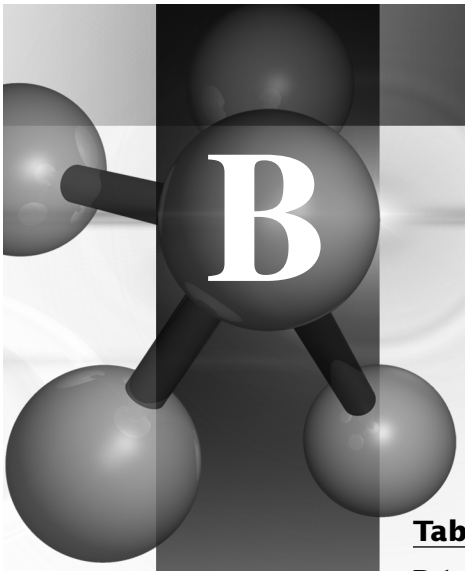

APPENDIX B

B Physical Properties

More extensive tabulation of physical property data is available in reference books such as:

Perry's Chemical Engineers' Handbook, edited by R. H. Perry and D. W. Green, McGraw-Hill, Inc., New York, NY.

CRC Handbook of Chemistry and Physics, CRC Press, Boca Raton, FL.

Lange's Handbook of Chemistry, J. A. Dean, McGraw-Hill, Inc., New York, NY.

Chemical Properties Handbook, C. L. Yaws, (1999) McGraw-Hill, Inc., New York, NY.

Physical and Thermodynamic Properties of Pure Chemicals: Evaluated Process Design Data, T. E. Daubert et al., (1999), Taylor & Francis, Philadelphia, PA.

NIST Chemistry Webbook, edited by P. J. Linstrom and W. G. Mallard, (2005) National Institute of Standards and Technology, Gaithersburg, MD. (http.//webbook.nist.gov.)

The Knovel scientific and engineering online database (www.knovel.com) provides searchable access to many reference books but requires a subscription.

The data in this appendix were compiled from these and other sources. For critical applications, you should consult one or more of the original sources.

B.1 Atomic Mass and Number of the Elements

Table B.1 Atomic Mass and Number of the First 100 Elements

Element	Symbol	Atomic number	Atomic mass	Element	Symbol	Atomic number	Atomic mass
Hydrogen	H	1	1.00794	Oxygen	O	8	15.9994
Helium	He	2	4.00260	Fluorine	F	9	18.99840
Lithium	Li	3	6.941	Neon	Ne	10	20.1797
Beryllium	Be	4	9.012182	Sodium	Na	11	22.989768
Boron	B	5	10.811	Magnesium	Mg	12	24.3050
Carbon	C	6	12.011	Aluminum	Al	13	26.981539
Nitrogen	N	7	14.00674	Silicon	Si	14	28.0855

Element	Symbol	Atomic number	Atomic mass	Element	Symbol	Atomic number	Atomic mass
Phosphorous	P	15	30.97362	Cadmium	Cd	48	112.411
Sulfur	S	16	32.066	Indium	In	49	114.82
Chlorine	Cl	17	35.4527	Tin	Sn	50	118.71
Argon	Ar	18	39.948	Antimony	Sb	51	121.75
Potassium	K	19	39.0983	Tellurium	Te	52	127.60
Calcium	Ca	20	40.078	Iodine	I	53	126.90447
Scandium	Sc	21	44.95591	Xenon	Xe	54	131.29
Titanium	Ti	22	47.88	Cesium	Cs	55	132.90543
Vanadium	V	23	50.9415	Barium	Ba	56	137.327
Chromium	Cr	24	51.9961	Lanthanum	La	57	138.9055
Manganese	Mn	25	54.93085	Cerium	Ce	58	140.115
Iron	Fe	26	55.847	Praseodymium	Pr	59	140.90765
Cobalt	Co	27	58.9332	Neodymium	Nd	60	144.24
Nickel	Ni	28	58.69	Promethium	Pm	61	(145)
Copper	Cu	29	63.546	Samarium	Sm	62	150.36
Zinc	Zn	30	65.39	Europium	Eu	63	151.965
Gallium	Ga	31	69.723	Gadolinium	Gd	64	157.25
Germanium	Ge	32	72.61	Terbium	Tb	65	158.92534
Arsenic	As	33	74.92159	Dysprosium	Dy	66	162.50
Selenium	Se	34	78.96	Holmium	Ho	67	164.93032
Bromine	Br	35	79.904	Erbium	Er	68	167.26
Krypton	Kr	36	83.80	Thulium	Tm	69	168.93421
Rubidium	Rb	37	85.4678	Ytterbium	Yb	70	173.04
Strontium	Sr	38	87.62	Lutetium	Lu	71	174.967
Yttrium	Y	39	88.90585	Hafnium	Hf	72	178.49
Zirconium	Zr	40	91.224	Tantalum	Ta	73	180.9479
Niobium	Nb	41	92.90638	Wolfram	W	74	183.85
Molybdenum	Mo	42	95.94	Rhenium	Re	75	186.207
Technetium	Tc	43	(98)	Osmium	Os	76	190.2
Ruthenium	Ru	44	101.07	Iridium	Ir	77	192.22
Rhodium	Rh	45	102.9055	Platinum	Pt	78	195.09
Palladium	Pd	46	106.42	Gold	Au	79	196.96654
Silver	Ag	47	107.8682	Mercury	Hg	80	200.59

(*continued*)

Table B.1 (continued)

Element	Symbol	Atomic number	Atomic mass	Element	Symbol	Atomic number	Atomic mass
Thallium	Tl	81	204.3833	Protactinium	Pa	91	231.03588
Lead	Pb	82	207.2	Uranium	U	92	238.0289
Bismuth	Bi	83	208.98037	Neptunium	Np	93	237.0482
Polonium	Po	84	(209)	Plutonium	Pu	94	(244)
Astatine	At	85	(210)	Americium	Am	95	(243)
Radon	Rn	86	(222)	Curium	Cm	96	(247)
Francium	Fr	87	(223)	Berkelium	Bk	97	(247)
Radium	Ra	88	226.025	Californium	Cf	98	(251)
Actinium	Ac	89	227.028	Einsteinium	Es	99	(252)
Thorium	Th	90	232.0381	Fermium	Fm	100	(257)

Mass numbers in parentheses are those for the most stable or best known isotope.
Source: *CRC Handbook of Chemistry and Physics,* 70th edition; *Perry's Chemical Engineers' Handbook,* 6th ed.

B.2 Nonideal Gas Model Equation and Critical Properties

One way to write the ideal gas law is

$$\frac{P\hat{V}}{RT} = 1$$

where P = pressure, T = temperature, R = ideal gas constant, and $\hat{V}$ = specific molar volume (volume per mole). The ideal gas law is a very useful model equation for calculating specific volumes (or, equivalently, densities) of gases at low to moderate pressures. For accurate calculations at higher pressures, either experimental data or more complicated model equations are required. Many such equations have been proposed; *Perry's Chemical Engineers' Handbook* or any chemical engineering thermodynamics textbook is a good source of information. Although differing in detail and complexity, these equations share the common feature of calculating a value for the compressibility factor Z, where

$$Z = \frac{P\hat{V}}{RT}$$

For an ideal gas, $Z = 1$. Most of the time, for real gases $Z < 1$. (You will typically see values of roughly $0.7 < Z < 1$.) One of the most widely used model

equations for predicting specific volumes of real gases is the Redlich-Kwong equation:

$$Z^3 - Z^2 + (A - B^2 - B)\,Z - AB = 0$$

where

$$A = \frac{aP}{R^2\,T^{2.5}} \qquad a = \frac{\Omega_a R^2\,T_c^{2.5}}{P_c} \qquad \Omega_a = \frac{1}{9\left(\sqrt[3]{2} - 1\right)}$$

$$B = \frac{bP}{RT} \qquad b = \frac{\Omega_b RT_c}{P_c} \qquad \Omega_b = \frac{\sqrt[3]{2} - 1}{3}$$

Knowing just the critical temperature T_c and critical pressure P_c for the compound of interest is sufficient to calculate Z (and hence specific volume or density) for that gas at a given T and P. Since the Redlich-Kwong equation is a cubic equation, there are three roots. The largest real root is the correct value of Z for a gas. Critical temperatures and pressures for selected compounds are in Table B.2. Convert T_c to an absolute temperature scale before using in the Redlich-Kwong equation.

Table B.2 Critical Temperature T_c and Critical Pressure P_c of Selected Compounds

Compound	Formula	T_c, °C	P_c, atm	Compound	Formula	T_c, °C	P_c, atm
Acetaldehyde	C_2H_4O	188.0		Carbon disulfide	CS_2	273.0	76.0
Acetic acid	$C_2H_4O_2$	321.6	57.2	Carbon monoxide	CO	−139	35.0
Acetic anhydride	$C_4H_6O_3$	296.0	46.0	Chlorine	Cl_2	144.0	76.1
Acetone	C_3H_6O	235.0	47.0	Diethylamine	$(C_2H_5)_2NH$	223.5	36.2
Acetonitrile	C_2H_3N	274.7	47.7	Dimethylamine	$(CH_3)_2NH$	164.6	51.7
Acetylene	C_2H_2	36.0	62.0	Ethane	C_2H_6	32.1	48.8
Air		−140.7	37.2	Ethyl acetate	$CH_3COOC_2H_5$	250.1	37.8
Ammonia	NH_3	132.4	111.5	Ethanol	C_2H_5OH	243.1	63.1
Argon	Ar	−122	48.0	Ethylene	C_2H_4	9.7	50.5
Benzene	C_6H_6	288.5	47.7	Ethylene oxide	C_2H_4O	192.0	
Bromine	Br_2	311	102	Fluorine	F	−155	25.0
Butadiene, 1,3	C_4H_6	152	42.7	Helium	He	−267.9	2.26
n-butane	C_4H_{10}	153	36.0	Heptane	C_7H_{16}	266.8	26.8
Carbon dioxide	CO_2	31.1	73.0	Hydrazine	N_2H_4	380.0	145.0

(*continued*)

Table B.2 (continued)

Compound	Formula	T_c, °C	P_c, atm	Compound	Formula	T_c, °C	P_c, atm
Hydrogen	H_2	−239.9	12.8	*n*-Pentane	C_5H_{12}	197.2	33.0
Hydrogen chloride	HCl	51.4	81.6	Phenol	C_6H_5OH	419.0	60.5
Hydrogen cyanide	HCN	183.5	53.2	Phosgene	$COCl_2$	182.0	56.0
Hydrogen sulfide	H_2S	100.4	88.9	*n*-Propane	C_3H_8	96.8	42.0
Isobutane	C_4H_{10}	134.0	37.0	Propionic acid	C_2H_5COOH	339.5	53.0
Isopentane	C_5H_{12}	187.8	32.8	*n*-Propanol	C_3H_7OH	263.7	49.95
Mercury	Hg	>1550	>200	Propylene	C_3H_6	92.3	45.0
Methyl acetate	CH_3COOCH_3	233.7	46.3	Pyridine	C_6H_5N	344.0	60.0
Methanol	CH_3OH	240.0	78.7	Radon	Rn	104.0	62.0
Methyl ethyl ether	$CH_3OC_2H_5$	164.7	43.4	Sodium	Na	2546	343
Neon	Ne	−228.7	25.9	Silicon tetrafluoride	SiF_4	−1.5	50.0
Nitric oxide	NO	−94.0	65.0	Sulfur dioxide	SO_2	157.2	77.7
Nitrogen	N_2	−147.1	33.5	Sulfur trioxide	SO_3	218.3	83.6
Nitrogen tetroxide	N_2O_4	158.0	100	Toluene	$C_6H_5CH_3$	320.6	41.6
Nitrous oxide	N_2O	36.5	71.7	Triethylamine	$(C_2H_5)_3N$	262.0	30.0
n-Octane	C_8H_{18}	296.0	24.6	Trimethylamine	$(CH_3)_3N$	161.0	41.0
Oxygen	O_2	−118.8	49.7	Water	H_2O	374.15	218.4

To convert to T (K), add 273.15.
To convert to P (bar), divide by 1.01325.
Source: *Perry's Chemical Engineers' Handbook*, 6th ed.

B.3 Gibbs Energy, Enthalpy of Formation, and Enthalpy of Combustion

The standard Gibbs energy of formation is useful for calculating the Gibbs energy change with reaction at 298 K, as in Eq. (4.14):

$$\Delta \hat{G}_r^\circ = \sum \nu_i \Delta \hat{G}_{i,f}^\circ$$

To a good approximation, we can calculate the Gibbs energy change at any temperature T by using the van't Hoff expression, Eq. (4.15):

$$\ln K_{a,T} = -\frac{\Delta \hat{G}^\circ_T}{RT} = -\frac{1}{R}\left[\frac{\Delta \hat{G}^\circ_r - \Delta \hat{H}^\circ_r}{298} + \frac{\Delta \hat{H}^\circ_r}{T}\right]$$

where

$$\Delta \hat{H}^\circ_r = \sum \nu_i \Delta \hat{H}^\circ_{i,f}$$

or

$$\Delta \hat{H}^\circ_r = -\sum \nu_i \Delta \hat{H}^\circ_{i,c}$$

Table B.3 Standard Gibbs Energy of Formation $\Delta \hat{G}^\circ_f$, Enthalpy of Formation $\Delta \hat{H}^\circ_f$, and Enthalpy of Combustion $\Delta \hat{H}^\circ_c$ at 298 K

Compound	Formula	$\Delta \hat{G}^\circ_f$ kJ/gmol	$\Delta \hat{H}^\circ_f$ kJ/gmol	$\Delta \hat{H}^\circ_c$ kJ/gmol
Acetaldehyde (g)	C_2H_4O	−133.1	−166.2	−1104.5
Acetic acid (g)	$C_2H_4O_2$	−374.6	−432.8	−814.6
(l)		−392.5	−486.18	
Acetic anhydride (g)	$C_4H_6O_3$	−473.4	−572.5	−1675
Acetone (g)	C_3H_6O	−151.3	−215.7	−1659
(l)		−155.5	−248.2	
Acetonitrile (g)	C_2H_3N	91.868	74.04	−1190.4
Acetylene (g)	C_2H_2	210.68	228.2	−1257
Adipic acid (l)	$C_6H_{10}O_4$	−985.4	−741.3	
Ammonia (g)	NH_3	−16.6	−46.15	−316.8
Ammonium nitrate (s)	$N_2H_5NO_3$		−251.58	
(aq)		−28.9	−215.1	
Argon (g)	Ar	0	0	0
Benzene (g)	C_6H_6	129.6	82.88	−3136
Butadiene, 1,3 (g)	C_4H_6	149.7	109.24	−2409
n-Butane (g)	C_4H_{10}	−15.707	−124.73	−2657.3
Calcium carbonate (s)	$CaCO_3$	−1133.0	−1211.3	

(*continued*)

Table B.3 (continued)

Compound	Formula	$\Delta\hat{G}_f^\circ$ kJ/gmol	$\Delta\hat{H}_f^\circ$ kJ/gmol	$\Delta\hat{H}_c^\circ$ kJ/gmol
Calcium chloride (s)	$CaCl_2$	−752.28	−797.47	
Carbon dioxide (g)	CO_2	−394.37	−393.5	0
Carbon disulfide (g)	CS_2	66.8	116.9	−1076.9
Carbon monoxide (g)	CO	−137.27	−110.53	−283
Carbonyl sulfide (g)	COS	−165.5	−141.5	
Chlorine (g)	Cl_2	0	0	0
Chlorobenzene (l)	C_6H_5Cl	89.2	11.5	
Chloroform (g)	$CHCl_3$	−103.61	−70.1	
Cyclohexane (g)	C_6H_{12}	31.8	−123.1	
(l)		26.7	−156.2	
Diethylamine (g)	$(C_2H_5)_2NH$	73.08	−71.42	−2800.3
Diethyl ether (g)	$(C_2H_5)_2O$		−252.7	
(l)		−116.1	−272.8	
Dimethylamine (g)	$(CH_3)_2NH$	68.0	−18.6	
Dimethyl carbonate (l)	$C_3H_6O_3$	−482	−365	
Dimethyl ether (g)	$(CH_3)_2O$	−109.0	−184.1	−28.84
Ethane (g)	C_2H_6	−31.92	−83.82	−1428.6
Ethanol (g)	C_2H_5OH	−167.85	−234.95	−1235
(l)		−174.72	−277.61	
Ethyl acetate (g)	$CH_3COOC_2H_5$	−328.0	−444.5	−2061
(l)		−318.4	−463.3	
Ethylamine (g)	$C_2H_5NH_2$	36.16	−47.15	−1587.4
Ethylbenzene (g)	C_8H_{10}	130.73	29.92	−4345
(l)		119.7	−12.5	
Ethylene (g)	C_2H_4	68.44	52.51	−1323
Ethylene glycol (g)	C_2HO_2	−302.6	−387.5	−1059
(l)		−319.8	−451.5	
Ethylene oxide (g)	C_2H_4O	−13.23	−52.63	−1218
Formaldehyde (g)	CH_2O	−102.6	−108.6	−526.8
Formic acid (g)	CH_2O_2	−351.0	−378.6	−211.5

Compound	Formula	$\Delta\hat{G}_f^\circ$ kJ/gmol	$\Delta\hat{H}_f^\circ$ kJ/gmol	$\Delta\hat{H}_c^\circ$ kJ/gmol
Gallium nitride (s)	GaN		−109.6	
Glycerol (glycerin) (g)	$C_3H_8O_3$		−577.9	
(l)		−475.5	−665.9	
n-Heptane (g)	C_7H_{16}	8.165	−187.8	−4464.7
(l)		1.757	−224.4	
Hexamethylenediamine (g)	$C_6H_{16}N_2$	120.96	−127.9	
n-Hexane (g)	C_6H_{14}	−0.066	−166.94	−3855.1
(l)		−3.81	−198.8	
Hydrazine (g)	N_2H_4	159.17	95.353	−5342
(l)			50.46	
Hydrogen (g)	H_2	0	0	0
Hydrogen chloride (g)	HCl	−95.30	−92.31	−28.6
Hydrogen peroxide (g)	H_2O_2	−105.48	−136.11	
(l)		−118.11	−188.95	
Hydrogen cyanide (g)	HCN	124.7	135.14	−623.3
Hydrogen sulfide (g)	H_2S	−32.84	−19.96	
Iron oxide (ferrous) (s)	FeO	−248.45	−270.37	
(ferric, hematite) (s)	Fe_2O_3	−749.35	−830.5	
(magnetite) (s)	Fe_3O_4	−1013.8	−1116.7	
Isobutane (g)	C_4H_{10}	−20.76	−131.418	−2649
Isobutene (g)	C_4H_8	70.27	−0.54	−2540.8
Isopentane (g)	C_5H_{12}	−14.05	−153.7	−3239.5
Magnesium chloride (s)	$MgCl_2$	−601.5	−641.1	
Methane (g)	CH_4	−50.49	−74.52	−802.6
Methyl acetate (g)	CH_3COOCH_3		−410.0	
Methanol (g)	CH_3OH	−162.32	−200.94	
(l)		−166.12	−238.655	−638.46
Methyl ethyl ether	$CH_3OC_2H_5$	−117.1	−216.4	−1931.4
Naphthalene (g)	C_8H_{10}	224.08	150.58	−498.09
Nitric acid (g)	HNO_3	−73.51	−133.85	
(l)		−79.91	−173.22	

(*continued*)

Table B.3 (continued)

Compound	Formula	$\Delta\hat{G}_f^\circ$ kJ/gmol	$\Delta\hat{H}_f^\circ$ kJ/gmol	$\Delta\hat{H}_c^\circ$ kJ/gmol
Nitric oxide (g)	NO	86.57	90.25	−90.2
Nitroglycerin	$C_3H_5(NO_3)_3$		−279.1	
Nitrogen (g)	N_2	0	0	0
Nitrogen dioxide (g)	NO_2	51.3	33.3	
Nitrogen tetroxide (g)	N_2O_4	97.95	9.33	
Nitrous oxide (g)	N_2O	104.16	82.05	−82
n-Octane (g)	C_8H_{18}	16.0	−208.75	−5074.2
(l)		7.4	−249.95	
Oxygen (g)	O_2	0	0	0
n-Pentane (g)	C_5H_{12}	−8.81	−146.76	−3244.9
(l)		−9.25	−173.05	
Phenol (g)	C_6H_5OH	−32.637	−96.399	−2921
(l)		−46.11	−158.16	
Phosgene (g)	$COCl_2$	−206.8	−220.1	
n-Propane (g)	C_3H_8	−24.39	−104.68	−2043.1
Propionic acid (g)	C_2H_5COOH	−366.7	−453.5	−1395
(l)		−383.5	−509.2	
n-Propanol (g)	C_3H_7OH	−159.9	−255.2	−1843.8
(l)		−166.69	−300.70	
Propylene (g)	C_3H_6	62.15	19.71	−1925.7
Silicon tetrachloride (l)	$SiCl_4$	−560.24	−627	
Silicon dioxide (c,quartz)	SiO_2	−796.6	−850.8	
Sodium borohydride (aq)	$NaBH_4$	−147.61	−199.6	
Sodium carbonate (c)	Na_2CO_3	−1044.12	−1127.42	
Sodium chloride (c)	NaCl	−384.485	−411.375	
Sodium cyanide (c)	NaCN		−94.0	
Sodium hydroxide (s)	NaOH	−379.4	−425.9	
(aq)		−419.2	−469.15	
Sodium metaborate (aq)	$NaBO_2$	−940.81	−1012.49	
Styrene	C_8H_8	213.9	147.4	−4219

Compound	Formula	$\Delta\hat{G}^\circ_f$ kJ/gmol	$\Delta\hat{H}^\circ_f$ kJ/gmol	$\Delta\hat{H}^\circ_c$ kJ/gmol
Sulfur dioxide (g)	SO_2	−299.9	−296.81	0
Sulfur trioxide (g)	SO_3	−370.66	−394.93	
Sulfuric acid (l)	H_2SO_4		−810.4	
(aq)			−887.1	
Toluene (g)	$C_6H_5CH_3$	122.0	50.17	−3734
(l)		114.148	11.996	
Triethylamine (g)	$(C_2H_5)_3N$	114.1	−95.8	−4040.5
Trimethylamine	$(CH_3)_3N$	98.99	−243.1	−2244.9
Trinitrotoluene (g)	$C_7H_5(NO_2)_3$		24.1	
(s)			−65.6	
Urea (g)	$(NH_2)_2CO$	−152.7	−235.5	
(l)		−194.3	−324.5	
(s)		−196.8	−333.6	
Vinyl chloride (g)	C_2H_3Cl	41.95	28.45	−1178
Water (g)	H_2O	−228.59	−241.83	0
(l)		−237.19	−285.84	−44.0
o-Xylene (g)	C_8H_{10}	122.2	19.08	−4333.0
(l)		110.33	−24.44	
m-Xylene (g)	C_8H_{10}	118.76	17.32	−4331.8
(l)		107.654	−25.418	
p-Xylene (g)	C_8H_{10}	121.4	18.03	−4333.0
(l)		110.08	−24.246	

$\Delta\hat{H}^\circ_c$ is the enthalpy change associated with combustion of the compound in the gas phase, with CO_2 (g), H_2O (g), Cl_2 (g), N_2 (g), and SO_2 (g) as products. With H_2O (l) as product, $\Delta\hat{H}^\circ_c$ decreases (becomes more negative) by 44.0n kJ/gmol, where n is the number of moles of H_2O. $-\Delta\hat{H}^\circ_c$ is sometimes called the lower heating value with water vapor and the higher heating value with liquid water as the product.

Source: Compiled from data in *Perry's Chemical Engineers' Handbook,* 6th and 7th eds., *Lange's Handbook of Chemistry,* 14th ed., and NIST Chemistry Webbook.

B.4 Antoine Equation Constants

The Antoine equation

$$\log_{10} P^{\text{sat}}(\text{mmHg}) = A - \frac{B}{T(^\circ\text{C}) + C}$$

is a useful equation for modeling saturation pressures of liquids and solids. The constants should not be used outside the indicated temperature range.

Table B.4 Antoine Equation Constants for Selected Compounds

Compound	Formula	Range, °C	*A*	*B*	*C*
Acetaldehyde	CH_3CHO	−45 to +70	8.0055	1600	291.8
Acetic acid	CH_3COOH		7.38782	1533.313	222.309
Acetic anhydride	$C_4H_6O_3$		7.14948	1444.718	199.817
Acetone	CH_3COCH_3		7.02447	1161.0	224
Acetonitrile	CH_3CN		7.11988	1314.4	230
Acrylonitrile	C_3H_3N	−20 to +140	7.03855	1232.53	222.47
Ammonia	NH_3	−83 to +60	7.36050	926.132	240.17
Benzene	C_6H_6	+8 to +103	6.90565	1211.033	220.790
Benzoic acid	C_6H_5COOH	96 to 250	7.3533	1771.4	145.67
Bromine	Br_2		6.87780	1119.68	221.38
n-Butanol	C_4H_9OH	+15 to +131	7.47680	1362.39	178.77
Butadiene, 1,3	C_4H_6	−58 to +15	6.84999	930.546	238.854
Carbon disulfide	CS_2	3 to 80	6.94279	1169.11	241.59
Chlorine	Cl_2		6.93790	861.34	246.33
Chloroform	$CHCl_3$	−35 to 61	6.4934	929.44	196.03
Diethanolamine	$(C_2H_5O)_2NH$	194 to 241	8.1388	2327.9	174.4
Diethylamine	$(C_2H_5)_2NH$	31 to 61	5.8016	583.30	144.1
Dimethylamine	$(CH_3)_2NH$	−72 to +6.9	7.08212	960.242	221.67
Ethanol	C_2H_5OH	−2 to +100	8.04494	1554.3	222.65
Ethanolamine	C_2H_7ON	65 to 171	7.4568	1577.67	173.37
Ethyl acetate	$CH_3COOC_2H_5$	15 to 76	7.10179	1244.95	217.88
Ethylamine	$C_2H_5NH_2$	−20 to +90	7.05413	987.31	220.0
Ethylbenzene	C_8H_{10}	26 to 164	6.95719	1424.255	213.21
Ethylene glycol	$C_2H_6O_2$	50 to 200	8.0908	2088.9	203.5

Compound	Formula	Range, °C	*A*	*B*	*C*
Ethylene oxide	C_2H_4O	−49 to +12	7.12843	1054.54	237.76
Formic acid	CH_2O_2	37 to 101	7.5818	1699.2	260.7
Glycerol	$C_3H_8O_3$	183 to 260	6.165	1036	28
n-Heptane	C_7H_{16}	−2 to +124	6.89677	1264.90	216.54
n-Hexane	C_6H_{14}	−25 to 92	6.87601	1171.17	224.41
Hydrogen cyanide	HCN	−16 to 46	7.5282	1329.5	260.4
Hydrogen peroxide	H_2O_2		7.96917	1886.76	220.6
Isopentane	C_5H_{12}		6.78967	1020.012	233.097
Isopropanol	C_3H_7OH	0 to 100	8.11778	1580.92	219.61
Lactic acid	$C_3H_6O_3$		8.06	1823.7	134
Methanol	CH_3OH	−14 to 65	7.89750	1474.08	229.13
		65 to 110	7.97328	1515.14	232.85
Methyl acetate	CH_3COOCH_3	1 to 56	7.0652	1157.63	219.73
Methyl ethyl ketone	$CH_3COC_2H_5$		6.97	1210	216
Naphthalene (s)	$C_{10}H_8$	86 to 250	7.01065	1733.71	201.86
(l)		125 to 218	6.8181	1585.86	184.82
Nitrogen	N_2		6.49457	255.68	266.55
n-Octane	C_8H_{18}	19 to 152	6.91868	1351.99	209.15
Oxygen	O_2		6.69144	319.013	266.697
n-Pentane	C_5H_{12}	−50 to 58	6.85221	1064.63	233.01
Phosgene	$COCl_2$	−68 to 68	6.84297	941.25	230
Phenol	C_6H_5OH	107 to 182	7.133	1516.79	174.95
n-Propanol	C_3H_7OH	2 to 120	7.84767	1499.21	204.64
Propionic acid	C_2H_5COOH	56 to 139	6.403	950.2	130.3
Silicon tetrachloride	$SiCl_4$	0 to 53	6.85726	1138.92	228.88
Styrene	C_8H_8	32 to 82	7.14016	1574.51	224.09
Tetramethyl lead	$C_4H_{12}Pb$	0 to 60	6.9377	1335.3	219.1
Toluene	C_7H_8	6 to 137	6.95464	1344.8	219.48
Water	H_2O	0 to 60	8.10765	1750.286	235.0
		60 to 150	7.96681	1668.21	228.0
n-Xylene	C_8H_{10}	32 to 172	6.99891	1474.679	213.69
m-Xylene	C_8H_{10}	28 to 166	7.00908	1462.266	215.11
p-Xylene	C_8H_{10}	27 to 166	6.99052	1453.43	215.31

Source: *Lange's Handbook of Chemistry,* 14th ed and NIST Chemistry Webbook.

B.5 Phase Equilibrium Data

Table B.5 Henry's Law Constant (atm), $H_i = {}^{y_i P}/_{x_i} = {}^{p_i}/_{x_i}$, for Gas Dissolved in Water

	0°C	10°C	20°C	30°C	40°C	50°C
He	129,000	126,000	125,000	124,000	121,000	115,000
H_2	57,900	63,600	68,300	72,900	75,100	76,500
N_2	52,900	66,800	80,400	92,400	104,000	113,000
CO	35,200	44,200	53,600	62,000	69,600	76,100
O_2	25,500	32,700	40,100	47,500	53,500	58,800
CH_4	22,400	29,700	37,600	44,900	52,000	57,700
C_2H_6	12,600	18,900	26,300	34,200	42,300	50,000
C_2H_4	5,520	7,680	10,200	12,700		
CO_2	728	1,040	1,420	1,860	2,330	2,830
H_2S	268	367	483	609	745	884

Adapted from Hines and Maddox, *Mass Transfer Fundamentals and Applications,* 1985.

Table B.6 Partial Pressures of SO_2 in Equilibrium with Dissolved SO_2 in Water

	Partial pressure of SO_2, p_{SO_2}, mmHg									
Grams SO_2 per 100 grams water	10°C	20°C	30°C	40°C	50°C	60°C	70°C	80°C	90°C	100°C
0.5	21	29	42	60	83	111	144	182	225	274
1.0	42	59	85	120	164	217	281	356	445	548
1.5	64	90	129	181	247	328	426	543	684	850
2.0	86	123	176	245	333	444	581	756	940	
2.5	108	157	224	311	421	562	739	956		
3.0	130	191	273	378	511	682	897			
3.5	153	227	324	447	603	804				
4.0	176	264	376	518	698					
4.5	199	300	428	588	793					
5.0	223	338	482	661						
5.5	247	375	536	733						

Grams SO_2 per 100 grams water	Partial pressure of SO_2, p_{SO_2}, mmHg									
	10°C	20°C	30°C	40°C	50°C	60°C	70°C	80°C	90°C	100°C
6.0	271	411	588	804						
6.5	295	448	642							
7.0	320	486	698							
8.0	370	562	806							
9.0	421	638								
10.0	473	714								
11.0	526	789								
12.0	580									
13.0	635									
14.0	689									
15.0	743									
16.0	799									

Source: *Perry's Chemical Engineers' Handbook,* 6th ed.

Table B.7 Partial Pressures of NH_3 in Equilibrium with Dissolved NH_3 in Water

Grams NH_3 per 100 grams solution	Partial Pressure of NH_3, p_{NH_3}, mmHg								
	0°C	10°C	21°C	32°C	43°C	54°C	65.5°C	77°C	88°C
4.74	13.4	24.3	42.9	70	111	170	247	349	477
9.5	26.9	46	78.6	130	207	315	461	655	
14.3	46.5	78	134	220	344	520	760		
19.1	78	131	221	356	550				
23.9	138	215	355	563					
28.8	221	343	556						
33.7	338	530							
38.6	462	788							
43.6	731								

Source: Adapted from data in *Perry's Chemical Engineers' Handbook,* 6th ed.

Table B.8 Solubility of Salts in Water

Compound	Formula	0°C	10°C	20°C	30°C	40°C	50°C	60°C	70°C	80°C	90°C	100°C
Calcium bicarbonate	$Ca(HCO_3)_2$	16.15		16.6		17.05		17.50		17.95		18.4
Magnesium chloride	$MgCl_2 \cdot 6H_2O$	52.8	53.5	54.5		57.5		61.0		66.0		73.0
Potassium nitrate	KNO_3	13.3	20.9	31.6	45.8	63.9	85.5	110.0	138	169	202	246
Potassium sulfate	K_2SO_4	7.35	9.22	11.11	12.97	14.76	16.50	18.17	19.75	21.4	22.8	24.1
Sodium chloride	NaCl	35.7	35.8	36.0	36.3	36.6	37.0	37.3	37.8	38.4	39.0	39.8
Sodium sulfate	$Na_2SO_4 \cdot 10H_2O$	5.0	9.0	19.4	40.8							
	$Na_2SO_4 \cdot 7H_2O$	19.5	30	44								
	Na_2SO_4					48.8	46.7	45.3		43.7		42.5

Data are listed as grams of anhydrous substance per 100 g water, in a saturated liquid solution. The formula shows the solid phase (hydrated or anhydrous) that is in equilibrium with the saturated solution.
Source: *Perry's Chemical Engineers' Handbook,* 6th ed.

Table B.9 Benzene-Naphthalene Solid-Liquid Equilibrium

Mole fraction naphthalene in liquid phase, x_n	Temperature, °C	Solid phase
0.0	5.5	Benzene
0.023	4	Benzene
0.039	3	Benzene
0.083	0	Benzene
0.135	−3	Benzene
0.148	0	Naphthalene
0.17	5	Naphthalene
0.20	10	Naphthalene
0.26	20	Naphthalene
0.34	30	Naphthalene
0.43	40	Naphthalene
0.54	50	Naphthalene
0.67	60	Naphthalene
0.82	70	Naphthalene
1.0	80.2	Naphthalene

Saturated liquid solution of benzene and naphthalene in equilibrium with a single-component solid phase. (Calculated by assuming ideal solution behavior and using melting points and enthalpies of melting of pure components.)

Table B.10 *m*-Xylene–*p*-Xylene Solid-Liquid Equilibrium

Mole fraction *p*-xylene in liquid phase, x_p	Temperature, °C	Solid phase
0.0	−47.2	*m*-xylene
0.074	−50	*m*-xylene
0.125	−52	*m*-xylene
0.165	−45	*p*-xylene
0.20	−40	*p*-xylene
0.285	−30	*p*-xylene
0.396	−20	*p*-xylene
0.536	−10	*p*-xylene
0.71	0	*p*-xylene
0.923	10	*p*-xylene
1.0	13.2	*p*-xylene

Saturated liquid solution of *m*-xylene and *p*-xylene in equilibrium with a single-component solid phase. (Calculated by assuming ideal solution behavior and using melting points and enthalpies of melting of pure components.)

Table B.11 Ethanol-Water Vapor-Liquid Equilibrium at 1 atm

Temperature, °C	Mole fraction ethanol in liquid phase, x_e	Mole fraction ethanol in vapor phase, y_e
100.0	0.000	0.000
95.5	0.019	0.17
89.0	0.0721	0.3891
86.7	0.0966	0.4375
85.3	0.1238	0.4704
84.1	0.1661	0.5089
82.7	0.2337	0.5445
82.3	0.2608	0.5580
81.5	0.3273	0.5826
80.7	0.3965	0.6122
79.8	0.5079	0.6564
79.7	0.5198	0.6599
79.3	0.5732	0.6841
78.74	0.6763	0.7385
78.41	0.7472	0.7815
78.15	0.8943	0.8943

Source: *Perry's Chemical Engineers' Handbook,* 6th ed.

Table B.12 Methanol-Benzene Vapor-Liquid Equilibrium at 1 atm

Temperature, °C	Mole fraction methanol in liquid phase, x_m	Mole fraction methanol in vapor phase, y_m
70.67	0.026	0.267
66.44	0.050	0.371
62.87	0.088	0.457
60.20	0.164	0.526
58.64	0.333	0.559
58.02	0.549	0.595
58.10	0.699	0.633
58.47	0.782	0.665
59.90	0.898	0.760
62.71	0.973	0.907

Source: *Perry's Chemical Engineers' Handbook,* 6th ed.

Table B.13 Water-Acetic Acid-Methyl Isobutyl Ketone Liquid-Liquid Equilibrium, at 25°C

Weight % in raffinate			Weight % in extract		
Water	**Acetic acid**	**MIBK**	**Water**	**Acetic acid**	**MIBK**
98.45	0	1.55	2.12	0	97.88
95.46	2.85	1.7	2.80	1.87	95.33
85.8	11.7	2.5	5.4	8.9	85.7
75.7	20.5	3.8	9.2	17.3	73.5
67.8	26.2	6.0	14.5	24.6	60.9
55.0	32.8	12.2	22.0	30.8	47.2
42.9	34.6	22.5	31.0	33.6	35.4

Each row shows the compositions of the raffinate and extract phases at equilibrium.
Source: *Perry's Chemical Engineers' Handbook,* 6th ed.

Table B.14 Ethylbenzene-Styrene-Ethylene Glycol Liquid-Liquid Equilibrium, at 25°C

Weight % in raffinate			Weight % in extract		
Ethylbenzene	**Styrene**	**Ethylene glycol**	**Ethylbenzene**	**Styrene**	**Ethylene glycol**
90.56	8.63	0.81	9.85	1.64	88.51
80.40	18.67	0.93	9.31	3.49	87.20
70.49	28.51	1.00	8.72	5.48	85.80
60.93	37.98	1.09	8.07	7.45	84.48
53.55	45.25	1.20	7.35	9.25	83.40
52.96	45.84	1.20	7.31	9.49	83.20
43.29	55.32	1.39	6.30	12.00	81.70
41.51	57.09	1.40	6.06	12.54	81.40

Each row shows the compositions of the raffinate and extract phases at equilibrium.
Source: *Perry's Chemical Engineers' Handbook*, 6th ed.

Table B.15 Distribution Coefficient, $K_D = x_{A,\text{ phase II}}/x_{A,\text{ phase I}}$, for Solute a Distributing between Two Immiscible Liquids

Solute A	Solvent phase I	Solvent phase II	K_D
Acetic acid	Water	Methyl acetate	1.273
Acetic acid	Water	Furfural	0.787 (26.7°C)
Acetic acid	Water	Heptadecanol	0.312
Acetic Acid	Water	Benzene	0.0328
Acetic Acid	Water	1-Butanol	1.613 (26.7°C)
Oleic acid	Cottonseed oil	Propane	0.150 (85°C)
Chlorine	Water	Carbon tetrachloride	5.0
Bromine	Water	Carbon tetrachloride	27
Iodine	Water	Carbon tetrachloride	55
Ammonia	Water	Carbon tetrachloride	0.0042
Diethylamine	Water	Chloroform	2.2

(*continued*)

Table B.15 (continued)

Solute A	Solvent phase I	Solvent phase II	K_D
Diethylamine	Water	Benzene	1.8
Diethylamine	Water	Toluene	0.63
Diethylamine	Water	Xylene	0.20
Ethanol	Water	Benzene	0.1191
Ethanol	Water	Heptadecanol	0.270
Ethanol	Water	*n*-Butanol	3.00 (20°C)
Methyl ethyl ketone	Water	Gasoline	1.686
Methyl ethyl ketone	Water	2-Methyl furan	84.0
Penicillin F	Water (pH 6.0)	Amyl acetate	0.06
Penicillin F	Water (pH 4.0)	Amyl acetate	32

Data at 25°C unless otherwise noted. Reliable only at dilute solute concentrations.
Compiled from data in *Perry's Chemical Engineers' Handbook*, 6th ed., *Biochemical and Biotechnology Handbook*, 1991, 2nd ed., and *Process Synthesis*, D. F. Rudd, G. J. Powers and J. J. Siiroia, 1973.

B.6 Steam Tables

$\hat{H}$ and $\hat{U}$ are given in units of kJ/kg, with the reference condition as the triple point of liquid water (273.15 K, 0.00611 bar). $\hat{V}$ is given in units of m^3/kg.
Source: E. W. Lemmon, M. O. McLinden and D. G. Friend, "Thermophysical Properties of Fluid Systems" in *NIST Chemistry WebBook, NIST Standard Reference Database Number 69,* Eds. P. J. Linstrom and W. G. Mallard, June 2005, National Institute of Standards and Technology, Gaithersburg MD, 20899 (http://webbook.nist.gov).

(See table on next page.)

Table B.16 Specific Enthalpy $\hat{H}$, Internal Energy $\hat{U}$, and Volume $\hat{V}$ of H_2O at Several Temperatures and Pressures

P, bar (T^{sat}, °C)		Sat'd liquid	Sat'd vapor	Temperature (°C) 50	100	150	200	250	300	350
0.006116	$\hat{H}$	0.00	2500.9	2594.5	2688.6	2783.7	2880.0	2977.8	3077.0	3177.7
(0.01)	$\hat{U}$	0.00	2374.9	2445.4	2516.4	2588.4	2661.7	2736.3	2812.5	2890.1
	$\hat{V}$	0.00100	206.55	244.45	282.30	320.14	357.98	395.81	433.64	470.69
0.1	$\hat{H}$	191.81	2583.9	2592.0	2687.5	2783.1	2879.6	2977.5	3076.8	3177.6
(45.806)	$\hat{U}$	191.80	2437.2	2443.3	2515.5	2587.9	2661.4	2736.1	2812.3	2890.0
	$\hat{V}$	0.00101	14.670	14.867	17.197	19.514	21.826	24.137	26.446	28.755
1.0	$\hat{H}$	417.50	2674.9	209.46	2675.8	2776.6	2875.5	2974.5	3074.6	3175.8
(99.606)	$\hat{U}$	417.40	2505.6	209.36	2506.2	2583.0	2658.2	2733.9	2810.7	2888.7
	$\hat{V}$	0.00104	1.6939	0.00101	1.6959	1.9367	2.1725	2.4062	2.6389	2.8710
5.0	$\hat{H}$	640.09	2748.1	209.80	419.51	632.24	2855.9	2961.1	3064.6	3168.1
(151.83)	$\hat{U}$	639.54	2560.7	209.30	418.99	631.69	2643.3	2723.8	2803.3	2883.0
	$\hat{V}$	0.00109	0.37481	0.00101	0.00104	0.00109	0.4250	0.4744	0.5226	0.57016
10.0	$\hat{H}$	762.52	2777.1	210.19	419.84	632.5	2828.3	2943.1	3051.6	3158.2
(179.88)	$\hat{U}$	761.39	2582.7	209.18	418.80	631.41	2622.2	2710.4	2793.6	2875.7
	$\hat{V}$	0.00113	0.1944	0.00101	0.00104	0.00109	0.2060	0.2328	0.2580	0.2825
20.0	$\hat{H}$	908.5	2798.3	211.06	420.59	633.12	852.45	2903.2	3024.2	3137.7
(212.38)	$\hat{U}$	906.14	2599.1	209.03	418.51	630.94	850.14	2680.2	2773.2	2860.5
	$\hat{V}$	0.00118	0.0996	0.00101	0.00104	0.00109	0.00116	0.1115	0.1255	0.1386
40.0	$\hat{H}$	1087.5	2800.8	212.78	422.10	634.36	853.27	1085.8	2961.7	3093.3
(250.35)	$\hat{U}$	1082.5	2601.7	208.74	417.93	630.01	848.65	1080.8	2726.2	2827.4
	$\hat{V}$	0.00125	0.04978	0.00101	0.00104	0.00109	0.00115	0.00125	0.0589	0.0665
60.0	$\hat{H}$	1213.9	2784.6	214.50	423.60	635.61	854.09	1085.7	2885.5	3043.9
(275.58)	$\hat{U}$	1206.0	2589.9	208.44	417.36	629.08	847.18	1078.2	2668.4	2790.4
	$\hat{V}$	0.00132	0.03245	0.00101	0.00104	0.00109	0.00115	0.00125	0.0362	0.0423
100.0	$\hat{H}$	1408.1	2725.5	217.94	426.62	638.11	855.8	1085.8	1343.3	2924.0
(311.00)	$\hat{U}$	1393.5	2545.2	207.86	416.23	627.27	844.31	1073.4	1329.4	2699.6
	$\hat{V}$	0.00145	0.0180	0.00101	0.00104	0.00108	0.00115	0.00124	0.00140	0.0224
150.0	$\hat{H}$	1610.2	2610.7	222.23	430.39	641.27	857.99	1086.1	1338.3	2693.1
(342.16)	$\hat{U}$	1585.3	2455.6	207.15	414.85	625.05	840.84	1067.6	1317.6	2520.9
	$\hat{V}$	0.00166	0.01034	0.00101	0.00104	0.00108	0.00114	0.00123	0.00138	0.0115
200	$\hat{H}$	1827.2	2412.3	226.51	434.17	644.45	860.27	1086.7	1334.4	1646.0
(365.75)	$\hat{U}$	1786.4	2295.0	206.44	413.50	622.89	837.49	1062.2	1307.1	1612.7
	$\hat{V}$	0.00204	0.00586	0.00100	0.00103	0.00108	0.00114	0.00123	0.00136	0.00166
220.64	$\hat{H}$	2084.3	2084.3	228.28	435.73	645.77	861.23	1087.0	1333.0	1635.6
(373.95)	$\hat{U}$	2015.7	2015.7	206.16	412.95	622.01	836.14	1060.0	1303.1	1599.6
	$\hat{V}$	0.00311	0.00311	0.00100	0.00103	0.00108	0.00114	0.00122	0.00135	0.00163

(*continued*)

Table B.16 (continued)

P, bar (T^{sat}, °C)		Sat'd liquid	Sat'd vapor	Temperature (°C) 400	500	600	700	800	900	1000
0.006116	$\hat{H}$	0	2500.9	3280.1	3489.8	3706.3	3930	4160.7	4398.4	4642.8
(0.01)	$\hat{U}$	0.00	2374.9	2969.4	3133	3303.4	3480.8	3665.4	3856.9	4055.3
	$\hat{V}$	0.00100	206.55	507.96	583.42	658.88	734.35	809.81	885.27	960.73
0.1	$\hat{H}$	191.81	2583.9	3279.9	3489.7	3706.3	3929.9	4160.6	4398.3	4642.8
(45.806)	$\hat{U}$	191.80	2437.2	2969.3	3132.9	3303.3	3480.8	3665.3	3856.9	4055.2
	$\hat{V}$	0.00101	14.670	31.063	35.680	40.296	44.911	49.527	54.142	58.758
1.0	$\hat{H}$	417.50	2674.9	3278.6	3488.7	3705.6	3929.4	4160.2	4398.0	4642.6
(99.606)	$\hat{U}$	417.40	2505.6	2968.3	3132.2	3302.8	3480.4	3665.0	3856.6	4055.0
	$\hat{V}$	0.00104	1.6939	3.1027	3.5655	4.0279	4.4900	4.9519	5.4137	5.8754
5.0	$\hat{H}$	640.09	2748.1	3272.3	3484.5	3702.5	3927.0	4158.4	4396.6	4641.4
(151.83)	$\hat{U}$	639.54	2560.7	2963.7	3129.0	3300.4	3478.5	3663.6	3855.4	4054.0
	$\hat{V}$	0.00109	0.37481	0.6173	0.7109	0.8041	0.897.0	0.9897	1.0823	1.1748
10.0	$\hat{H}$	762.52	2777.1	3264.5	3479.1	3698.6	3924.1	4156.1	4394.8	4639.9
(179.88)	$\hat{U}$	761.39	2582.7	2957.9	3125.0	3297.5	3476.2	3661.7	3853.9	4052.7
	$\hat{V}$	0.00113	0.1944	0.3066	0.3541	0.4011	0.4478	0.4944	0.5408	0.5872
20.0	$\hat{H}$	908.5	2798.3	3248.3	3468.2	3690.7	3918.2	4151.5	4391.1	4637.0
(212.38)	$\hat{U}$	906.14	2599.1	2945.9	3116.9	3291.5	3471.6	3658.0	3850.9	4050.2
	$\hat{V}$	0.00118	0.0996	0.1512	0.1757	0.1996	0.2233	0.2467	0.2701	0.2934
40.0	$\hat{H}$	1087.5	2800.8	3214.5	3446.0	3674.9	3906.3	4142.3	4383.9	4631.2
(250.35)	$\hat{U}$	1082.5	2601.7	2920.7	3100.3	3279.4	3462.4	3650.6	3844.8	4045.1
	$\hat{V}$	0.00125	0.04978	0.0734	0.0864	0.0989	0.1110	0.1229	0.1348	0.1465
60.0	$\hat{H}$	1213.9	2784.6	3178.2	3423.1	3658.7	3894.3	4133.1	4376.6	4325.4
(275.58)	$\hat{U}$	1206.0	2589.9	2893.7	3083.1	3267.2	3453.0	3643.2	3838.8	4040.1
	$\hat{V}$	0.00132	0.03245	0.0474	0.0567	0.0653	0.0735	0.0816	0.0896	0.0976
100.0	$\hat{H}$	1408.1	2725.5	3097.4	3375.1	3625.8	3870.0	4114.5	4362.0	4613.8
(311.00)	$\hat{U}$	1393.5	2545.2	2833.1	3047.0	3242.0	3434.0	3628.2	3826.5	4029.9
	$\hat{V}$	0.00145	0.0180	0.0264	0.0328	0.0384	0.0436	0.0486	0.0535	0.0584
150.0	$\hat{H}$	1610.2	2610.7	2975.7	3310.8	3583.1	3839.1	4091.1	4343.7	4599.2
(342.16)	$\hat{U}$	1585.3	2455.6	2740.6	2998.4	3209.3	3409.8	3609.2	3811.2	4017.1
	$\hat{V}$	0.00166	0.01034	0.0157	0.0208	0.0249	0.0286	0.0321	0.0355	0.0388
200.0	$\hat{H}$	1827.2	2412.3	2816.9	3241.2	3539.0	3807.8	4067.5	4325.4	4584.7
(365.75)	$\hat{U}$	1786.4	2295.0	2617.9	2945.3	3175.3	3385.1	3590.1	3795.7	4004.3
	$\hat{V}$	0.00204	0.00586	0.00995	0.0148	0.0182	0.0211	0.0239	0.0265	0.0290
220.64	$\hat{H}$	2084.3	2084.3	2732.9	3210.8	3520.4	3794.7	4057.7	4317.8	4578.8
(373.95)	$\hat{U}$	2015.7	2015.7	2551.9	2922.0	3160.9	3374.7	3582.1	3789.3	3999.0
	$\hat{V}$	0.00311	0.00311	0.0082	0.0131	0.0163	0.019.0	0.0216	0.0239	0.0263

B.7 Heat Capacities

Table B.17 Heat Capacity C_p of Selected Liquids and Vapors

Compound	Formula	C_p (approx.)	*A*	*B*	*C*	*D*
Acetaldehyde (g)	C_2H_4O	54.7				
(l)		89.05				
Acetic acid (g)	$C_2H_4O_2$	66.5	4.840	0.2549	−1.753e-4	4.949e-8
(l)		124.4				
Acetone (g)	C_3H_6O	74.5	6.301	0.2606	−1.253e-4	2.038e-8
(l)			72.2	0.186		
Acetonitrile (g)	C_2H_3N	52.2	20.48	0.1196	−4.492e-5	3.203e-9
Acetylene (g)	C_2H_2	44.2	26.82	0.07578	−5.007e-5	1.412e-8
Ammonia (g)	NH_3	35.6	27.31	0.02383	1.707e-5	−1.185e-8
Argon (g)	Ar	20.8	20.8			
Benzene (g)	C_6H_6	81.7	−33.92	0.4739	−3.017e-4	7.13e-8
(l)		134.3	−6.2106	0.5650	−3.141e-4	
Bromine (g)	Br_2	36.3	33.86	0.01125	−1.192e-5	4.534e-9
Butadiene, 1,3 (g)	C_4H_6	79.5	−1.687	0.3419	−2.340e-4	6.335e-8
n-Butane (g)	C_4H_{10}	98.9	9.487	0.3313	−1.108e-4	−2.822e-9
Carbon dioxide (g)	CO_2	37.0	19.80	0.07344	−5.602e-5	1.7115e-8
Carbon disulfide (g)	CS_2	34.2	27.44	0.08127	−7.666e-5	2.673e-8
Carbon monoxide (g)	CO	29.1	30.87	−0.01285	2.789e-5	−1.272e-8
Carbon tetrachloride (g)	CCl_4	84.0	40.72	0.2049	−2.270e-4	8.843e-8
Chlorine (g)	Cl_2	34.0	26.93	0.03348	−3.869e-5	1.547e-8
Chloroform (g)	$CHCl_3$	65.8	24.00	.1893	−1.841e-4	6.657e-8
(l)		114.8	159.75	−0.3566	6.902e-4	
Chlorobenzene (l)	C_6H_5Cl	150.8	93.77	0.2732	−2.652e-4	
Cyclohexane (l)	C_6H_{12}	155.9	−75.225	1.1754	−1.344e-3	
Diethylamine (g)	$(C_2H_5)_2NH$	119.5				
(l)		172.5				
Diethyl ether (g)	$(C_2H_5)_2O$	112.5	21.42	.3359	−1.035e-4	−9.357e-9
Dimethylamine (g)	$(CH_3)_2NH$	115.7				
(l)		136.8				

(*continued*)

Table B.17 (continued)

Compound	Formula	C_p (approx.)	A	B	C	D
Dimethyl ether (g)	$(CH_3)_2O$	65.6				
(l)		102.3				
Ethane (g)	C_2H_6	52.5	5.409	0.1781	−6.94e-5	8.71e-9
(e)		68				
Ethanol (g)	C_2H_5OH	65.5	9.014	.2141	−8.39e-5	1.373e-9
(l)		112.0				
Ethyl acetate (g)	$CH_3COOC_2H_5$	113.6				
(l)		169.9				
Ethylbenzene (g)	C_8H_{10}	128.4	−43.10	.7072	−4.811e-4	1.301e-7
(l)		185.6				
Ethylene (g)	C_2H_4	43.7	3.806	.1566	−8.348e-5	1.755e-8
Ethylene glycol (g)	C_2HO_2	78.0				
Ethylene oxide (g)	C_2H_4O	48.2	−7.519	.2222	−1.256-e4	2.592e-8
Formaldehyde (g)	CH_2O	35.4				
Glycerol (glycerin) (l)	$C_3H_8O_3$	150.2				
n-Heptane (g)	C_7H_{16}	165.9	−5.146	0.6762	−3.651e-4	7.658e-8
(l)		212				
n-Hexane (g)	C_6H_{14}	143.1	−4.413	0.528	−3.119e-4	6.498e-8
(l)		189.1				
Hydrazine (g)	N_2H_4	45.5	9.768	0.1895	−1.657e-4	6.025e-8
(l)		98.9				
Hydrogen (g)	H_2	29.1	27.14	0.0093	−1.381e-5	7.645e-9
Hydrogen chloride (g)	HCl	29.5	30.67	−0.0072	1.246e-5	−3.898e-9
Hydrogen cyanide (g)	HCN	36.0	21.86	0.06062	−4.961e-5	1.815e-8
Hydrogen sulfide (g)	H_2S	34.2	31.94	0.001436	2.432e-5	−1.176e-8
Isobutane (g)	C_4H_{10}	97.2	−1.390	0.3847	−1.846e-4	2.895e-8
Isobutene (g)	C_4H_8	89.9	16.05	0.2804	−1.091e-4	9.098e-9
Isopentane (g)	C_5H_{12}	118.7	−9.525	0.5066	−2.729e-4	5.723e-8
Isopropanol (g)	C_3H_7OH	80	32.43	0.1885	6.406e-5	−9.261e-8
(l)		155				
Lactic acid (g)	$C_3H_6O_3$	145				
(l)		262				

Compound	Formula	C_p (approx.)	*A*	*B*	*C*	*D*
Methane (g)	CH_4	35.7	19.25	0.05213	1.197e-5	−1.132e-8
Methyl acetate (l)	CH_3COOCH_3	155.6				
Methanol (g)	CH_3OH	43.9	21.15	0.07092	2.587e-5	−2.852e-8
(l)		81.2				
Nitric oxide (g)	NO	29.8	29.35	−9.378e-4	9.747e-6	−4.187e-9
Nitrogen (g)	N_2	29.1	31.15	−1.357e-2	2.680e-5	−1.168e-8
Nitrogen dioxide (g)	NO_2	36.97				
Nitrogen tetroxide (g)	N_2O_4	77.26				
(l)		142.51				
Nitrous oxide (g)	N_2O	38.5	21.62	7.281e-2	−5.778e-5	1.830e-8
n-Octane (g)	C_8H_{18}	188.7	−6.096	0.7712	−4.195e-4	8.855e-8
(l)		255				
Oxygen	O_2	29.3	29.1	0.01158	−6.076e-6	1.311e-8
n-Pentane (g)	C_5H_{12}	120.1	−3.626	0.4873	−2.58e-4	5.305e-8
(l)		168.6				
Phenol (g)	C_6H_5OH	103.6				
Phosgene (g)	$COCl_2$	57.7				
Potassium nitrate (l)	KNO_3	123.4				
n-Propane (g)	C_3H_8	73.6	−4.224	0.3063	−1.586e-4	3.215e-8
n-Propanol (g)	C_3H_7OH	87.3	2.470	.3325	−1.855e-4	4.296e-8
(l)		150.9	346.30	−1.749	3.552e-3	
Propylene (g)	C_3H_6	63.9	3.710	.2345	−1.160e-4	2.205e-8
Silicon tetrachloride (l)	$SiCl_4$	135.6				
Sodium nitrate (l)	$NaNO_3$	155.6				
Styrene (g)	C_8H_8	122.1	−28.25	.6159	−4.023e-4	9.935e-8
(l)		182.6				
Sulfur (g)	S_8	156.1				
(l)	S	32				
Sulfur dioxide (g)	SO_2	39.9	23.85	0.06699	−4.961e-5	1.328e-8
Sulfur trioxide (g)	SO_3	50.8	19.21	0.1374	−1.176e-4	3.700e-8
Toluene (g)	$C_6H_5CH_3$	103.8	−24.35	0.5125	−2.765e-4	4.991e-8
(l)		157.2	125.8	0.0565	1.3593-4	
Triethylamine (g)	$(C_2H_5)_3N$	160.9				

(*continued*)

Table B.17 (continued)

Compound	Formula	C_p (approx.)	A	B	C	D
Trimethylamine (g)	$(CH_3)_3N$	91.8				
Water (g)	H_2O	33.6	32.24	0.01924	1.055e-5	−3.596e-9
(l)		75.4	72.43	0.0104		
o-Xylene (g)	C_8H_{10}	133.3	−15.85	0.5962	−3.443e-4	7.528e-8
m-Xylene (g)	C_8H_{10}	127.6	−29.27	0.6297	−3.747e-4	8.478e-8
p-Xylene (g)	C_8H_{10}	126.9	−25.09	0.6042	−3.374e-4	6.820e-8

For approximate calculations, use the number in the column labeled "C_p (approx.)," which is the heat capacity at 25°C. For more accurate calculations, use the polynomial expression $C_p = A + BT + CT^2 + DT^3$, where C_p is in J/gmol K (or J/gmol °C) and T is in K. To convert to cal/gmol K or to Btu/lbmol °F, multiply by 0.239.
Source: Compiled from data in *Introductory Chemical Engineering Thermodynamics*, J. R. Elliott and C. T. Lira, Prentice-Hall, 1999; *Perry's Chemical Engineers' Handbook,* 6th ed.; and *Lange's Handbook of Chemistry,* 14th ed.

Table B.18 Heat Capacity C_p of Selected Solids

Compound	Formula	C_p, J/gmol K (with T in K)
Benzoic acid	C_6H_5COOH	147
Calcium carbonate	$CaCO_3$	$82.3 + 0.497T - 1.287e6/T^2$
Carbon (graphite)	C	$11.2 + 0.0109T - 4.89e5/T^2$
Glucose	$C_6H_{12}O_6$	226 (25°C)
Gold	Au	$23.47 + 0.006T$
Iron oxide	FeO	$52.8 + 0.006T - 3.188e5/T^2$
	Fe_2O_3	$103.4 + 0.69T - 1.77e6/T^2$
	Fe_3O_4	$172.3 + 0.0787T - 4.1e\text{-}6/T^2$
Magnesium chloride	$MgCl_2$	$72.4 + 0.0158T$
Naphthalene	$C_{10}H_8$	$150.5 + 0.6T$
Phenol	C_6H_5OH	220.6 (20°C)
Silicon	Si	$24.0 + 0.0025T - 4.225e5/T^2$
Silicon dioxide (quartz)	SiO_2	$45.5 + 0.036T - 1.01e6/T^2$
Sodium chloride	NaCl	$45.15 + 0.0176T$
Sucrose	$C_{12}H_{22}O_{11}$	428 (at 20°C)
Titanium dioxide	TiO_2	$49.4 + 0.0315T - 1.75e5/T^2$
Urea	CH_4N_2O	80.3 (at 20°C)

Source: Compiled from data in *Perry's Chemical Engineers' Handbook*, 6th ed, and NIST Chemistry Webbook.

Table B.19 Heat Capacity C_p of Miscellaneous Materials

Material	C_p, J/g K
Cellulose	1.34
Clay	0.94
Coal	1.09 to 1.55
Concrete	0.65
Diamond	0.61
Fireclay brick	1.25 (1500°C)
Glass (pyrex)	0.8
Limestone	0.91
Rubber	1.74
Sand	0.8
Silk	1.38
Steel	0.50
Wood	1.9 to 2.7
Wool	1.36

Source: *Perry's Chemical Engineers' Handbook*, 6th ed.

B.8 Temperature and Enthalpy of Phase Change

Table B.20 Enthalpy of Melting $\Delta\hat{H}_m$ at the Normal Melting Temperature T_m and Enthalpy of Vaporization $\Delta\hat{H}_v$ at the Normal Boiling Temperature T_b at 1.0 atm

Compound	Formula	T_m (°C)	$\Delta\hat{H}_m$ kJ/gmol	T_b (°C)	$\Delta\hat{H}_v$ kJ/gmol
Acetaldehyde	C_2H_4O	−123.5	3.2	21	25.8
Acetic acid	$C_2H_4O_2$	16.6	11.535	118.3	23.7
Acetic anhydride	$C_4H_6O_3$	−73.1	10.5	137	41.2
Acetone	C_3H_6O	−94.8	5.691	56.5	29.1
Acetonitrile	C_2H_3N	−45	8.2	81.6	34.2
Acetylene	C_2H_2	−80.8	3.8	−84	17.0
Acrylonitrile	C_3H_3N	−83.5	6.23	77.3	32.6
Adipic acid	$C_6H_{10}O_4$	153.2	34.58		

(*continued*)

Table B.20 (continued)

Compound	Formula	T_m (°C)	$\Delta\hat{H}_m$ kJ/gmol	T_b (°C)	$\Delta\hat{H}_v$ kJ/gmol
Ammonia	NH_3	−77.7	5.66	−33.4	23.35
Argon	Ar	−189.3	1.2	−185.8	6.65
Benzene	C_6H_6	5.5	9.951	80.1	30.7
Benzoic acid	C_6H_5COOH	122	18.0	249	90.6
Bromine	Br_2	−7.2	10.79	58.0	31.045
Bromoform	$CHBr_3$	−6	11.1	149	39.66
Butadiene, 1,3	C_4H_6	−108.9	7.984	−4.4	22.5
n-Butane	C_4H_{10}	−138.3	4.664	−0.5	22.4
Calcium carbonate	$CaCO_3$	1282	(53)		
Calcium chloride	$CaCl_2$	782	25.5		
Carbon (graphite)	C	3600	46		
Carbon dioxide	CO_2	−57.5	7.95	−78.4	25.23
Carbon disulfide	CS_2	−112	4.395	46.5	
Carbon monoxide	CO	−205.0	0.837	−191.5	6.04
Carbon tetrachloride	CCl_4	−24.0	2.69	77	30.46
Chlorine	Cl_2	−100.98	6.41	−34.6	20.41
Chlorobenzene	C_6H_5Cl	−45	9.55	131.8	35.19
Chloroform	$CHCl_3$	−63.6	8.80	61	29.24
Diethylamine	$(C_2H_5)_2NH$	−93	5.94	58	29.1
Diethyl ether	$(C_2H_5)_2O$	−116.3	7.272	34.6	27.39
Dimethylamine	$(CH_3)_2NH$	−92.2	5.943	7.8	26.4
Dimethyl carbonate	$C_3H_6O_3$	−5.6		90	33.2
Dimethyl ether	$(CH_3)_2O$	−141.6	4.94	−24	21.51
Ethane	C_2H_6	−183.3	2.859	−88.9	14.7
Ethyl acetate	$CH_3COOC_2H_5$	−83.6	10.481	77.1	31.9
Ethylbenzene	C_8H_{10}	−94	9.2	136.2	35.6
Ethanol	C_2H_5OH	−114.5	5.021	78.3	38.6
Ethylamine	$C_2H_5NH_2$	−81		15	27.5
Ethylene	C_2H_4	−169.4	3.4	−103.7	14.45
Ethylene glycol	$C_2H_6O_2$	−11.5	11.234	197	49.6
Ethylene oxide	C_2H_4O	−112.44	5.2	13	25.5
Formaldehyde	CH_2O	−92		−19	23.3

Compound	Formula	T_m (°C)	$\Delta\hat{H}_m$ kJ/gmol	T_b (°C)	$\Delta\hat{H}_v$ kJ/gmol
Formic acid	CH_2O_2	8.3	12.72	101	22.7
Gallium	Ga	29.8	5.59	2071	
Glycerol	$C_3H_8O_3$	18.2	8.475	287	91.7
n-Heptane	C_7H_{16}	−90.6	14.162	98.4	31.8
n-Hexane	C_6H_{14}	−95.3	13.078	68.74	28.9
Hydrazine	N_2H_4	2	12.7	113.3	45.3
Hydrogen	H_2	−259.2	0.117	−252.7	0.904
Hydrogen chloride	HCl	−114.2	1.99	−85.0	16.15
Hydrogen peroxide	H_2O_2	−2	10.54	158	42.97
Hydrogen cyanide	HCN	−13.4	8.412	25.7	25.217
Hydrogen sulfide	H_2S	−85.5	2.376	−60.3	18.67
Iron	Fe	1530	14.895	2735	354
Iron oxide	FeO	1380			
Isobutane	C_4H_{10}	−159.42	4.611	−11.7	
Isopentane	C_5H_{12}	−159.9	5.147	27.86	
Isopropanol	C_3H_8O	−89.5	5.373	82.3	39.9
Lactic acid	$C_3H_6O_3$	16.8		217	63.4
Methane	CH_4	−182.5	0.937	−161.4	8.535
Methyl acetate	CH_3COOCH_3	−98		56.3	30.3
Methanol	CH_3OH	−97.9	3.177	64.7	
Methylamine	CH_2NH_3	−93.5	6.133		25.6
Methyl ethyl ether	$CH_3OC_2H_5$			10.8	26.7
Naphthalene	$C_{10}H_8$	80.2	19.123	218	43.3
Nitric acid	HNO_3	−47	2.51	83	
Nitric oxide	NO	−163.6	2.3	−151.7	13.83
Nitrogen	N_2	−210.0	0.720	−195.8	5.59
Nitrogen dioxide	NO_2			21.93	
Nitrogen tetroxide	N_2O_4	−13	23.2	30	29.5
Nitroglycerin	$C_3H_5N_3O_9$	13		256	92
Nitrous oxide	N_2O	−90.8	6.5	−88.5	16.53
n-Octane	C_8H_{18}	−56.8	20.652	125.66	34.4
Oxygen	O_2	−218.9	0.444	−182.9	6.816

(*continued*)

Table B.20 (continued)

Compound	Formula	T_m (°C)	$\Delta\hat{H}_m$ kJ/gmol	T_b (°C)	$\Delta\hat{H}_v$ kJ/gmol
n-Pentane	C_5H_{12}	−129.7	8.419	36.08	25.8
Phenol	C_6H_5OH	40.9	11.289	181.8	45.9
Phosgene	$COCl_2$	−127.9	5.74	7.6	24.4
Propane	C_3H_8	−181.7	3.526	−42.1	19.0
Propionic acid	C_2H_5COOH	−21	10.66	139.3	55
n-Propanol	C_3H_7OH	−126.1	5.195	97.2	41.4
Propylene	C_3H_6	−185.3	3.004	−47.7	18.4
Silicon	Si	1427	39.6	2290	
Silicon tetrachloride	$SiCl_4$	−67.6	7.7	56.8	28.7
Silicon dioxide (quartz)	SiO_2	1470	14.226	2230	
Sodium carbonate	Na_2CO_3	854	29		
Sodium chloride	NaCl	747	25.69	1392	158.78
Sodium cyanide	NaCN	562		1500	155.98
Sodium hydroxide	NaOH	322	8.4	1378	
Sulfur	S	114	1.727	444.6	9.20
Sulfur dioxide	SO_2	−75.5	7.401	−5	24.94
Sulfur trioxide	SO_3	17			
Sulfuric acid	H_2SO_4	10.5	9.87		
Styrene	C_8H_8	−30.6	11.0	145.1	37.05
Toluene	$C_6H_5CH_3$	−95	6.851	110.6	33.2
Triethylamine	$(C_2H_5)_3N$	−114		89.6	31.0
Trimethylamine	$(CH_3)_3N$	−117.1	6.5	2.9	22.9
Trinitrotoluene	$C_7H_5N_3O_6$	79	23.4	explodes	
Urea	CH_4N_2O	133	14.5	decomposes	87.9 (sublim.)
Water	H_2O	0.0	6.008	100.0	40.65
o-Xylene	C_8H_{10}	−25.2	13.611	144.4	36.2
m-Xylene	C_8H_{10}	−47.2	11.554	139.1	36.7
p-Xylene	C_8H_{10}	13.2	16.805	138.4	35.7

Source: Compiled from data in *Perry's Chemical Engineers' Handbook,* 6th ed., *CRC Handbook of Chemistry and Physics,* 70th ed., *Lange's Handbook of Chemistry,* 14th ed.

B.9 Enthalpies of Solution and of Mixing

Table B.21 Enthalpy of Solution of Organic Solids Dissolved in Water, $\Delta\hat{H}_{soln}$, at Infinite Dilution and 25°C

Compound	Formula	$\Delta\hat{H}_{soln}$ kJ/gmol solute
Acetic acid	$C_2H_4O_2$	−9.418
Citric acid	$C_6H_8O_7$	−22.598
Lactose	$C_{11}H_{22}O_{11}\cdot H_2O$	−15.50
Maleic acid	$C_4H_4O_4$	−18.58
Menthol	$C_{10}H_{20}O$	0
Phenol	C_6H_5OH	−10.9
Phthalic acid	$C_8H_6O_4$	−20.38
Picric acid	$C_6H_3N_3O_7$	−29.7
Potassium citrate		+11.8
Sodium citrate(tri)		+22.05
Sucrose	$C_{12}H_{22}O_{11}$	−5.518
Urea	CH_4N_2O	−15.1
Vanillin		−21.8

+ denotes heat evolved (exothermic), − denotes heat absorbed (endothermic).
Source: Compiled from data in *Perry's Chemical Engineers' Handbook.*

Table B.22 Enthalpy of Solution of Inorganic Solids Dissolved in Water, $\Delta\hat{H}_{soln}$, at Indicated Dilution and 18°C

Compound	Formula	Dilution, gmol water per g substance	$\Delta\hat{H}_{soln}$ kJ/gmol solute
Aluminum chloride	$AlCl_3$	600	−325.9
Ammonium chloride	NH_4Cl	∞	+15.98
Ammonium sulfate	$(NH_4)_2SO_4$	∞	+11.5
Calcium chloride	$CaCl_2$	∞	−20.5
Calcium chloride	$CaCl_2.H_2O$	∞	−51.46

(*continued*)

Table B.22 (continued)

Compound	Formula	Dilution, gmol water per g substance	$\Delta\hat{H}_{soln}$ kJ/gmol solute
Ferric chloride	$FeCl_2$	1000	−132.6
Phosphoric acid	H_3PO_4	400	−11.67
Sodium bicarbonate	$NaHCO_3$	1800	+17.15
Sodium carbonate	Na_2CO_3	∞	−23.30
Sodium carbonate	$Na_2CO_3.H_2O$	∞	−9.16
Sodium carbonate	$Na_2CO_3.7H_2O$	∞	+45.22
Sodium carbonate	$Na_2CO_3.10H_2O$	∞	+67.86
Sodium hydroxide	NaOH	∞	−42.59

− denotes heat evolved (exothermic), + denotes heat absorbed (endothermic).
Note: $\Delta\hat{H}_{soln}$ is very sensitive to waters of hydration and to dilution factor.
Source: Compiled from data in *Perry's Chemical Engineers' Handbook.*

Table B.23 Enthalpy of Mixing of Liquids or Gases with Water at 25°C

Compound	Formula	$\Delta\hat{H}_{mix}$ kJ/gmol solute
Acetic acid (l)	CH_3COOH	−1.506
Ammonia (g)	HN_3	−30.5
Formic acid (l)	HCOOH	−0.85
Hydrogen chloride (g)	HCl	−74.84
Nitric acid (l)	HNO_3	−33.27

− denotes heat evolved.
Source: *Perry's Chemical Engineers' Handbook*, 6th ed.