ₂ O ₄
273	0	0	0	0	0
291	524	537	686	658	1,384
298	728	746	957	917	1,937
300	786	686	1,034	985	2,083
400	3,695	3,785	5,121	4,865	10,543
500	6,644	6,811	9,582	9,070	19,915
600	9,627	9,895	14,386	13,564	30,124
700	12,652	13,054	19,513	18,305	
800	15,756	16,292	24,950	23,242	
900	18,961	19,597	30,693	28,334	
1,000	22,171	22,970	36,748	33,551	
1,100	25,472	26,392	43,129	38,869	
1,200	28,819	29,861	49,862	44,266	
1,300	32,216	33,371		49,731	
1,400	35,639	36,915		55,258	
1,500	39,145	40,488		60,826	
1,750	47,940	49,505			
2,000	56,902	58,634			
2,250	65,981	67,856			
2,500	75,060	77,127			

TABLE D.5 Enthalpies of Sulfur Compound Vapors (J/g mol) (at 1 atm)
To convert to Btu/lb mol, multiply by 0.4306.

K	S ₂ (g)	SO ₂	SO ₃	H ₂ S	CS ₂
273	0	0	0	0	0
291	579	706	899	607	807
298	805	984	1,255	845	1,125
300	869	1,064	1,338	909	1,217
400	4,196	5,234	6,861	4,372	5,995
500	7,652	9,744	13,033	7,978	11,108
600	11,192	14,514	19,832	11,752	16,455
700	14,790	19,501	27,154	15,706	21,974
800	18,426	24,647	34,748	19,840	27,631
900	22,087	29,915	42,676	24,145	33,388
1,000	25,769	35,275	50,835	28,610	39,220
1,100	29,463	40,706	59,203	33,216	45,103
1,200	33,174	46,191	67,738	37,953	51,044
1,300	36,898	51,714	76,399	42,802	57,027
1,400	40,630	57,320		47,739	63,052
1,500	44,371	62,927		52,802	69,119
1,600	48,116	68,533		57,906	75,186
1,700	51,881	74,182		63,094	81,295
1,800	55,605	79,872		68,324	87,361
1,900	59,370	85,520			
2,000	63,136	91,253			
2,500	82,006	119,871			
3,000	100,959	148,657			

TABLE D.6 Enthalpies of Combustion Gases* (J/g mol)[†]

K	N ₂	O ₂	Air	H ₂	CO	CO ₂	H ₂ O
273	0	0	0	0	0	0	0
291	524	527	523	516	525	655	603
298	728	732	726	718	728	912	837
300	786	790	784	763	786	986	905
400	3,695	3,752	3,696	3,655	3,699	4,903	4,284
500	6,644	6,811	6,660	6,589	6,652	9,204	7,752
600	9,627	9,970	9,673	9,518	9,665	13,807	11,326
700	12,652	13,225	12,736	12,459	12,748	18,656	15,016
800	15,756	16,564	15,878	15,413	15,899	23,710	18,823
900	18,961	19,970	19,116	18,384	19,125	28,936	22,760
1,000	22,171	23,434	22,367	21,388	22,413	34,308	26,823
1,100	25,472	26,940	25,698	24,426	25,760	39,802	31,011
1,200	28,819	30,492	29,078	27,509	29,154	45,404	35,312
1,300	32,216	34,078	32,501	30,626	32,593	51,090	39,722
1,400	35,639	37,693	35,953	33,789	36,070	56,860	44,237
1,500	39,145	41,337	39,463	36,994	39,576	62,676	48,848
1,750	47,940	50,555	48,325	45,275	48,459	77,445	60,751
2,000	56,902	59,914	57,320	53,680	57,488	92,466	73,136
2,250	65,981	69,454	66,441	62,341	66,567	107,738	85,855
2,500	75,060	79,119	75,646	71,211	75,772	123,176	98,867
2,750	84,265	88,910	84,935	80,290	85,018	138,699	112,089
3,000	93,512	98,826	94,265	89,453	94,265	154,347	125,520
3,500	112,131	119,034	113,135	108,030	112,968	185,895	152,799
4,000	130,875	141,410	132,172	127,528	131,796	217,777	180,414

[†]To convert to cal/g mol, multiply by 0.2390.

*Pressure = 1 atm.

SOURCE: Page 30 of Reference in Table D.7.

TABLE D.7 Enthalpies of Combustion Gases* (Btu/lb mol)

$^{\circ}\text{R}$	N_2	O_2	Air	H_2	CO	CO_2	H_2O
492	0.0	0.0	0.0	0.0	0.0	0.0	0.0
500	55.67	55.93	55.57	57.74	55.68	68.95	64.02
520	194.9	195.9	194.6	191.9	194.9	243.1	224.2
537	313.2	315.1	312.7	308.9	313.3	392.2	360.5
600	751.9	758.8	751.2	744.4	752.4	963	867.5
700	1,450	1,471	1,450	1,433	1,451	1,914	1,679
800	2,150	2,194	2,153	2,122	2,154	2,915	2,501
900	2,852	2,931	2,861	2,825	2,863	3,961	3,336
1,000	3,565	3,680	3,579	3,511	3,580	5,046	4,184
1,100	4,285	4,443	4,306	4,210	4,304	6,167	5,047
1,200	5,005	5,219	5,035	4,917	5,038	7,320	5,925
1,300	5,741	6,007	5,780	5,630	5,783	8,502	6,819
1,400	6,495	6,804	6,540	6,369	6,536	9,710	7,730
1,500	7,231	7,612	7,289	7,069	7,299	10,942	8,657
1,600	8,004	8,427	8,068	7,789	8,072	12,200	9,602
1,700	8,774	9,251	8,847	8,499	8,853	13,470	10,562
1,800	9,539	10,081	9,623	9,219	9,643	14,760	11,540
1,900	10,335	10,918	10,425	9,942	10,440	16,070	12,530
2,000	11,127	11,760	11,224	10,689	11,243	17,390	13,550
2,100	11,927	12,610	12,030	11,615	12,050	18,730	14,570
2,200	12,730	13,460	12,840	12,160	12,870	20,070	15,610
2,300	13,540	14,320	13,660	12,890	13,690	21,430	16,660
2,400	14,350	15,180	14,480	13,650	14,520	22,800	17,730
2,500	15,170	16,040	15,300	14,400	15,350	24,180	18,810

*Pressure = 1 atm.

SOURCE: Page 30 Kobe, K.A., et al. *Thermochemistry of Petrochemicals*, Reprint No. 44 from the *Petroleum Refiner*, Gulf Publishing Houston, TX (1958).

APPENDIX E

HEAT CAPACITY EQUATIONS

TABLE E.1 Heat Capacity Equations for Organic and Inorganic Compounds (at Low Pressures)*

Forms: (1) $C_p^\circ = a + b(T) + c(T)^2 + d(T)^3$;

(2) $C_p^\circ = a + b(T) + c(T)^{-2}$.

Units of C_p° are J/(g mol)(K or °C).

To convert to cal/(g mol)(K or °C) = Btu/(lb mol)(°R or °F), multiply by 0.2390.

Note: $b \cdot 10^2$ means the value of b is to be multiplied by 10^{-2} , e.g., 20.10×10^{-2} for acetone.

Compound	Formula	Mol. Wt.	State	Form	T	a	$b \cdot 10^2$	$c \cdot 10^5$	$d \cdot 10^9$	Temp. Range (in T)
Acetone	CH ₃ COCH ₃	58.08	g	1	°C	71.96	20.10	-12.78	34.76	0-1200
Acetylene	C ₂ H ₂	26.04	g	1	°C	42.43	6.053	-5.033	18.20	0-1200
Air		29.0	g	1	°C	28.94	0.4147	0.3191	-1.965	0-1500
Ammonia	NH ₃	17.03	g	1	K	28.09	0.1965	0.4799	-1.965	273-1800
Ammonium sulfate	(NH ₄) ₂ SO ₄	132.15	c	1	°C	35.15	2.954	0.4421	-6.686	0-1200
Benzene	C ₆ H ₆	78.11	l	1	K	215.9				275-328
					K	-7.27329	77.054	-164.82	1,897.9	279-350
Isobutane	C ₄ H ₁₀	58.12	g	1	°C	74.06	32.95	-25.20	77.57	0-1200
n-Butane	C ₄ H ₁₀	58.12	g	1	°C	89.46	30.13	-18.91	49.87	0-1200
Isobutene	C ₄ H ₈	56.10	g	1	°C	92.30	27.88	-15.47	34.98	0-1200
Calcium carbide	CaC ₂	64.10	c	2	K	82.88	25.64	-17.27	50.50	0-1200
Calcium carbonate	CaCO ₃	100.09	c	2	K	68.62	1.19	-8.66 × 10 ¹⁰	—	298-720
Calcium hydroxide	Ca(OH) ₂	74.10	c	1	K	82.34	4.975	-12.87 × 10 ¹⁰	—	273-1033
Calcium oxide	CaO	56.08	c	2	K	89.5				276-373
Carbon	C	12.01	c [†]	2	K	41.84	2.03	-4.52 × 10 ¹⁰		10273-1173
Carbon dioxide	CO ₂	44.01	g	1	°C	11.18	1.095	-4.891 × 10 ¹⁰		273-1373
Carbon monoxide	CO	28.01	g	1	°C	36.11	4.233	-2.887	7.464	0-1500
Carbon tetrachloride	CCl ₄	153.84	l	1	K	28.95	0.4110	0.3548	-2.220	0-1500
Chlorine	Cl ₂	70.91	g	1	°C	12.285	0.01095	-318.26	3,425.2	273-343
Copper	Cu	63.54	c	1	K	33.60	1.367	-1.607	6.473	0-1200
					K	22.76	0.06117			273-1357

[†]Graphite. [‡]Rhombic. [§]Monoclinic. * (at 1 atm)

TABLE E.1 (cont.)

Compound	Formula	Mol. Wt.	State	Form	<i>T</i>	<i>a</i>	<i>b</i> · 10 ²	<i>c</i> · 10 ⁵	<i>d</i> · 10 ⁹	Temp. Range (in <i>T</i>)
Cumene (Isopropyl benzene)	C ₉ H ₁₂	120.19	g	1	°C	139.2	53.76	-39.79	120.5	0-1200
Cyclohexane	C ₆ H ₁₂	84.16	g	1	°C	94.140	49.62	-31.90	80.63	0-1200
Cyclopentane	C ₅ H ₁₀	70.13	g	1	°C	73.39	39.28	-25.54	68.66	0-1200
Ethane	C ₂ H ₆	30.07	g	1	°C	49.37	13.92	-5.816	7.280	0-1200
Ethyl alcohol	C ₂ H ₆ O	46.07	l	1	K	-325.137	0.041379	-1.403.1	1.7035 × 10 ⁴	250-400
Ethylene	C ₂ H ₄	28.05	g	1	°C	61.34	15.72	-8.749	19.83	0-1200
Ferric oxide	Fe ₂ O ₃	159.70	g	1	°C	40.75	11.47	-6.891	17.66	0-1200
Formaldehyde	CH ₂ O	30.03	g	2	K	103.4	6.711	-17.72 × 10 ¹⁰	—	273-1097
Helium	He	4.00	g	1	°C	34.28	4.268	0.0000	-8.694	0-1200
<i>n</i> -Hexane	C ₆ H ₁₄	86.17	l	1	°C	20.8				All
Hydrogen	H ₂	2.016	g	1	K	31.421	0.97606	-235.37	3,092.7	273-400
Hydrogen bromide	HBr	80.92	g	1	°C	137.44	40.85	-23.92	57.66	0-1200
Hydrogen chloride	HCl	36.47	g	1	°C	28.84	0.00765	0.3288	-0.8698	0-1500
Hydrogen cyanide	HCN	27.03	g	1	°C	29.10	-0.0227	0.9887	-4.858	0-1200
Hydrogen sulfide	H ₂ S	34.08	g	1	°C	29.13	-0.1341	0.9715	-4.335	0-1200
Magnesium chloride	MgCl ₂	95.23	g	1	°C	35.3	2.908	1.092		0-1200
Magnesium oxide	MgO	40.32	g	1	°C	33.51	1.547	0.3012	-3.292	0-1500
Methane	CH ₄	16.04	c	2	K	72.4	1.58			273-991
Methyl alcohol	CH ₃ OH	32.04	c	1	K	45.44	0.5008	-8.732 × 10 ¹⁰		273-2073
Methyl cyclohexane	C ₇ H ₁₄	98.18	g	1	°C	34.31	5.469	0.3661	-11.00	0-1200
Methyl cyclopentane	C ₆ H ₁₂	84.16	g	1	K	19.87	5.021	1.268	-11.00	273-1500
Nitric acid	HNO ₃	63.02	l	1	K	-259.25	0.03358	-1.1639	1.4052 × 10 ⁴	273-400
			g	1	°C	42.93	8.301	-1.87	-8.03	0-700
			g	1	°C	121.3	56.53	-37.72	100.8	0-1200
			g	1	°C	98.83	45.857	-30.44	83.81	0-1200
			l	1	°C	110.0				25

Nitric oxide	NO	30.01	g	l	°C	29.50	0.8188	-0.2925	0.3652	0-3500
Nitrogen	N ₂	28.02	g	l	°C	29.00	0.2199	0.5723	-2.871	0-1500
Nitrogen dioxide	NO ₂	46.01	g	l	°C	36.07	3.97	-2.88	7.87	0-1200
Nitrogen tetraoxide	N ₂ O ₄	92.02	g	l	°C	75.7	12.5	-11.3		0-300
Nitrous oxide	N ₂ O	44.02	g	l	°C	37.66	4.151	-2.694	10.57	0-1200
Oxygen	O ₂	32.00	g	l	°C	29.10	1.158	-0.6076	1.311	0-1500
n-Pentane	C ₅ H ₁₂	72.15	l	l	K	33.24	192.41	-236.87	17,944	270-350
Propane	C ₃ H ₈	44.09	g	l	°C	114.8	34.09	-18.99	42.26	0-1200
Propylene	C ₃ H ₆	42.08	g	l	°C	68.032	22.59	-13.11	31.71	0-1200
Sodium carbonate	Na ₂ CO ₃	105.99	c	l	°C	59.580	17.71	-10.17	24.60	0-1200
Sodium carbonate	Na ₂ CO ₃ · 10H ₂ O	286.15	c	l	K	535.6				288-371
										298
Sulfur	S	32.07	c [†]	l	K	15.2	2.68			273-368
			c [§]	l	K	18.5	1.84			368-392
Sulfuric acid	H ₂ SO ₄	98.08	l	l	°C	139.1	15.59			10-45
Sulfur dioxide	SO ₂	64.07	g	l	°C	38.91	3.904	-3.104	8.606	0-1500
Sulfur trioxide	SO ₃	80.07	g	l	°C	48.50	9.188	-8.540	32.40	0-1000
Toluene	C ₇ H ₈	92.13	l	l	K	1.8083	81.222	-151.27	1,630	270-370
			g	l	°C	94.18	38.00	-27.86	80.33	0-1200
Water	H ₂ O	18.016	l	l	K	18.2964	47.212	-133.88	1,314.2	273-373
			g	l	°C	33.46	0.6880	0.7604	-3.593	0-1500

[†]Graphite. [‡]Rhombic. [§]Monoclinic.

APPENDIX F

HEATS OF FORMATION AND COMBUSTION

TABLE F.1 Heats of Formation and Heats of Combustion of Compounds at 25°C*

Standard states of products for $\Delta\hat{H}_c^\circ$ are $\text{CO}_2(\text{g})$, $\text{H}_2\text{O}(\text{l})$, $\text{N}_2(\text{g})$, $\text{SO}_2(\text{g})$, and $\text{HCl}(\text{aq})$. To convert to Btu/lb mol, multiply by 430.6.

Compound	Formula	Mol. wt.	State	$\Delta\hat{H}_f^\circ$ (kJ/g mol)	$\Delta\hat{H}_c^\circ$ (kJ/g mol)
Acetic acid	CH_3COOH	60.05	l	-486.2	-871.69
			g		-919.73
Acetaldehyde	CH_3CHO	40.052	g	-166.4	-1192.36
Acetone	$\text{C}_3\text{H}_6\text{O}$	58.08	aq, 200	-410.03	
			g	-216.69	-1821.38
Acetylene	C_2H_2	26.04	g	226.75	-1299.61
Ammonia	NH_3	17.032	l	-67.20	
			g	-46.191	-382.58
Ammonium carbonate	$(\text{NH}_4)_2\text{CO}_3$	96.09	c		
			aq	-941.86	
Ammonium chloride	NH_4Cl	53.50	c	-315.4	
Ammonium hydroxide	NH_4OH	35.05	aq	-366.5	
Ammonium nitrate	NH_4NO_3	80.05	c	-366.1	
			aq	-339.4	
Ammonium sulfate	$(\text{NH}_4)_2\text{SO}_4$	132.15	c	-1179.3	
			aq	-1173.1	
Benzaldehyde	$\text{C}_6\text{H}_5\text{CHO}$	106.12	l	-88.83	
			g	-40.0	

TABLE F.1 (cont.)

Compound	Formula	Mol. wt.	State	$\Delta \hat{H}_f^\circ$ (kJ/g mol)	$\Delta \hat{H}_c^\circ$ (kJ/g mol)
Benzene	C_6H_6	78.11	l	48.66	-3267.6
			g	82.927	-3301.5
Boron oxide	B_2O_3	69.64	c	-1263	
			l	-1245.2	
Bromine	Br_2	159.832	l	0	
			g	30.7	
<i>n</i> -Butane	C_4H_{10}	58.12	l	-147.6	-2855.6
			g	-124.73	-2878.52
Isobutane	C_4H_{10}	58.12	l	-158.5	-2849.0
			g	-134.5	-2868.8
1-Butene	C_4H_8	56.104	g	1.172	-2718.58
Calcium arsenate	$Ca_3(AsO_4)_2$	398.06	c	-3330.5	
Calcium carbide	CaC_2	64.10	c	-62.7	
Calcium carbonate	$CaCO_3$	100.09	c	-1206.9	
Calcium chloride	$CaCl_2$	110.99	c	-794.9	
Calcium cyanamide	$CaCN_2$	80.11	c	-352	
Calcium hydroxide	$Ca(OH)_2$	74.10	c	-986.56	
Calcium oxide	CaO	56.08	c	-635.6	
Calcium phosphate	$Ca_3(PO_4)_2$	310.19	c	-4137.6	
Calcium silicate	$CaSiO_3$	116.17	c	-1584	
Calcium sulfate	$CaSO_4$	136.15	c	-1432.7	
			aq	-1450.5	
Calcium sulfate (gypsum)	$CaSO_4 \cdot 2H_2O$	172.18	c	-2021.1	
Carbon	C	12.01	c	0	-393.51
			Graphite (β)		
Carbon dioxide	CO_2	44.01	g	-393.51	
			l	-412.92	
Carbon disulfide	CS_2	76.14	l	87.86	-1075.2
			g	115.3	-1102.6
Carbon monoxide	CO	28.01	g	-110.52	-282.99
Carbon tetrachloride	CCl_4	153.838	l	-139.5	-352.2
			g	-106.69	-384.9
Chloroethane	C_2H_5Cl	64.52	g	-105.0	-1421.1
			l	-41.20	-5215.44
Cumene (isopropylbenzene)	$C_6H_5CH(CH_3)_2$	120.19	g	3.93	-5260.59
			c	-769.86	
Cupric sulfate	$CuSO_4$	159.61	aq	-843.12	
			c	-751.4	
Cyclohexane	C_6H_{12}	84.16	g	-123.1	-3953.0
Cyclopentane	C_5H_{10}	70.130	l	-105.8	-3290.9
			g	-77.23	-3319.5

TABLE F.1 (cont.)

Compound	Formula	Mol. wt.	State	$\Delta\hat{H}_f^\circ$ (kJ/g mol)	$\Delta\hat{H}_c^\circ$ (kJ/g mol)
Ethane	C ₂ H ₆	30.07	g	-84.667	-1559.9
Ethyl acetate	CH ₃ CO ₂ C ₂ H ₅	88.10	l	-442.92	-2274.48
Ethyl alcohol	C ₂ H ₅ OH	46.068	l	-277.63	-1366.91
			g	-235.31	-1409.25
Ethyl benzene	C ₆ H ₅ · C ₂ H ₅	106.16	l	-12.46	-4564.87
			g	29.79	-4607.13
Ethyl chloride	C ₂ H ₅ Cl	64.52	g	-105	
Ethylene	C ₂ H ₄	28.052	g	52.283	-1410.99
Ethylene chloride	C ₂ H ₃ Cl	62.50	g	31.38	-1271.5
3-Ethyl hexane	C ₈ H ₁₈	114.22	l	-250.5	-5470.12
			g	-210.9	-5509.78
Ferric chloride	FeCl ₃		c	-403.34	
Ferric oxide	Fe ₂ O ₃	159.70	c	-822.156	
Ferric sulfide	FeS ₂	<i>see Iron sulfide</i>		<i>see Iron sulfide</i>	
Ferrosoferric oxide	Fe ₃ O ₄	231.55	c	-1116.7	
Ferrous chloride	FeCl ₂		c	-342.67	-303.76
Ferrous oxide	FeO	71.85	c	-267	
Ferrous sulfide	FeS	87.92	c	-95.06	
Formaldehyde	H ₂ CO	30.026	g	-115.89	-563.46
<i>n</i> -Heptane	C ₇ H ₁₆	100.20	l	-224.4	-4816.91
			g	-187.8	-4853.48
<i>n</i> -Hexane	C ₆ H ₁₄	86.17	l	-198.8	-4163.1
			g	-167.2	-4194.753
Hydrogen	H ₂	2.016	g	0	-285.84
Hydrogen bromide	HBr	80.924	g	-36.23	
Hydrogen chloride	HCl	36.465	g	-92.311	
Hydrogen cyanide	HCN	27.026	g	130.54	
Hydrogen sulfide	H ₂ S	34.082	g	-20.15	-562.589
Iron sulfide	FeS ₂	119.98	c	-177.9	
Lead oxide	PbO	223.21	c	-219.2	
Magnesium chloride	MgCl ₂	95.23	c	-641.83	
Magnesium hydroxide	Mg(OH) ₂	58.34	c	-924.66	
Magnesium oxide	MgO	40.32	c	-601.83	
Methane	CH ₄	16.041	g	-74.84	-890.4
Methyl alcohol	CH ₃ OH	32.042	l	-238.64	-726.55
			g	-201.25	-763.96
Methyl chloride	CH ₃ Cl	50.49	g	-81.923	-766.63 [†]
Methyl cyclohexane	C ₇ H ₁₄	98.182	l	-190.2	-4565.29
			g	-154.8	-4600.68
Methyl cyclopentane	C ₆ H ₁₂	84.156	l	-138.4	-3937.7
			g	-106.7	-3969.4

TABLE F.1 (cont.)

Compound	Formula	Mol. wt.	State	$\Delta\hat{H}_f^\circ$ (kJ/g mol)	$\Delta\hat{H}_c^\circ$ (kJ/g mol)
Nitric acid	HNO ₃	63.02	l	-173.23	
			aq	-206.57	
Nitric oxide	NO	30.01	g	90.374	
Nitrogen dioxide	NO ₂	46.01	g	33.85	
Nitrous oxide	N ₂ O	44.02	g	81.55	
<i>n</i> -Pentane	C ₅ H ₁₂	72.15	l	-173.1	-3509.5
			g	-146.4	-3536.15
Phosphoric acid	H ₃ PO ₄	98.00	c	-1281	
			aq (1H ₂ O)	-1278	
Phosphorus	P ₄	123.90	c	0	
Phosphorus pentoxide	P ₂ O ₅	141.95	c	-1506	
Propane	C ₃ H ₈	44.09	l	-119.84	-2204.0
			g	-103.85	-2220.0
Propene	C ₃ H ₆	42.078	g	20.41	-2058.47
<i>n</i> -Propyl alcohol	C ₃ H ₈ O	60.09	g	-255	-2068.6
<i>n</i> -Propylbenzene	C ₆ H ₅ · CH ₂ · C ₂ H ₅	120.19	l	-38.40	-5218.2
			g	7.824	-5264.5
Silicon dioxide	SiO ₂	60.09	c	-851.0	
Sodium bicarbonate	NaHCO ₃	84.01	c	-945.6	
Sodium bisulfate	NaHSO ₄	120.07	c	-1126	
Sodium carbonate	Na ₂ CO ₃	105.99	c	-1130	
Sodium chloride	NaCl	58.45	c	-411.00	
Sodium cyanide	NaCN	49.01	c	-89.79	
Sodium nitrate	NaNO ₃	85.00	c	-466.68	
Sodium nitrite	NaNO ₂	69.00	c	-359	
Sodium sulfate	Na ₂ SO ₄	142.05	c	-1384.5	
Sodium sulfide	Na ₂ S	78.05	c	-373	
Sodium sulfite	Na ₂ SO ₃	126.05	c	-1090	
Sodium thiosulfate	Na ₂ S ₂ O ₃	158.11	c	-1117	
Sulfur	S	32.07	c	0	
			(rhombic)		
			c	0.297	
			(monoclinic)		
Sulfur chloride	S ₂ Cl ₂	135.05	l	-60.3	
Sulfur dioxide	SO ₂	64.066	g	-296.90	
Sulfur trioxide	SO ₃	80.066	g	-395.18	
Sulfuric acid	H ₂ SO ₄	98.08	l	-811.32	
			aq	-907.51	
Toluene	C ₆ H ₅ CH ₃	92.13	l	11.99	-3909.9
			g	50.000	-3947.9

TABLE F.1 (cont.)

Compound	Formula	Mol. wt.	State	$\Delta\hat{H}_f^\circ$ (kJ/g mol)	$\Delta\hat{H}_c^\circ$ (kJ/g mol)
Water	H ₂ O	18.016	l	-285.840	
			g	-241.826	
<i>m</i> -Xylene	C ₆ H ₄ (CH ₃) ₂	106.16	l	-25.42	-4551.86
			g	17.24	-4594.53
<i>o</i> -Xylene	C ₆ H ₄ (CH ₃) ₂	106.16	l	-24.44	-4552.86
			g	19.00	-4596.29
<i>p</i> -Xylene	C ₆ H ₄ (CH ₃) ₂	106.16	l	-24.43	-4552.86
			g	17.95	-4595.25
Zinc sulfate	ZnSO ₄	161.45	c	-978.55	
			aq	-1059.93	

*Sources of data are given at the beginning of Appendix D, References 1, 4, and 5.

†Standard state HCl(g).

APPENDIX G

VAPOR PRESSURES

TABLE G.1 Vapor Pressures of Various Substances

Antoine equation:

$$\ln(p^*) = A - \frac{B}{C + T}$$

where p^* = vapor pressure, mm Hg

T = temperature, K

A, B, C = constants

Name	Formula	Range (K)	A	B	C
Acetic acid	C ₂ H ₄ O ₂	290–430	16.8080	3405.57	–56.34
Acetone	C ₃ H ₆ O	241–350	16.6513	2940.46	–35.93
Ammonia	NH ₃	179–261	16.9481	2132.50	–32.98
Benzene	C ₆ H ₆	280–377	15.9008	2788.51	–52.36
Carbon disulfide	CS ₂	288–342	15.9844	2690.85	–31.62
Carbon tetrachloride	CCl ₄	253–374	15.8742	2808.19	–45.99
Chloroform	CHCl ₃	260–370	15.9732	2696.79	–46.16
Cyclohexane	C ₆ H ₁₂	280–380	15.7527	2766.63	–50.50
Ethyl acetate	C ₄ H ₈ O ₂	260–385	16.1516	2790.50	–57.15
Ethyl alcohol	C ₂ H ₆ O	270–369	18.5242	3578.91	–50.50
Ethyl bromide	C ₂ H ₅ Br	226–333	15.9338	2511.68	–41.44
<i>n</i> -Heptane	C ₇ H ₁₆	270–400	15.8737	2911.32	–56.51
<i>n</i> -Hexane	C ₆ H ₁₄	245–370	15.8366	2697.55	–48.78
Methyl alcohol	CH ₄ O	257–364	18.5875	3626.55	–34.29
<i>n</i> -Pentane	C ₅ H ₁₂	220–330	15.8333	2477.07	–39.94
Sulfur dioxide	SO ₂	195–280	16.7680	2302.35	–35.97
Toluene	C ₆ H ₅ CH ₃	280–410	16.0137	3096.52	–53.67
Water	H ₂ O	284–441	18.3036	3816.44	–46.13

SOURCE: R. C. Reid, J. M. Prausnitz, and T. K. Sherwood. *The Properties of Gases and Liquids*, 3rd ed., Appendix A. New York: McGraw-Hill (1977).